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Aids to Navigation State Risk Assessment Model and Application Based on AHP and Entropy Weight Method

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Abstract. The assessment and analysis of the operational status and safety risks associated with Aids to navigation hold paramount significance in ensuring the safety of maritime navigation. This paper constructs a risk assessment system for Aids to navigation based on the AHP (Analytic Hierarchy Process) and entropy weight method. The evaluation system employs the AHP to subjectively weight both discrete and continuous data, while the entropy weight method is applied to objectively weight data that can be continuously monitored. The subjective and objective weights are combined with nonlinear weights to construct a risk assessment model. The model has been applied to analyze and evaluate the Aids to navigation data of the waters of Guangzhou Maritime Safety Bureau in 2023. The evaluation results show that the power risk of the aids to navigation is the main risk of the existing aids to navigation.

Key words. Aids to navigation; Risk assessment; AHP; Entropy weight

1. Introduction

Aids to navigation are the navigational aid facilities for ship navigation, which have the role of calibrating obstructive objects. Aids to navigation are not only an indispensable component of the maritime and port safety systems, but also essential means of ensuring the safety of vessel navigation. The technical status of the Aids to navigation directly affects the safe navigation of the ship. However, the current remote control and telemetry technology for Aids to navigation fall short in providing comprehensive monitoring for them. Therefore, it is of paramount importance to comprehensively and effectively assess

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the status and risks associated with Aids to navigation.

The maintenance and management of early Aids to navigation were mainly based on manual patrol inspection, which was long, laborious and inefficient. With the development of Aids to navigation telemetry remote control technology, it has transcended the traditional forms of Aids to navigation maintenance and management, ushering in a higher quality of service [1]. Relevant research institutions at home and abroad carried multiple types of sensors on traditional Aids to navigation to dynamically manage and monitor Aids to navigation [2,3]. In the early stage, relevant R&D institutions have introduced information measurement and control technology into Aids to navigation management [4,5]. With the development of technology, Ma Jialin et al. applied NB-IoT technology to the telemetry remote control system of the Aids to navigation [6]. Yue Zhiyong et al. introduced Beidou satellite communication technology to the remote control telemetry system of the Aids to navigation, which improved the maintenance quality of the Aids to navigation [7]. However, in practical applications, various factors can lead to a significant number of false and missed alarms in Aids to navigation remote monitoring and control systems [8]. Therefore, it is essential to conduct a risk assessment of Aids to navigation. In the research of Aids to navigation evaluation and maintenance, Hye-Ri et al. developed objective indicators and evaluation models for Aids to navigation, using the AHP for the evaluation of these aids [9]. Nie Ziyi et al. combined Fuzzy and AHP to quantitatively evaluate the Aids to navigation [10], but the evaluation index system was incomplete. Deng Zhusen used the GM(1,1) model to forecast Aids to navigation workload in the northern waters of China [11]. They employed continuous grey differential equations to analyze system development, which has contributed to the management and maintenance of Aids to navigation.

Due to the presence of both continuous and discrete data in Aids to navigation risk assessment indicators, previous studies primarily addressed qualitative assessments of discrete indicators, lacking quantitative evaluations based on continuous data, and exhibiting an incomplete evaluation indicator system. Therefore, this paper establishes a risk evaluation index system for Aids to navigation in terms of lamps, power supply, appearance, and environment. Additionally, it endeavors to develop a Aids to navigation risk assessment model by amalgamating qualitative and quantitative methodologies.

2. Evaluation System of Aids to Navigation System

According to the maintenance technical specifications of Aids to navigation in the Technical Specifications for Maintenance of Inland Waterways, this paper establishes a set of risk assessment indicators based on Aids to navigation, which are shown in Table 1.

The first level indicator of the evaluation system is the Aids to navigation. As for the second level, on one hand, the natural channel where the Aids to navigation are located has turbulent water flow and high air humidity, which is easy to cause the abnormality of the Aids to navigation and brings potential safety hazards to the passage of ships. Thus, it is necessary to evaluate the influence of hydrological and meteorological environment on the Aids to navigation. On the other hand, the appearance of the Aids to navigation is required to meet the relevant standards, with bright colors, long-lasting and bright lighting, and excellent lighting quality. Therefore, the second level consists of the main component structure of the Aids to navigation and the environment in which the Aids to navigation are located, including the Aids to navigation light, the appearance of the Aids to navigation, the power supply of the Aids to navigation, and the environment in which the beacon is located. All these indicators are recorded as the first-level indicators. The third level of the evaluation system is the specific evaluation index of the Aids to navigation, including voltage, power supply, light color, light range, light cycle, light rhythm, number of remaining bulbs, daylight threshold, voltage, internal resistance, battery temperature, appearance, color, location, structure, temperature, humidity, light intensity, water depth, flow rate, wind speed, which are recorded as the second-level indicators.

Table 1. Aids to navigation risk evaluation index system

The total indicator	The first-level indicators	The second-level indicators
		Light color (X_{11})
		Light range (X_{12})
	Aids to navigation light (X_1)	Light cycle (X_{13})
		Light rhythm (X_{14})
		Number of bulbs remaining (X_{15})
		Voltage (X_{21})
		Current (X_{22})
	Power supply (X_2)	Resistance (X_{23})
Aids to navigation		Temperature (X_{24})
		Appearance (X_{25})
		Color (X_{31})
	Appearance (X_{3})	Location (X_{32})
		Structure (X_{33})
		Temperature (X_{41})
		Humidity (X_{42})
	Environment (X_4)	Light intensity (X_{43})
		The depth of the Water (X_{44})
		Water flow rate(X_{45})
		Wind velocity(X_{46})

3. AHP-entropy Weight Method Aids to Navigation Risk Evaluation Model

The evaluation system of Aids to navigation includes discrete properties (such as appearance, etc.) and continuous properties (such as current, etc.). Among them, for discrete risk indicators, the common assessment method is to score experts; and for the evaluation index of continuous nature, the evaluation method of calculating the mathematical characteristic value is normally adopted. In this paper, for the risk evaluation of navigation standard equipment, the subjective weight of discrete and continuous index data are determined by analytic hierarchy method [13, 14], and the objective continuous index data is objectively weighted by the entropy method. Finally, the subjective and objective weights are combined nonlinear to determine the final weights. The calculation process is shown in Fig. 1.

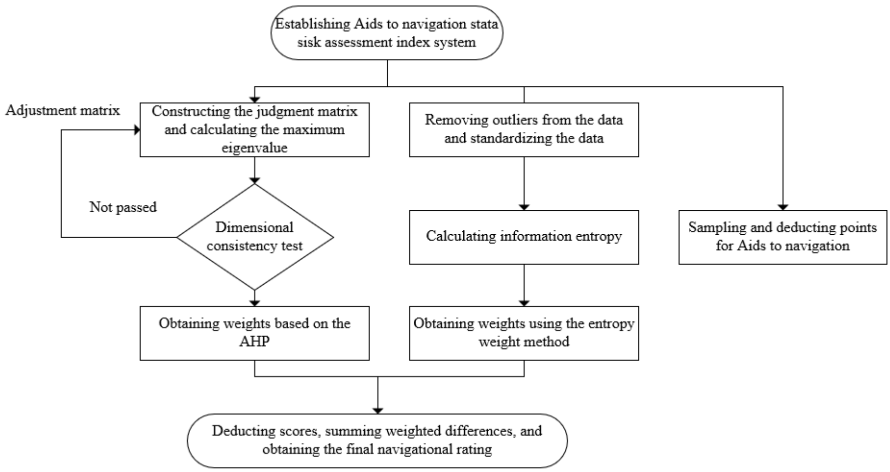

Figure 1. Calculation process of navigation mark risk system based on AHP-entropy method

3.1 Weight Calculation Based on the AHP Method

From the established risk evaluation index system of Aids to navigation, different risk factors of the same index layer are compared in pairs, so as to obtain a judgment matrix. The weight vector of the judgment matrix is calculated and the consistency test is performed as follows:

1) Build a judgment matrix

According to the established risk assessment system of Aids to navigation, the risk factors of the same index layer of Aids to navigation are compared. The comparative results were numerically quantified using relative measures, and the quantitative result values were given using T.L. Saaty's 1-9 scale method.

$$X = \left(x_{ij}\right)_{n \times n} = \begin{pmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nn} \end{pmatrix} \tag{1}$$

X is the judgment matrix; x_{ij} is the ith row and jth column elements of matrix X; n is the order of the matrix.

2) Normalize X and Calculate the feature vector

$$\overline{w}_i = \left(\prod_{j=1}^{n} x_{ij}\right)^{\frac{1}{n}}, i, j = 1, 2, \ldots, \text{n} \tag{2}$$

x_{ij} is the element of the jth column of row i in the judgment matrix X; $\overline{w}_i$ is the geometric mean of row i in the judgment matrix X.

3) Calculate the weight vector

$$w_i' = \overline{w}_i / \sum_{i=1}^{n} \overline{w}_i, i = 1,2,...,n \tag{3}$$

w_i' is the weight of the ith indicator, $\overline{w}_i$ is the geometric mean of row i in the judgment matrix X

4) Calculates the maximum feature root $\lambda_{\max}$ of the matrix

$$\lambda_{\max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(Xw')_i}{nw_i'} \tag{4}$$

$\lambda_{\max}$ is the maximum eigenvalue of the judgment matrix, w_i' is the weight of the ith indicator

5) Consistency indicators: CI and consistency ratio: CR

$$CR = \frac{CI}{RI} \tag{5}$$

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{6}$$

n is the order of the judgment matrix *X*. The selection of *RI* is shown in Table 2. If $CR< 0.10$, the judgment matrix B of the risk assessment of the Aids to navigation is consistent.

6) Normalization determines indicator weights

If the judgment matrix is tested for consistency, the normalization of the feature vectors w_i' can obtain the weights of risk indicators at all levels in the risk evaluation of the Aids to navigation.

Table 2. RI comparison

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.54	0.89	1.12	1.25	1.34	1.42	1.45

3.2 Weight Calculation Based on the Entropy Weight Method

The entropy weight method is objectively weighted, and the degree of influence of this index on the evaluation is determined by calculating the degree of discreteness of the index data [15, 16, 17], and this paper introduces the entropy weight method to calculate the weights for the third layer of continuous indicators $X\text{-}X_2\text{-}X_{21}$ and $X\text{-}X_2\text{-}X_{22}$.

3.2.1 Removing Extreme Values and Data Normalization

In order to reduce the influence of extreme values on entropy values, if the data values of a single sample exceed 20% of the total sum of the overall data, the data values are excluded after referring to relevant studies.

The entropy value is calculated logarithmically, and the data after extreme values are standardized by the critical value method with reference formula (7).

$$z_{i,t} = \frac{x_{i,t} - \min\limits_{t} x_{i,t}}{\max\limits_{t} x_{i,t} - \max\limits_{t} x_{i,t}} \tag{7}$$

$x_{i,t}$ is the tth data in the monitoring data of the evaluation index i of the Aids to navigation.

$z_{i,t}$ is the tth data in the monitoring data of the Aids to navigation evaluation index i after removing the extreme value.

3.2.2 Entropy Calculation

The data set that excludes the extreme values is substituted into the formula (6)~(7), and the objective weights w_i'' are calculated.

$$H_i = -k\sum_{t=1}^{m} f_{it} \cdot \ln\left(f_{it}\right) \tag{8}$$

$$f_{it} = z_{it} / \sum_{t=1}^{m} z_{it} \tag{9}$$

$$k = \frac{1}{\ln m} \tag{10}$$

$$w_i'' = \frac{1 - H_i}{\sum\limits_{i}\left(1 - H_i\right)} \tag{11}$$

w_i'' is the entropy weight of indicator i, m is the total number of samples after z_{jt} removed from extreme values. H_i is the entropy value corresponding to the Aids to navigation index i.

3.3 The Final Weight

The analytic hierarchy method subjectively determines the weights by experts, the entropy method determines the weights from objective information data, and the weights calculated by the analytic hierarchy method and the weights calculated by the entropy method are nonlinear weighted to obtain the final weight w_i.

$$w_i = \frac{w_i' w_i''}{\sum_{i=1}^{t} w_i' w_i''} \tag{12}$$

w_i' is the subjective weight determined by analytic hierarchy. w_i'' is the objective weight determined by entropy method.

3.4 The Total Score of the Risk Assessment of the Aids to Navigation

Points are deducted from the evaluation indicators, multiplied by the corresponding weights and then summed, and the calculation formula is shown in equation (9).

$$D = \sum_i w_i d_i \tag{13}$$

D—Weighted total demerit points for Aids to navigation

d_i—The demerit value of the evaluation indicator i of the Aids to navigation

Referring to the current assessment specifications, this paper divides the risk level of the beacon into three levels, as shown in Table 3, of which the level 1 risk is the smallest risk, the level 2 risk is the medium risk, and the level 3 risk is the larger risk.

Table 3. navigation risk classification

Risk level	Level I risk	Level II risk	Level III risk
Score interval	（0,25）	(25,40)	(40,100)

4. Research on the Application of Risk Evaluation System for Aids to Navigation

4.1 Evaluation Process

This paper explores the historical data of navigation beacons in the waters of the Guangzhou Maritime Safety Bureau to take sensor data from 8 am to 12 am on March 21, 2023.

According to the chromatographic analysis method, the first-level factors set $U=\{X_1, X_2, X_3, X_4\}$={Aids to navigation lamp, power supply, appearance, environment} are es tablished, and the judgment matrix of the Aids to navigation index is constructed. Throu gh the investigation of the Aids to navigation, after the analysis of the Aids to navigatio n failure, relevant experts were invited to make judgment decisions on this matrix, and t he judgment matrix of the criterion layer to the target layer was obtained, as shown in T able 4.

Table 4. Judgment matrix for the first-level indicators

	X_{11}	X_{12}	X_{13}	X_{14}
Aids to navigation light	1	1/3	5	3
Aids to navigation power supply	3	1	7	4
Aids to navigation appearance	1/5	1/7	1	1/2
Waterway environment	1/3	1/4	2	1

According to the judgment matrix in Table 3, the weight of the first-level indicators are calculated, and the calculation process is as follows:

1) The judgment matrix B of the criterion layer for the target layer.

$$X=\begin{bmatrix} 1 & \frac{1}{3} & 5 & 3 \\ 3 & 1 & 7 & 4 \\ \frac{1}{5} & \frac{1}{7} & 1 & \frac{1}{2} \\ \frac{1}{3} & \frac{1}{4} & 2 & 1 \end{bmatrix}$$

2) According to formulas (2)-(3), calculate the eigenvector w_i' of the criterion layer relative to the target layer.

$$w_i'=\begin{bmatrix} 0.272 \\ 0.549 \\ 0.063 \\ 0.116 \end{bmatrix}$$

3) According to formula (4), calculate and judge the maximum eigenvalue λ_{max}=4.07 of matrix X.

4) According to the formula (5) and (6), calculate and judge the matrix consistency index CI and the consistency ratio CR.

CI=0.023, CR=0.026, because CR=0.026<0.1, so the judgment matrix meets the requirements.

Similarly, the judgment matrix formula (2)-(6) of the construction scheme layer for the criterion layer calculates the subjective weight w' of each evaluation index of the third level as shown in Table 5-8 and the total ranking of the consistency test level, CR is less than 1, which meets the consistency requirements.

Table 5. X_{1j}'s judgment matrix and weight for X_1（j=1,2,3,4,5）

X_1-X_{1j}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	w_{1j}
X_{11}	1	1/3	1/3	2	1/3	0.1
X_{12}	3	1	2	3	1/2	0.26
X_{13}	3	1/2	1	2	1/3	0.17
X_{14}	1/2	1/3	1/2	1	1/5	0.07
X_{15}	3	2	3	5	1	0.41

Table 6. X_{2j}'s judgment matrix and weight for X_2（j=1,2,3,4,5）

X_2-X_{2j}	X_{21}	X_{22}	X_{23}	X_{24}	X_{25}	w_{2j}
X_{21}	1	1	1/2	2	5	0.23
X_{22}	1	1	1/2	2	5	0.23
X_{23}	2	2	1	3	4	0.36
X_{24}	1/2	1/2	1/3	1	2	0.12
X_{25}	1/5	1/5	1/4	1/2	1	0.06

Table 7. X_{3j}'s judgment matrix and weight for X_3（j=1,2,3）

X_3-X_{3j}	X_{31}	X_{32}	X_{33}	w_{3j}
X_{31}	1	1/3	3	0.26
X_{32}	3	1	5	0.64
X_{33}	1/3	1/5	1	0.1

Table 8. X_{4j}'s judgment matrix and weight for X_4（j=1,2,3,4,5,6）

X_4-X_{4j}	X_{41}	X_{42}	X_{43}	X_{44}	X_{45}	X_{46}	w_{4j}
X_{41}	1	2	1/3	2	1/5	1/5	0.08
X_{42}	1/2	1	1/3	1	1/5	1/4	0.06
X_{43}	3	3	1	2	1/3	1/3	0.14
X_{44}	1/2	1	1/2	1	1/5	1/5	0.06
X_{45}	5	5	3	5	1	2	0.38
X_{46}	5	4	3	5	1/2	2	0.29

The weights w'' of the indicators X-X_2-X_{21} and X-X_2-X_{22} of continuity are calculated by formulas (8)-(12), and the final weight calculation results are shown in Table 9.

Table 9. The final calculated weight for the secondary metric

Evaluation indicators	w_i'	w_i''	w_i
X-X_1-X_{11}	0.1	-	0.1
X-X_1-X_{12}	0.26	-	0.26

Evaluation indicators	w_i'	w_i''	w_i
$X\text{-}X_1\text{-}X_{13}$	0.17	-	0.17
$X\text{-}X_1\text{-}X_{14}$	0.07	-	0.07
$X\text{-}X_1\text{-}X_{15}$	0.41	-	0.41
$X\text{-}X_2\text{-}X_{21}$	0.23	0.231	0.23
$X\text{-}X_2\text{-}X_{22}$	0.23	0.769	0.55
$X\text{-}X_2\text{-}X_{23}$	0.36	-	0.36
$X\text{-}X_2\text{-}X_{24}$	0.12	-	0.12
$X\text{-}X_2\text{-}X_{25}$	0.06	-	0.06
$X\text{-}X_3\text{-}X_{31}$	0.26	-	0.26
$X\text{-}X_3\text{-}X_{32}$	0.64	-	0.64
$X\text{-}X_3\text{-}X_{33}$	0.1	-	0.1
$X\text{-}X_4\text{-}X_{41}$	0.08	-	0.08
$X\text{-}X_4\text{-}X_{42}$	0.06	-	0.06
$X\text{-}X_4\text{-}X_{43}$	0.14	-	0.14
$X\text{-}X_4\text{-}X_{44}$	0.06	-	0.06
$X\text{-}X_4\text{-}X_{45}$	0.38	-	0.38
$X\text{-}X_4\text{-}X_{46}$	0.29	-	0.29

4.2. Analysis of Evaluation Results

The weight calculation based on the combination of AHP and the Entropy Weight Method addresses the limitations of subjective assessments and allows for the comprehensive consideration of both subjective and objective factors. This approach enhances the overall comprehensiveness, objectivity, and accuracy of the evaluation results. Based on Equation (13), the final calculated total score is 23 points, indicating a Level I risk. Because the total score of the Aids to navigation risk is close to the level II risk score, it has certain potential risks and needs to be strengthened maintenance and overhaul. The results of the existing risk analysis of the Aids to navigation show that the existing risk of the Aids to navigation mainly has four first-level factors: the Aids to navigation light, the power supply of the Aids to navigation, the appearance of the Aids to navigation, and the channel environment. The weights of its indicators are 0.27, 0.55, 0.06, 0.116, respectively. It can be seen that the risk of the power supply of the Aids to navigation is the main risk of the existing Aids to navigation, followed by the Aids to navigation light, and the environmental safety risk of the waterway is the smallest.

5. Conclusion

In this paper, the risk evaluation system of the Aids to navigation is constructed, which is divided into four first-level indicators and nineteen second-level indicators, and the analytic hierarchy method-entropy method is used to evaluate the navigation target in a certain water area in Guangzhou.

1) In this paper, the analytic hierarchy method is used to determine the subjective weight, the entropy method is used to determine the objective weight, and the subjective evaluation and objective evaluation are combined to obtain the final weight.

2) Taking the Aids to navigation in a certain water area in Guangzhou as an example for risk evaluation, it is concluded that the total demerit points of this navigation beacon risk are in the first-level risk range, but close to the second-level risk range, and the buoy needs to be maintained and overhauled.

3) This paper calculates the weights of individual evaluation criteria for Aids to navigation and arranges them in order of importance. This information can offer valuable guidance and recommendations for prioritizing the treatment of high-risk indicators, as well as determining inspection and maintenance frequencies for Aids to navigation.

4) In this paper, a static risk assessment of Aids to navigation is conducted using the AHP-entropy method. However, as a future research direction, it is recommended to explore dynamic methods for assessing the dynamic risks associated with Aids to navigation.

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