Navigational safety evaluation of cautionary area based on improved topological cloud model

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ABSTRACT

In order to ensure the safety of navigation of ships at the intersection of traffic flow, the design scheme of the cautionary area in the area of dense traffic flow should be evaluated for risk. This paper constructs a navigation safety evaluation index system for the cautionary area from four aspects: natural environment, traffic environment, ship factors, and management factors. Making full use of the advantages of COWA operator and improved topological cloud theory, the safety level of navigation in the cautionary area is evaluated based on the improved topological cloud model, and the safety evaluation of navigation before and after setting up the cautionary area is carried out with the example of the No.1 cautionary area in Qinzhou Bay. The example proves that the evaluation model is correct and practical, and can be used for the safety evaluation of navigation in the cautionary area.

Keywords: Safety evaluation of navigational safety in cautionary areas, COWA operator, topologically tractable cloud models

1. INTRODUCTION

Along with the development of China's shipping industry, shipping economic activities have become more frequent, the density of ship navigation in China's coastal waters has continued to increase, the ship traffic flow has become more and more complex, and the potential ship hazardous accidents are also increasing. While the ship routing system restrains and guides the traffic flow, multiple streams of traffic flow constantly converge to the cautionary area, resulting in the cautionary area of large ship traffic, complex traffic flow and navigational risks and other outstanding problems, the cautionary area has become a key link affecting the safe operation of China's coastal arterial shipping routes. Therefore, it is necessary to carry out navigation safety research on the cautionary area and compare the navigation safety evaluation level of ships before and after setting up the cautionary area in order to prove that the setting up of the cautionary area can guarantee the navigation safety of ships in the area of dense traffic flow.

In recent years, scholars at home and abroad have carried out a large number of studies on the safety of water navigation and the safety of cautionary areas. Fan et al.[1] used the coefficient of variation method to assign values to the evaluation indexes, and used the advantages of cloud model theory and object element topologisable theory, combined with the coefficient of variation method to construct a coefficient of variation cloud object element model to assess the risk of ship collision in the waters of conflict between ships out of the harbour and the traffic flow of ships in near-shore shipping routes; Xu[2] took Ningbo-Zhoushan core port area deep water shipping routes main intersection divided into three cautionary areas as the object, using grey correlation analysis method to establish a grey evaluation model, quantitative analysis and comparison of the danger of each cautionary area; Li et al.[3] to use the research method of the traffic conflict technology, to the cautionary area of the traffic flow conflict as the focus of the contents of the proposed change. The cautionary area small angle diagonal intersection channel crossing for large angle or orthogonal, as well as the cautionary area channelised traffic design and other methods. We try to reduce the number of traffic flow conflict points in the cautionary area, lower the conflict intensity, and improve the hazardous encounter conditions of ships at the micro level. Mikhail et al.[4] discussed the legitimacy of international law for the establishment of safety exclusion zones within 500 meters of the offshore waters, and required all countries, especially foreign backward countries, to implement safety exclusion zones, strictly abide by them, and take measures. The above research on navigation safety mainly focuses on harbours and waterways, and rarely compares the safety level of navigable waters before and after the setting up of the cautionary area. In terms of research methodology, through reviewing relevant literature, it is found that the topological cloud model combines the advantages of the uncertain reasoning characteristic of the cloud

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International Conference on Optics, Electronics, and Communication Engineering (OECE 2024),
edited by Yang Yue, Proc. of SPIE Vol. 13395, 133951M · doi: 10.1117/12.3048390

model and the qualitative and quantitative analyses of the physical element topological model, which is suitable for the problems of complex factors, insufficient information and difficult data collection in the evaluation of maritime safety. However, the existing research only adopts the cloud entropy calculation method of the " $3En$ " rule or the "50 per cent correlation" rule, without fully considering the distinct and fuzzy problems of the two methods.

In view of this, this paper analyses the influencing factors of navigational safety in the cautionary area and constructs the navigational safety index system in the cautionary area. Then COWA operator is introduced to determine the weights. In order to avoid the entropy value conflict problem brought by the traditional cloud entropy solution, the cloud entropy optimisation algorithm is introduced to construct an improved topable cloud model, and the improved comprehensive cloud correlation is combined with the indicator weights to get the comprehensive evaluation eigenvalue to determine the navigation safety evaluation level of the cautionary area, and the confidence factor is quoted to test the reliability of the results. Finally, taking Qinzhou Bay No.1 cautionary area as an example, the comprehensive evaluation of navigation safety in the maritime cautionary area is carried out to verify the adaptability and validity of the model in this paper, with a view to providing a reference for the research of navigation safety in the cautionary area afterwards.

2. ESTABLISHMENT OF THE INDEX SYSTEM FOR EVALUATING THE SAFETY OF NAVIGATION IN THE MARITIME CAUTIONARY AREA

By analysing and identifying the risk factors of navigation safety of ships in the cautionary area, fully considering the complexity and diversity of navigation safety in the cautionary area, combining with the relevant regulations and standards, and on the basis of referring to a large number of References[5-7] and experts' suggestions, a research index system for evaluating the navigation safety in the cautionary area is established. The following four level indicators are mainly considered: natural environment factors, traffic environment factors, ship factors and management factors. On this basis, 11 secondary indicators are expanded. The index system of navigation safety evaluation in the cautionary area is shown in Table 1.

Table 1. Research index system for evaluating navigation safety in the cautionary area.

Evaluation goal	First-level evaluation index	Secondary evaluation index
Indicator system for navigational safety evaluation research in the cautionary area A	Environment A_1	Wind A_{11}
		Flow A_{12}
		Visibility A_{13}
	Navigation environment A_2	Ship density A_{21}
		Traffic congestion point A_{22}
		Traffic accidents A_{23}
		Channel depth A_{24}
	Vessel factors A_3	Vessel length A_{31}
		Ship's speed A_{32}
	Management factors A_4	Aids to navigation A_{41}
		Maritime supervision A_{42}

3. DETERMINATION OF HIERARCHICAL BOUNDARIES FOR EVALUATION INDICATORS

After reviewing the literature related to the indicator system[8-10], and combining with the actual situation of Qinzhou Bay No. 1 cautionary area, the affiliation degree of each indicator corresponding to the indicator system is divided, as shown in Table 2.

Table 2. Hazard level grading criteria for evaluation indicators.

Degree of risk	**Very low risk**	**Low risk**	**Average risk**	**High risk**	**Very high risk**
Wind level	<3	3-5	5-8	8-10	>10
Maximum flow rate/kn	<0.5	0.5-1.5	1.5-2.5	2.5-4.0	>4.0
Number of days with poor visibility (days/year)	<15	15-25	25-40	40-50	>50
Vessel density (ships/day)	<30	30-60	60-120	120-150	>150
Number of traffic conflict points	<10	10-50	50-100	100-150	>150
Number of traffic accidents (cases/year)	<3	3-8	8-15	15-20	>20
Relative channel depth (ship's draught/channel depth)	<0.25	0.25-0.5	0.5-0.7	0.7-0.8	>0.8
Vessel length/m	<60	60-100	100-230	230-300	>300
Vessel speed/knot	<6.0	6.0-10.0	10.0-14.0	14.0-18.0	>18.0
Aids to navigation/pc	>10	8-10	6-8	3-6	<3
Maritime regulatory/equipment improvement rate	>80	60-80	40-60	20-40	<20

4. A SAFETY EVALUATION METHOD FOR CORDONED-OFF AREAS BASED ON IMPROVED TOPOLOGICAL CLOUD MODELS

4.1 The COWA operator determines the weights

Yager, a United States scholar, proposed the Ordered Weighted Averaging (OWA) operator, which weights the data and rearranges the extreme values of the data, which weakens the influence of the extreme values of the data on the results[11]. On this basis, Chinese scholar Wang Yu proposed a new method of OWA operator weighting, that is, the improved C-OWA operator weighting, which processes the position of the extreme value through the combination number, and selects the position that has less impact on the overall series, so as to avoid the deviation of the index weight calculation result caused by less data, and make the weight result more objective.Since the safety assessment of the ship's cautionary area under the fixed-line system is characterised by uncertainty and randomness, the COWA operator is used to assign weights to the indicators. The step-by-step process is as follows:

(1) N experts were invited to score the risk factors to form the original dataset $A(a_1, a_2, \cdots a_n)$, the collected data is then reordered in descending order to form a new data set B, i.e. $b_0 > b_1 > b_2 \cdots > b_{n-1}$.

(2) Computing the weighted vector ω_{m+1} of the data in dataset B by using the combination number C_{n-1}^m , $\sum_{m=0}^{n-1} \omega_{m+1} = 1$.

$$\omega_{m+1} = \frac{C_{n-1}^m}{\sum_{m=0}^{n-1} C_{n-1}^m} = \frac{C_{n-1}^m}{2^{n-1}}, m = 0,1,2,\cdots,n-1 \tag{1}$$

where C_{n-1}^m denotes the number of combinations of m data from n-1 data.

(3) The weighting vector ω_{m+1} weights the decision data to obtain absolute weights:

$$\tilde{\omega}_i = \sum_{m=0}^{n-1} \omega_{m+1} b_j , j = 0,1,2,\cdots,n-1 \tag{2}$$

(4) Normalisation was performed to calculate the relative weights ω_i:

$$\omega_i = \frac{\tilde{\omega}_i}{\sum_{i=0}^{n} \tilde{\omega}_i}, i = 0,1,2,\cdots,n \tag{3}$$

4.2 Improved topable cloud models

4.2.1 Topological cloud theory. In topology, the object element is the basic element describing the object of study, which is an ordered triad consisting of the name of the object N, the feature of the object C, and the measure value of that feature V, denoted $R = (N,C,V)$. If the thing N has an n feature and the corresponding measure value, the ordered triad can be expressed in the form shown in equation (4):

$$R = (N,C,V) = \begin{bmatrix} N & C_1 & V_1 \\ & \vdots & \vdots \\ & C_n & V_n \end{bmatrix} \tag{4}$$

The security assessment of the cautionary area is an uncertain and complex system, and the feature quantity V describing the characteristics of things in the traditional object-element model is a definite value, ignoring the ambiguity and randomness of things. In the theory of the topable cloud model, the classical domain $V_i = [v_{i,\min}, v_{i,\max}]$ of the thing element feature is transformed into the cloud model numerical feature (E_{xi}, E_{ni}, H_{ei}) through the cloud model algorithm formula, so as to achieve the qualitative evaluation of the uncertainty transformation of language and quantitative mathematical calculations[12]. At this time, equation (5) is transformed into the topable cloud model, which can be expressed as:

$$R = \begin{bmatrix} N & C_1 & (E_{x1}, E_{n1}^{m}, H_{e1}) \\ & \vdots & \vdots \\ & C_n & (E_{xn}, E_{nn}^{m}, H_{en}) \end{bmatrix} \tag{5}$$

4.2.2 Improved topable cloud models. The boundary information in this paper uses a double constraint space to constrain the fuzzy and stochastic features of the navigational safety level boundary of the cautionary area.

(a) Determination of E_x

From equation (6), the average value of the parameters of the topable cloud model, E_x, is calculated, and E_x reflects the interval optimum point:

$$E_x = \frac{C_{\max} + C_{\min}}{2} \tag{6}$$

where: $C_{\max}$ and $C_{\min}$ are the maximum and minimum values of the grade boundary information, respectively.

(b) Determination of En

The key to the cloud characteristic parameters is the determination of the cloud entropy En. Its value not only reflects the acceptability of the index state level but also directly relates to the accuracy of the index-level decision. According to the relevant literature, two methods of calculating En can be derived:

According to the cloud entropy calculation method of $3E_n$ rule[13], it is calculated by equation (7):

$$E_n = \frac{C_{\max} - C_{\min}}{6} \tag{7}$$

The cloud entropy calculation method based on the 50% correlation rule[14] is calculated using equation (8):

$$E_n = \frac{C_{\max} - C_{\min}}{2.3548} \tag{8}$$

As the cloud entropy calculated by the $3E_n$ rule is small, the boundary is clear, and it is easy to give a very low affiliation degree under the rank; the cloud entropy value calculated by the 50% relevance rule is too large, which makes the boundaries of the boundary line become fuzzy.

In order to consider both the distinct and fuzzy aspects of the above hierarchy at the same time, this paper adopts the cloud entropy optimisation algorithm to solve the entropy problem[15].

Assuming that the data of an evaluation metric is x_i and its state level number is p, it corresponds to p sets of hierarchical cloud models. $E_x^{(m)}{}_{1\times p}$ and $H_e^{(m)}{}_{1\times p}$ denote the expectation set and super entropy set of the cloud, respectively; $E_n'^{(m)}{}_{1\times p}$ and $E_n''^{(m)}{}_{1\times p}$ denote the cloud entropy set obtained from $3E_n$ and 50% correlation, respectively, $E_n^{(m)}{}_{1\times p}$ denotes the optimised cloud entropy set, and $m(m=1,2,\cdots,p)$ denotes the rank order number, the maximum deviation of correlation for a certain rank m, $\Delta\delta(x)_{\max}^{(m)}$, is as shown in equation (9).

$$\Delta\delta(x)_{\max}^{(m)} = (\delta(x)_{\max}''^{(x)} - \delta(x)^m)^2 + (\delta(x)^m - \delta(x)_{\min}'^{(m)})^2 \tag{9}$$

where: $\delta(x)_{\min}'^{(m)}$ denotes the small correlation of rank m calculated based on the $3E_n$ rule; $\delta(x)_{\max}''^{(x)}$ denotes the maximum correlation of rank m calculated based on the 50% correlation rule; $\delta(x)^m$ denotes the relevance of the optimised rank m.

The cloud entropy optimisation algorithm minimises the sum of the maximum correlation deviations of the indicator data from the p-group normal cloud model to obtain a non-linear model:

$$\begin{cases} \min \Delta\delta(x)_{\max}^{(m)}(E_n) = \sum_{m=1}^{p} \Delta\delta(x)_{\max}^{(m)} \\ s.t. E_n'^{(m)} \leqslant E_n^{(m)} \leqslant E_n''^{(m)} \end{cases} \tag{10}$$

From equation (10), the optimised cloud entropy set for a given metric $E_n^{(m)}{}_{1\times p}$.

(c) Determination of H_e

$$H_e = \lambda E_n \tag{11}$$

where: λ is a constant determined according to the degree of fuzziness, and λ is generally taken as 0.1 by reviewing relevant literature.

In summary, it is finally determined that the improved topable cloud model can be expressed as:

$$R = \begin{bmatrix} N & C_1 & (E_{x1}, E_{n1}^m, H_{e1}) \\ & \vdots & \vdots \\ & C_n & (E_{xn}, E_{nn}^m, H_{en}) \end{bmatrix} \tag{12}$$

Considering each sample data of navigation safety evaluation index in the cautionary area as a cloud droplet, a normal random number E_n' obeying expectation E_n and standard deviation H_e is generated. Then the cloud correlation k of each evaluation index is calculated as:

$$k = \exp\left[-\frac{(x - E_x)^2}{2(E_n')^2} \right] \tag{13}$$

where: $E_n' \sim N(E_n, H_e)$.

Finally, a comprehensive judgement matrix U is obtained:

$$U = \begin{bmatrix} k_{11} & k_{12} & k_{13} & k_{14} & k_{15} \\ k_{21} & k_{22} & k_{23} & k_{24} & k_{25} \\ k_{31} & k_{32} & k_{33} & k_{34} & k_{35} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ k_{n1} & k_{n2} & k_{n3} & k_{n4} & k_{n5} \end{bmatrix} \tag{14}$$

4.2.3 Security classification of the cordoned-off area. Based on the indicator weights W and the integrated cloud correlation matrix U through equation (15), the integrated evaluation vector Q can be obtained:

$$Q = W \times U \tag{15}$$

5. CASE ANALYSIS

5.1 COWA operator assignment to determine weights

Seven senior experts in the field of safety assessment and captains engaged in ship transport in Qinzhou Bay were invited to form an expert scoring group to assign scores to the first-level and second-level indicators. In order to facilitate the collation of data, it is required that the assigned scores are integer multiples of 0.5, and the scores given by the experts to the various risk factors are collated so that according to the equations (1)-(3), the objective weights for the indicators of all levels can be derived as shown in Table 3.

Table 3. Indicator weights at various levels.

First-level evaluation index		**Secondary evaluation index**	
Index	**Weight**	**Index**	**Weight**
A1	0.15082	A11	0.05932
		A12	0.04984
		A13	0.07060
A2	0.39363	A21	0.12911
		A22	0.15444
		A23	0.17094
		A24	0.04298
A3	0.14418	A31	0.06292
		A32	0.06978
A4	0.31137	A41	0.02893
		A42	0.16114

5.2 Determination of affiliation and evaluation level based on the improved topological cloud model

5.2.1 Determination of evaluation index values. Through field research and analysis of the navigation data of the nearby shipping routes of Qinzhou Bay in recent years, and listening to the guidance and suggestions of the expert group of the Maritime Safety Administration, the two demonstration schemes before and after the establishment of the cautionary area were improved and refined. The evaluation index values were obtained according to the natural environment data of the project waters, the traffic environment condition, the AIS data of each waterway, and the completeness of the navigation guide and aid facilities in the field research. The evaluation index values of the two programmes are shown in Table 4.

Table 4. Evaluation indicator values.

Evaluation indicators	Before setting up the cautionary area	After setting up the cautionary area
Wind	2	2
Flow	1.1	1.1
Visibility	42.3	42.3
Ship density	96	96
Traffic congestion point	13	7
Traffic accidents	13.6	5.4
Channel depth	0.6	0.6
Vessel length	128	128
Ship's speed	9.2	9.2
Aids to navigation	9	9
Maritime supervision	50	93

5.2.2 Determination of the parameters of the hierarchical boundary normal cloud model. The grade of navigational risk level in the cautionary area is divided into five types: excellent, good, fair, poor, and very poor. According to the range of values of the indicators corresponding to each grade, the parameters of the grade cloud object meta-model for each indicator can be obtained through equations (6)-(11), as shown in Table 5.

Table 5. Parameters of the class boundary normal cloud model.

Index	Very low risk	Low risk	Average risk	High risk	Very high risk
A11	(1.5,0.887,0.089)	(4,0.591,0.059)	(6.5,0.887,0.089)	(9,0.591,0.059)	(11,0.591,0.059)
A12	(0.25,0.148,0.015)	(1,0.296,0.030)	(2,0.296,0.030)	(3.25,0.443,0.044)	(4.5,0.296,0.030)
A13	(7.5,4.435,0.443)	(20,2.957,0.296)	(32.5,4.435,0.443)	(45,2.957,0.296)	(57.5,4.435,0.443)
A21	(15,8.870,0.887)	(45,8.870,0.887)	(90,17.740,1.774)	(135,8.870,0.887)	(180,17.740,1.774)
A22	(5,2.957,0.296)	(30,11.827,1.183)	(75,14.783,1.478)	(125,14.783,1.478)	(170,11.827,1.183)
A23	(1.5,0.887,0.089)	(5.5,1.478,0.148)	(11.5,2.070,0.207)	(17.5,1.478,0.148)	(23,1.774,0.177)
A24	(0.125,0.074,0.007)	(0.375,0.074,0.007)	(0.6,0.059,0.006)	(0.75,0.030,0.003)	(0.9,0.059,0.006)
A31	(30,17.740,1.774)	(80,11.827,1.183)	(165,38.437,3.844)	(265,20.697,2.070)	(340,23.653,2.365)
A32	(3,1.774,0.177)	(8,1.183,0.118)	(12,1.183,0.118)	(16,1.183,0.118)	(20,1.183,0.118)
A41	(11.5,0.887,0.089)	(9,0.591,0.059)	(7,0.591,0.059)	(4.5,0.887,0.089)	(1.5,0.887,0.089)
A42	(90,5.913,0.591)	(70,5.913,0.591)	(50,5.913,0.591)	(30,5.913,0.591)	(10,5.913,0.591)

5.2.3 Determination of cloud model relevance. According to equations (12)-(14) and the evaluation indicator values, the correlation function values of each indicator about five different risk level classes are obtained, and 3,000 simulations are carried out to obtain the standardised indicator correlations, and the values of the correlation function of the corto cloud model in the two scenarios are shown in Tables (6) and (7):

Table 6. Correlation function values for each indicator for five different risk levels before setting the cautionary area.

Index	Very low risk	low risk	Average risk	High risk	Very high risk
A11	0.9944	0.0056	0.0000	0.0000	0.0000
A12	0.0000	0.9869	0.0131	0.0000	0.0000
A13	0.0000	0.0000	0.1212	0.8733	0.0056
A21	0.0000	0.0000	0.9998	0.0002	0.0000
A22	0.0772	0.9218	0.0010	0.0000	0.0000
A23	0.0000	0.0000	0.9446	0.0554	0.0000
A24	0.0000	0.0122	0.9878	0.0000	0.0000
A31	0.0000	0.0009	0.9991	0.0000	0.0000
A32	0.0052	0.8963	0.0986	0.0000	0.0000
A41	0.0219	0.9736	0.0045	0.0000	0.0000
A42	0.0000	0.0047	0.9905	0.0048	0.0000

Table 7. Correlation function values for each indicator for five different risk levels after setting the cautionary area.

Index	Very low risk	low risk	Average risk	High risk	Very high risk
A11	0.9944	0.0056	0.0000	0.0000	0.0000
A12	0.0000	0.9869	0.0131	0.0000	0.0000
A13	0.0000	0.0000	0.1212	0.8733	0.0056
A21	0.0000	0.0000	0.9998	0.0002	0.0000
A22	0.8372	0.1627	0.0001	0.0000	0.0000
A23	0.0002	0.9844	0.01543	0.0000	0.0000
A24	0.0000	0.0122	0.9878	0.0000	0.0000
A31	0.0000	0.0009	0.9991	0.0000	0.0000
A32	0.0052	0.8963	0.0986	0.0000	0.0000
A41	0.0219	0.9736	0.0045	0.0000	0.0000
A42	0.9952	0.005	0.0000	0.0000	0.0000

5.2.4 Calculation of the evaluation level of the object element to be evaluated. Combining the correlation function values of the two scenarios and the weights of each indicator, the integrated correlation of the two scenarios is calculated, the maximum correlation value is selected by comparison, and the risk level grade is determined according to the principle of maximum affiliation, as shown in Table 8.

Table 8. Risk level hierarchy correlation.

Programme of discussion	Very low risk	Low risk	Average risk	High risk	Very low risk	Max	Class
Before setting up the cautionary area	0.0719	0.2839	0.5719	0.0719	0.0004	0.5719	Average risk
After setting up the cautionary area	0.3497	0.3350	0.2533	0.0617	0.0004	0.3497	Very low risk

As shown in Table 8, according to the principle of maximum affiliation, the maximum integrated correlation of risk level grade before setting up the cautionary area is 0.5719, and the risk level is general; after setting up the cautionary area, the maximum integrated correlation of risk level grade is 0.3497, and the risk level is very low risk. Therefore, setting the cautionary area in Qinzhou Bay can effectively avoid the risk of ship navigation.

6. CONCLUSION

(1) According to the special characteristics of the waters at the intersection of shipping channels, the evaluation index system of navigation safety in the cautionary area is established, which consists of 4 first-level indexes and 11 second-level indexes, namely, natural environmental factors, traffic environmental factors, ship factors and management factors.

(2) Considering the impact of designing the cautionary area on the safety of ship navigation in the waterway intersection, the COWA method is used to solve the weights of the indicators, and based on the qualitative and quantitative problems of the evaluation indexes and the double uncertainty reasoning characteristics, the cautionary area navigation safety evaluation model is constructed with the help of the combination of the object element topology theory and the cloud model, and the introduction of the cloud entropy optimisation algorithm to improve the traditional topology cloud model.

(3) Taking Qinzhou Bay No.1 cautionary area as an example, through the rating study on the safety of ship navigation, it is concluded that the safety level of ship navigation is improved after the establishment of the cautionary area, which is basically in line with the actual situation in the research waters, and verifies the effectiveness of the evaluation model, which can also provide a reference for the research on the safety of navigation in other cautionary areas.

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