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Research on Safety Level Evaluation of Construction Ships in the Channel of Yangtze River Estuary

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Abstract. During water construction operations, engineering ships often occupy part of the traffic channel, resulting in a surge in the density of ships in the channel which increase navigation and operational risks of ships. However, the existing research on risk evaluation in navigable waters is mostly oriented to the influence of the natural environment under navigation conditions and cannot systematically elaborate on the multi-source risks faced by construction ships in navigable waters. With a view to analyzing the complex working conditions during the construction of the deep-water channel in the Yangtze River Estuary, this paper introduces a multi-level Bayesian network to establish a safety level evaluation model. Firstly, ten factors affecting water construction safety in three categories are extracted and a multi-level index system is established; secondly, the optimal conditional probability is extracted from the information inferred by experts using the modified entropy weighting method; finally, the prior probability of the root node is calculated for four actual working conditions and based on Bayesian probabilistic inference theory, the Bayesian network is determined and the safety level of construction ships under four working conditions is calculated. The main influencing factors of safety level are analyzed, and the evaluation results are consistent with the actual engineering situation, which provides decision-making references for construction safety management in navigable waters.

Keywords: component · deep-water channel construction · multi-level Bayesian network · safety level evaluation

1 Introduction

With the unceasing advancement of the national strategy of "One Belt, One Road", the main ports represented by the deep-water channel of the Yangtze River Estuary and the waterway bear the pressure of transportation and the demand for large water construction projects such as waterway improvement, wharf construction, and offshore energy development [1–3]. Such projects are characterized by high construction difficulty and a long

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construction period. Since the construction waters overlap or are adjacent to the navigable waters, the construction safety is not only affected by the environmental factors of the waters, but also by the navigable environment and the experience of the operators.

The relationship between the factors affecting the safety risk of construction ships in navigable waters is complex, the uncertainty of which is difficult to characterize [4, 5]. The Bayesian network model is built based on Bayesian inference theory, which has significant advantages in elaborating the application of uncertainty among elements. In this paper, based on the study of the main influencing factors of the deep-water channel project in the Yangtze River Estuary, the method of coupling fuzzy mathematics and Bayesian network is applied to establish the evaluation model of ship safety level for deep-water channel construction, which takes into account the fuzziness, grayness, and nonlinearity of the actual problem, providing guiding significance for the ship construction in the deep-water channel.

2 Multilevel Bayesian Model for Ship Safety Level Evaluation in Navigable Waters

2.1 Establishment of Safety evaluation index System

With respect to the analysis of the risk-causing mechanism of water construction safety accidents, combined with the construction experience, the factors affecting the safety of ships in construction waters are mainly categorized into three basic elements of hydrometeorology, channel conditions, and personnel management, and a total of 10 main impact indicators are selected in each basic element[6, 7]. With reference to the provisions of the Emergency Response Law of the People's Republic of China, the grading standard is divided into 4 levels, and the standard value of index grading is shown in Table 1.

2.2 Bayesian Networks

Bayesian network is composed of directed acyclic graphs, whose nodes represent an attribute variable, and the connection between nodes represents the probability relationship between attributes. This approach enables a clear representation of the relationships between variables and thus logical reasoning about uncertain information. Its schematic is shown in Fig. 1.

In this paper, the Bayesian network based on the construction ship safety evaluation index is established according to Table 1. It can be seen that not only the relationship between various levels is considered, but also the hydrometeorological and channel factors will have a certain impact on personnel management which is shown in Fig. 2.

The prior probability of the root node of the Bayesian network is obtained by calculating the membership transformation of each indicator under different working conditions, and the membership matrix is transformed into the required prior probability form according to Formula (1):

$$P(d_i) = \frac{A(d_{ij})\frac{1}{\theta}}{\sum_j A(d_{ij})\frac{1}{\theta}}, \quad 0 < \theta < 1 \tag{1}$$

Table 1. Classification standards for the safety levels of construction ships in navigable waters

Targets	Elements	Indicators	The standard value of safety level				Remark	Unit
			Level 1	Level 2	Level 3	Level 4		
Safety level in navigable waters	Hydrometeorology	Visibility	500	300	200	50	Visible meters	Meter
		Wind	6	8	10	12	Wind and wave forecast level	Class
		Flow rate	0.5	1	2	3	Water velocity	m/s
	Channel conditions	Channel width	0.77	0.5	0.17	0.1	The ratio of the ship's width to the channel's width	Ratio
		Channel depth	1.5	1.2	1.05	1	The actual water depth of the lane / the actual draft of the ship	Ratio
		Channel curvature	2.5	2	1.5	1	Channel bending radius / Ship turning spacing	Ratio
		Channel obstacles	0.005	0.01	0.02	0.05	Reciprocal of the distance between the obstruction and the channel	Ratio

(*continued*)

Table 1. (*continued*)

Targets	Elements	Indicators	The standard value of safety level				Remark	Unit
			Level 1	Level 2	Level 3	Level 4		
	Personnel management	Captain experience	12	7	3	1	The duration of the ship's chief pilots engaged in this type of work	Year
		Certificate status	0.8	0.6	0.4	0.2	Percentage of construction ship workers holding relevant certificates	Ratio
		Safety consciousness	90	80	65	60	Results of the Ship Safety Code Exam	Score

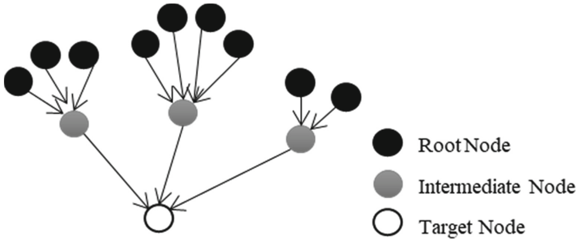

Fig. 1. Bayesian network diagram

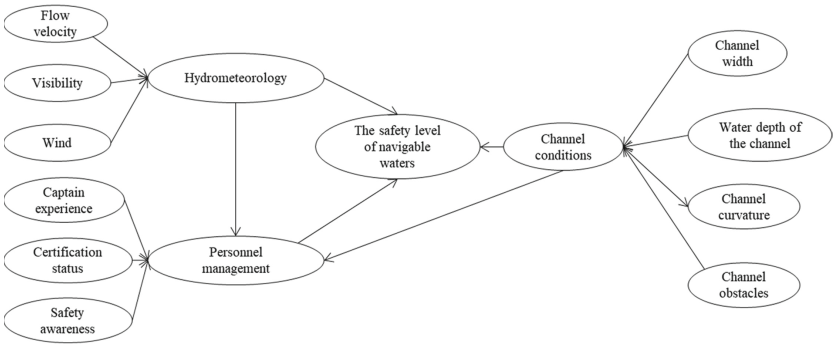

Fig. 2. Bayesian network for safety evaluation of construction ships in navigable waters

P(d_i) is the probability of occurrence of a given indicator;
A(d_{ij}) is the possibility that X $= d_j$ is subordinate to some rank j;
θ is the degree to which the likelihood probability conversion consistency is satisfied. Since it is necessary to make the difference between the conversion probability and the actual probability as small as possible. To this end, θ takes the value of 0.9. Through Bayesian network algorithm inference, the level with the highest probability of ship construction in navigable waters is obtained, and it is positioned as the final safety level.

2.3 Bayesian Network Node State and Probability

Determination of the prior probability of the root node.
In Bayesian networks, nodes usually have only two states, namely: "Yes" and "No". However, in the actual evaluation problem, the target problem will be graded and analyzed, which obviously cannot be represented by simple two states. According to the characteristics of the safety evaluation system for construction ships in navigable waters, this paper uses fuzzy numbers distributed in the interval [0,1] to represent the safety level status of nodes.

x_i (i = 1, 2,..,n), y_i (j = 1,2,…,m), and O represent the root node, intermediate node, and target node, respectively, and fuzzy numbers $x_i^{a_i}$ (a_i=1,2,.., k_i), $y_j^{b_j}$ ($b_j = 1, 2, ..., k_j$) and $O_q(q = 1, 2, ..., \xi)$ are used to describe the security levels of these nodes, respectively. Among them, k_i, k_j, and ξ are the number of security levels, respectively. Due to the lack of current construction ship state record data, this paper combines fuzzy theory and uses fuzzy subsets to describe the safety level status of nodes. The specific calculation method has been expounded in the previous section, and the trapezoidal membership function is used in this paper. In order to specify the probability that different index factors are rated as a certain grade, it is necessary to establish the corresponding membership matrix, with r_{ij} denoting the probability of factor i (1⩽i⩽n, n = 10 belongs to the grading j(1⩽j⩽m, m = 4), and the matrix form is given in Formula (2).

$$R = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \dots & \dots & & \dots \\ r_{n1} & r_{n2} & \dots & r_{nn} \end{bmatrix} \tag{2}$$

When the value of the safety evaluation level of the evaluation index is positively correlated, the ascending semi-trapezoidal membership function is used; otherwise, the descending semi-trapezoidal membership function is used.

Determination of the conditional probability at the node

The conditional probabilities at the nodes are combined with the experts' experience to reconstruct the conditional probability table to reflect the uncertainty of the interactions between different indicators [8, 9]. Due to the different experiences of experts and individual differences, the final rating result of the seminar is based on the value of the ratio matrix finally determined by the dominant direction of one or two experts [10–12]. Since there are more uncertainties brought by subjective factors, in order to reduce the influence brought by them, the modified entropy weighting method is used for the correction of index weights.

This paper sends a questionnaire to 30 experts in this field by organizing an expert seminar, and builds a corresponding judgment matrix as shown in Formula (3):

$$M = (m_{ij})_{n\times n} = \begin{bmatrix} m_{11} & m_{12} & \dots & m_{1n} \\ m_{21} & m_{22} & \dots & m_{2n} \\ \dots & \dots & & \dots \\ m_{n1} & m_{n2} & \dots & m_{nn} \end{bmatrix} \tag{3}$$

In the formula, mij signifies the relatively important comparison result of index i and index j, when mij > 0, mii = 1, mij = 1/mji; the weight vector $w^1 = (w_1^1, w_2^1, \dots, w_n^1)^T$ is calculated after the comparison matrix is normalized, and the calculation method is shown in Formulas (4), (5), and (6):

$$a_{ij} = \frac{c_{ij}}{\sum_{i=1}^{n} c_{ij}} \tag{4}$$

$$\overline{w}_i = \sum\nolimits_{j=1}^{n} a_{ij} \tag{5}$$

$$w_i = \frac{\overline{w}}{\sum_{i=1}^{n} \overline{w}_i} \tag{6}$$

where, a_{ij} is the result of normalizing each element in the M matrix, and $\overline{w}_i$ is the result of row-wise addition of the matrix after normalization. At the end of the calculation process of AHP, the consistency test of the indicators is also carried out, to verify whether it satisfies the following Formulas (7) and (8):

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{7}$$

$$CR = \frac{CI}{RI} < 0.1 \tag{8}$$

In Formulas (9) and (10), *RI* denotes the random consistency index, and λ_{max} refers to the largest characteristic root.

Each reviewer was individually asked to score the importance of individual indicators, and the scoring results were built into an evaluation matrix, i.e., the importance scoring matrix for 30 experts and *n* indicators per level is shown in Formula (9).

$$\overline{V} = (\overline{v}_{lj})_{m\times n} = \begin{bmatrix} \overline{v}_{11} & \overline{v}_{12} & \dots & \overline{v}_{1n} \\ \overline{v}_{21} & \overline{v}_{22} & \dots & \overline{v}_{2n} \\ \dots & \dots & & \dots \\ \overline{v}_{m1} & \overline{v}_{m2} & \dots & \overline{v}_{mn} \end{bmatrix} \tag{9}$$

In the formula, the score of the *l*-th expert for the *j*-th indicator is $\overline{a}_{lj}$. The weight obtained by calculating the evaluation provided by the *l*-th experts under the *j*-th indicator is shown in Formula (10):

$$p_{lj} = \frac{s_{lj}}{\sum_{l=1}^{m} s_{lj}} \tag{10}$$

The entropy value of index *j* is calculated according to Formula (11):

$$e_{ij} = \frac{1}{lnm} \sum\nolimits_{l=1}^{m} p_{lj}\, ln\, p_{lj} \tag{11}$$

Entropy is used to calculate entropy weight, as shown in Formula (12):

$$w_j = \frac{1 - e_j}{\sum\limits_{j=1}^{n} (1 - e_j)} \tag{12}$$

The indicator weights calculated by the above two methods, and the comprehensive weight w' obtained by the weighted combination are shown in Formula (13):

$$w' = \frac{w_i{}^1 w_i{}^2}{\sum_{i=1}^{m} w_i{}^1 w_i{}^2} \tag{13}$$

In the formula, w_i^1 is the subjective weight scored by experts, and w_i^2 is the entropy weight coefficient that considers different subjects to judge.

Influence degree of the root node

In order to provide safety precautions for engineering ships, it is necessary to determine the degree of influence of indicators before the safety rating and to increase the frequency and intensity of inspections for indicators with a greater degree of influence. In this paper, the fuzzy importance of the root node to the safety level of the target node can be calculated by using the weights obtained by the AHP to calculate the final influence of each factor on the safety level of the whole ship according to the Bayesian network.

3 Engineering Applications

Based on the actual engineering data of Hengsha Dongtan in the Yangtze River Estuary, and the relevant channel information and meteorological and hydrological information downloaded from the network of the Waterway Bureau and other departments, four typical working conditions in the navigable construction waters are selected for analysis.

3.1 Analysis of Main Influencing Factors of Construction Ship Safety Evaluation

Through the introduction in Sect. 2.3.3, the weight coefficient of nodes at each level can be obtained, reflecting the importance of different indicators in the security level evaluation system, which can assist in searching the main influence and provide guidance for security measures. The obtained importance degree results are shown in Fig. 3.

It can be seen from Fig. 3 that the main influencing factors for the safety of construction ships in navigable waters are flow speed, the captain's experience, and the water depth of the channel. In the safety hazard inspection work, the chart can be referred to from the most influential to the least influential for investigation and governance.

3.2 Index Collection and Membership Analysis of Construction Ships

Table 2 shows the typical working conditions extracted during the construction of the four ships, and the index values in working conditions 1, 2, and 3 are all from the same ship. Compared with working conditions 2 and 3, working condition 1 is the parameter collected under the influence of strong wind; compared with working condition 2, working condition 3 is located in the construction area with a narrower and more curved channel; working condition 4 is the construction data collected from another engineering ship operated by a less experienced captain, and except for the captain's relatively less experience, other conditions are similar to working condition 2. The specific index values collected are summarized in the following table, and the prior probability of the

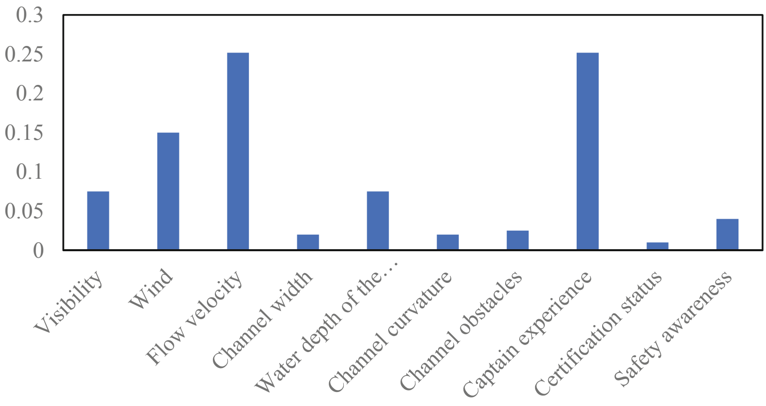

Fig. 3. Influence degree of construction ship safety evaluation factors

Table 2. Typical working condition data

Target node	Intermediate node	Root node	Working condition 1	Working condition 2	Working condition 3	Working condition 4
Safety of the construction ship	Hydrometeorology	Visibility	450	450	450	500
		Wind	7	6	6	6
		Flow rate	1.5	0.8	0.8	0.8
	Channel conditions	Channel width	0.8	0.8	0.3	0.8
		Water depth of the channel	1.5	1.5	1.5	1.5
		Curvature degree of the channel	3	3	1.5	3
		Channel obstacles	0.01	0.01	0.01	0.01
	Personnel management	Captain's experience	8	8	8	2
		Certificate status	1	1	1	1
		Safety consciousness	85	85	85	85

Table 3. Membership calculation results

Construction conditions	**Working condition 1**				**Working condition 2**				**Working condition 3**				**Working condition 4**			
Security Level	**L. 1**	**L.2**	**L. 3**	**L. 4**	**L. 1**	**L. 2**	**L. 3**	**L. 4**	**L. 1**	**L. 2**	**L. 3**	**L. 4**	**L. 1**	**L. 2**	**L. 3**	**L. 4**
Visibility	0.75	0.25	0	0	0.75	0.25	0	0	0.75	0.25	0	0	1	0	0	0
Wind	0.5	0.5	0	0	1	0	0	0	1	0	0	0	1	0	0	0
Flow rate	0	0.5	0.5	0	0.4	0.6	0	0	0.4	0.6	0	0	0.4	0.6	0	0
Channel width	1	0	0	0	1	0	0	0	0	0.39	0.61	0	1	0	0	0
Water depth of the channel	1	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0
Channel curvature	1	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0
Channel obstacles	0	1	0	0	0	1	0	0	0	1	0	0	0	1	0	0
Captain's experience	0.2	0.8	0	0	0.2	0.8	0	0	0.2	0.8	0	0	0	0	0.5	0.5
Certificate status	1	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0
Safety consciousness	0.5	0.5	0	0	0.5	0.5	0	0	0.5	0.5	0	0	0.5	0.5	0	0

Bayesian network root node under different working conditions is calculated using the index value and the rank standard listed in Sect. 2.1.

The membership degree of the index calculated according to the fuzzy mathematical calculation theory is shown in Table 3, and then the four working conditions are respectively substituted into the a priori probability calculation formula.

The fuzzy probability of the root node is substituted into the Bayesian network model, and the safety level probability of the construction ship under three typical working conditions is calculated as P1 = (0.32,0.45,0.23,0), P2 = (0.57,0.43,0,0), P3 = (0.55,0.41,0.04,0), and P4 = (0.49,0.31,0.1,0.1). According to the principle of probability extrapolation, working condition 1 is level 2, working conditions 2, 3, and 4 are level 1; comparing working condition 3 and working condition 4, it can be found that the main factor defined in Sect. 3.1, the captain's experience on the overall safety rating indeed have a more obvious impact. Although the final rating cannot be reflected, by checking the final rating probability, it can be seen that the final probability of working condition 4 reflects that there is a certain probability that the system will appear to be rated as level 4. In order to quantify the safety evaluation levels of construction ships in navigable waters, four levels are represented by 100, 75, 50, and 25, and the expected Formula (14) is selected to calculate the levels.

$$E = \sum\nolimits_{i=n}^{4} x_i p_i \tag{14}$$

The calculated safety level scores under the four working conditions are 77.25, 89.25, 87.75, and 79.75. It can be seen that when there is a major risk-causing factor, even if the safety rating of other elements of the system is higher, it is still more likely that the whole engineering ship is in a lower safety rating, so more attention should be paid to the rating of major risk-causing factors in the safety assessment of engineering ships.

4 Conclusion

(1) The use of the weights of nodes as the basis for factor importance analysis is proposed to quantitatively determine the importance ranking of safety influencing factors, which provides guidance for safety inspection and prevention work.
(2) A safety level evaluation model of construction ships in navigable waters applying a Bayesian network is put forward, which solves the problem of node state diversity and provides a basis for guiding the safe construction in navigable waters.

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