Risk Assessment of LNG Ship Navigation in Inland Water Based on FAHP-cloud Model

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Abstract. In order to understand the navigation safety risks of LNG ships in inland waterways, the paper combines the general accident risk assessment and the specific navigation environment of inland rivers[1], and analyzes the probability of collision accidents[9]. Combined with the characteristics of the specific navigation environment, to construct a hierarchical model of the risk factors for the navigation safety of inland LNG ships. Set the entry channel in the Dongsha operation area of Zhangjiagang Port area as the research scene, use the FAHP (fuzzy analytic hierarchy) process to determine the weight value of each navigation risk factor, use the cloud model to quantify the conversion of qualitative risk factors[13], quantitatively evaluate the risk level of risk factor indicators, and combine qualitative analysis to analyze the risk level of the approach channel in the Dongsha operation area from a quantitative perspective. The result objectively demonstrated the risk level of the channel, and verified that the evaluation result conforms to reality.

1. Introduction
In the "Outline of the Yangtze River Delta Regional Integrated Development Plan", it emphasizes the status of LNG receiving stations as important deployment facilities, to strengthen the construction of oil and gas facilities, improve the layout of regional oil and gas facilities, and promote the coordination and synchronization of cross-regional energy receiving facilities. In view of the flammable and explosive dangerous nature of LNG [1], LNG ships are always accompanied by certain risks during navigation. In the future, LNG ships will enter inland rivers, and ensuring the safety of ships’ navigation is the foundation of inland river traffic safety and economic benefits of inland rivers [2]. In order to maintain the navigation order of inland waterways and fully guarantee the safety of water traffic, it is very necessary to conduct research on the navigation risks of inland LNG ships [3].

2. Method introduction
This paper combines FAHP and cloud model to evaluate the navigation safety risks of inland LNG ships. FAHP determines the weight value of each risk factor [4][5]. In order to avoid the ambiguity caused by the artificial scoring process, the cloud model [6] is used for quantitative calculation, and the risk level of each influence factor of the channel is evaluated.
Calculate the availability of triangular fuzzy importance

Safety risk assessment model of inland water LNG ship navigation based on FAHP-cloud model

Construct a judgment matrix between indicators
Expert questionnaire

Consistency check

Y

Calculate the availability of triangular fuzzy importance

Get the global weight of the indicator layer

FAHP

Obtain the LNG ship navigation safety risk level

Figure 1. The Process of the Risk Assessment Model for the Navigation Safety of Inland Water LNG Ships

LNG ship navigation safety risk factors have the characteristics of complexity and ambiguity. After using FAHP to determine the weights of different risk factors, the cloud model is used to quantitatively evaluate the qualitative indicators, and then the risk equivalent of the channel is obtained. The realization process of the risk model in this paper is shown in Figure 1.

1. Establish a risk indicator system for navigation safety of inland LNG ships;
2. Make a questionnaire and invite experts to compare the risk indicators in pairs to obtain a judgment matrix. Calculate the weight values of the first and second level risk factors of the index system by FAHP [7];
3. According to the calculation method of the cloud model [8], introduce the index weight value in (2) to obtain the final parameter value of the target channel. Compare the standard risk and the cloud model diagram of the calculated risk, and get the final risk distribution level of the channel.

3. Identification of risk factors for navigation safety of inland water LNG ships
This chapter adopts the method of general risk assessment and combines the environmental factors of inland navigation to identify the navigation safety risk factors of LNG ships [9].

3.1. Screening of risk factors
It is common to conduct risk assessment based on the probability and consequences of accidents [10], as shown in formula (1):

\[ R = f(p, c) \]  \hspace{1cm} (1)

In the formula, \( R \) represents navigation risk; \( p \) represents probability of accident; \( c \) represents accident consequences.

For LNG ships, the navigation risk level is mainly dominated by collision accidents [11]. Through the IWRAP model, combined with the ship distribution function and its properties in the model, the probability of a collision event is shown in formula (2):

\[ P = f(V, B, Q, L, x) \]  \hspace{1cm} (2)

Among them, \( V \) is ship speed; \( B \) is ship speed; \( Q \) is ship traffic; \( L \) is channel length; \( x \) is other secondary factors.
Most of the consequences of collision accidents include damage to the hull, and there is exchange of kinetic energy in this process [12], thus showing the phenomenon of damage. The consequences of an LNG ship collision accident can be described by formula (3):

\[ c = f (M, V, y) \] (3)

Among them, \( M \) is the quality of the ship; \( V \) is the speed of the ship; and \( y \) is other minor factors.

According to formula (2-3), the navigation risk factors are summarized as: (1) channel parameters: channel length \( L \); (2) ship parameters: ship tonnage \( M \), ship width \( B \); (3) traffic flow parameters: ship traffic volume \( Q \), ship sailing speed \( V \); (4) Other factors \( x, y \): other parameters that affect the ship's navigation risk.

By studying the engineering data of the entry channel in the Dongsha operation area and consulting related documents, supplementing the “other parameters \( x, y \)”.

3.2. Hierarchical model of navigation safety risk factors

Based on the previous section 3.1, the ship parameters, channel parameters, traffic environment and natural environment are set as the first-level indicators of the hierarchical model, and the environmental factors of inland navigation are summarized as the bottom indicators.

**Figure 2. Hierarchical diagram of risk factors for navigation safety of inland water LNG ships**

Channel parameters: The connotation of channel parameters is channel dimensions. Based on the above analysis, the length of the channel affects the collision of LNG ships, and determines the ship's navigation time. In the case of different channel widths, LNG ships will choose exclusive or non-exclusive navigation [13].

Ship parameters: Ship parameters include two indicators of LNG ship's seaworthiness and maneuverability. LNG ships of different sizes have different degrees of restriction on maneuvering, and the navigation safety of ships during the navigation process will also be different.

Traffic environment: The traffic environment indicators are divided into five underlying indicators: distance between anchorage and navigation channel, number of channel intersections, number of obstructions, LNG ship emergency plan, and AIS coverage rate in water area.
Natural environment: The natural environment parameters comprehensively consider the hydrological and meteorological conditions of the Dongsha operation area in Zhangjiagang Port area, and choose wind, current and visibility as the bottom index. These four parameters are composed of an inland LNG ship navigation safety risk factor hierarchical model. The risk factor hierarchical model contains indicators as shown in Figure 2:

4. Example application

4.1. Risk weight calculation

This paper designs an expert questionnaire and invites 5 experts in the industry with theoretical and practical knowledge to comment on the above risk factors. Then, obtain a judgment matrix by comparing the importance of the factors. Sort out the results of one of the experts’ questionnaires and get the judgment matrix, which is calculated as an example.

\[
A = \begin{bmatrix}
(1.1,1) & (4.5,6) & (2.3,4) & (6.7,8) \\
(1,1,1) & (1,1,1) & (2,3,4) \\
(4,5,6) & (1,1,1) & (4,5,6) \\
(1,1,1) & (1,1,1) & (2,3,4) \\
\end{bmatrix}
\]

The weight vector of this judgment matrix is followed. The judgment matrix is calculated by consistency test, and the results are shown in Table 1:

| \( \lambda_{max} \) | CI      | CR      | test result |
|----------------------|---------|---------|-------------|
| 4.2177               | 0.0726  | 0.0806  | <0.1        |

Comprehensively obtain the initial weight of the first-level indicators:

\[
S = \begin{bmatrix}
0.3833 & 0.4789 & 0.5736 \\
0.0883 & 0.1317 & 0.1878 \\
0.2593 & 0.3392 & 0.4303 \\
0.0390 & 0.0502 & 0.0697 \\
\end{bmatrix}
\]

Then calculate the degree of importance of triangular fuzzy number availability:

\[
d(c_i) = \min v(S_1 \geq S_2, S_3, S_4) = 1
\]

\[
d(c_i) = \min v(S_2 \geq S_1, S_3, S_4) = 0.1855
\]

\[
d(c_i) = \min v(S_3 \geq S_1, S_2, S_4) = 0.3925
\]

\[
d(c_i) = \min v(S_4 \geq S_1, S_2, S_3) = 0.0903
\]

The above weight values are standardized, and the result of calculating the index weight is:

\[
(w_1, w_2, w_3, w_4) = (0.5994, 0.1112, 0.2353, 0.0541)
\]

After the weight of the first-level indicator is determined, the global weight of the second-level indicator is its weight multiplied by its corresponding upper-level weight. The calculation results of the weight of each indicator are shown in Table 2:
Table 2. Global weight values of risk indicators

| Risk indicator                      | Global weight |
|-------------------------------------|---------------|
| Channel parameters $e_1$            | 0.5994        |
| length of the channel $e_{11}$      | 0.1326        |
| bending radius $e_{12}$             | 0.1627        |
| depth of the channel $e_{13}$       | 0.1554        |
| width of the channel $e_{14}$       | 0.1487        |
| Ship parameters $e_2$               | 0.1112        |
| seaworthiness of LNG ships $e_{21}$ | 0.0574        |
| Maneuverability of LNG ships $e_{22}$| 0.0538        |
| Traffic environment $e_3$           | 0.2353        |
| distance between anchorage and navigation channel $e_{31}$ | 0.0498 |
| number of channel intersections $e_{32}$ | 0.0408 |
| number of obstructions $e_{33}$     | 0.0456        |
| LNG ship emergency plan $e_{34}$    | 0.0504        |
| AIS coverage rate in water area $e_{35}$ | 0.0487 |
| Natural environment $e_4$           | 0.0541        |
| Wind $e_{41}$                       | 0.0172        |
| Visibility $e_{42}$                 | 0.0188        |
| current $e_{43}$                    | 0.0181        |

4.2. Cloud model computing

According to the safety research of water transportation navigation, the safety level of ship navigation can be divided into five levels "lower, low, normal, high and higher", among which the evaluation criteria of the risk degree of each factor are shown in Table 3:

| impact factors                      | risk degree            | lower     | low       | normal     | high       | higher     |
|-------------------------------------|------------------------|-----------|-----------|------------|------------|------------|
| Visibility < 1000m days             | 15 below               | 15 ~ 25   | 25 ~ 40   | 40 ~ 50    | 50 above   |
| Standard wind days (d)              | 30 below               | 30 ~ 60   | 60 ~ 100  | 100 ~ 150  | 150 above  |
| Lateral flow velocity (m/s)         | 0.25 below             | 0.25 ~ 0.75| 0.75 ~ 1.25| 1.25 ~ 2   | 2 above    |
| Wave height (m)                     | 0.3 below              | 0.3 ~ 0.5 | 0.5 ~ 1   | 1 ~ 1.5    | 1.5 above  |
| The width of the narrowest part of  | 1 above                | 0.8 ~ 1   | 0.5 ~ 0.8 | 0.3 ~ 0.5  | 0.3 below  |
| the channel / Maximum captain       |                        |           |           |            |            |
| Channel curvature                   | 15° below              | 15° ~ 30° | 30° ~ 45° | 45° ~ 60°  | 60° above  |
| Channel Crossover situation         | 20° below              | 20° ~ 45° | 45° ~ 60° | 60° ~ 70°  | 70° above  |
| Traffic volume (ships/day)          | 10 below               | 10 ~ 15   | 15 ~ 25   | 25 ~ 70    | 70° above  |

Experts are invited to score the degree of danger of the first-level indicators in the navigation risk factor model. The scoring standards are shown in Table 4. The cloud model distribution of risk factor level is obtained with the help of the cloud generator of forward operation: $SC_{tot} = (0.67, 0.5)$,

$SC_{vi} = (3.33, 0.5)$, $SC_{st} = (5.00, 0.5)$, $SC_{wi} = (7.00, 0.5)$, $SC_{pi} = (10.00, 0.5)$. In view of the little correlation between the underlying indicators in the hierarchical model, the floating cloud algorithm is used to obtain the evaluation cloud. Among them, $E_{x_j}$, $E_{n_j}$, $H_{e_j}$, $w_j (j = 1, 2, ... , n)$ are the cloud model parameters and weights of the j-th second-level index under the first-level index.
Ex = \frac{E1w1 + E2w2 + \cdots + ExwX}{w1 + w2 + \cdots + wX}
En = \frac{w2^2E1n1 + w2^2E2n2 + \cdots + w2^2EnX}{w1^2 + w2^2 + \cdots + wX^2}
He = \frac{w2^2Hen1 + w2^2Hen2 + \cdots + w2^2HenX}{w1^2 + w2^2 + \cdots + wX^2}

(4)

Table 4. Risk levels and evaluation criteria

| Risk level      | Rating range | Grading                                      |
|-----------------|--------------|----------------------------------------------|
| Lower risk      | [0, 2)       | Risk is acceptable                           |
| Low risk        | [2, 4)       | The risk is acceptable, there are allowable conditions |
| Normal risk     | [4, 6)       | The risk is not expected and relevant safety measures must be taken |
| High risk       | [6, 8)       | The risk is unacceptable and relevant safety schemes must be implemented |
| Higher risk     | [8, 10)      | Risk is forbidden and must be avoided        |

According to the experts’ scoring of the security level of the waterway, combined with the weight value of the secondary index, using the cloud model calculation calculated by formula (4), the first level risk factor cloud model parameters are shown in Table 5:

Table 5. Cloud model parameter values of the first-level risk factor

| First level indicator | Weights | Cloud model parameters |
|-----------------------|---------|------------------------|
| e1                    | 0.5994  | (5.4424,0.33,0.5)      |
| e2                    | 0.1112  | (3,0.33,0.5)           |
| e3                    | 0.2353  | (4.2393,0.33,0.5)      |
| e4                    | 0.0541  | (1.0037,0.5560,0.5)    |

The comprehensive cloud algorithm in the virtual cloud is used to calculate the cloud model parameters of the target layer [14], as shown in formula (5):

\[
\begin{align*}
Ex &= \frac{Ex1w1 + Ex2w2 + \cdots + ExXwX}{En1w1 + En2w2 + \cdots + EnXwX}, \\
En &= \frac{En1w1 + En2w2 + \cdots + EnXwX}{He1w1 + He2w2 + \cdots + HeXwX}, \\
He &= \frac{He1w1 + He2w2 + \cdots + HeXwX}{w1 + w2 + \cdots + wX}
\end{align*}

(5)

Among them, \( Ex_j, En_j, He_j, w_j \) (\( j = 1, 2, \ldots, n \)) are the cloud model parameters and weights of a certain first-level index respectively. Bring the value to get: \( Ex = 4.5174, En = 0.3422, He = 0.5 \). That is, the cloud model parameters of the navigation safety evaluation of the approaching channel in the Dongsha operation area are \( (Ex, En, He) = (4.5174,0.3422,0.5) \). Through MATLAB software calculation, the risk assessment cloud model of this channel is obtained, as shown in Figure 3. It can be seen that the navigation risk of LNG ships entering the port channel in the Dongsha operation area is at the “normal risk” level, which is basically consistent with the actual conditions of the channel.
5. Conclusion

Combining the specific inland navigation environment, establish an inland LNG ship navigation safety risk factor hierarchical model, and use the fuzzy analytic hierarchy process to quantitatively obtain the weight value of each risk factor, in order to solve the ambiguity of the evaluation process in the fuzzy analytic hierarchy process and the randomness of expert scoring. Combining the characteristics of the cloud model that can achieve qualitative and quantitative concept conversion, comprehensively conduct an objective risk assessment of the entry channel in the Dongsha operation area, and the final assessment result of the channel risk level is "general risk" [15]. The weight of the risk factor presents the hazard distribution of LNG ship navigation, and gives ideas for maintaining the navigation safety of inland LNG ships.

6. References

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