Test of meteorological influence on sail based on fuzzy comprehensive evaluation

Kui Zhao 1,2,a, Baowei He 2,b, Haipeng Cui 2,c, Peng Du 2,d, Bingbing Han 2,e, Minjing Chen 2,g, Zhiqiang Wei 1,3,f*

1College of Information Science and Engineering, Ocean University of China; Qingdao 266100, China;
2Jiangsu Automation Research Institute, Lian yungang 222002, China;
3Pilot National Laboratory of Marine Science and Technology, Qingdao 266100, China)

aemail: 11190232058@stu.ouc.edu.cn, bemail: hbwqd@126.com,
cemail: hp1982@126.com, demail: 15610538689@163.com,
eemail: hanbingbing010@163.com, gemail: 17685731017@163.com

*Correspondence: femail: weizhiqiang_ouc@163.com

Abstract: In order to quantify the influence of port meteorological factors on sail of ships, an effective model of ship navigation restriction was established based on fuzzy comprehensive evaluation. The navigation influence was comprehensively assessed under different meteorological conditions. The influences of wind, fog, thunder and rainfall on sail were studied, and the calculation results were compared with the test results. The results show that the fitting degree between the calculation results and the test results is 85%. The navigation restriction model conforms to the requirements of engineering application. The influence of wind, fog and thunder on sail is gradually enhanced. When the wind force is less than 6, the influence factors of fog and thunder can reach 0.31 and 0.24.

1. Introduction
As a crucial economic window of foreign trade and an amphibious transportation hub, the port suffers from serious equipment damage and casualties caused by meteorological disasters every year. Meteorological conditions are a fatal factor for port risks and productivity reduction, which have a huge impact on port construction and port planning. The influence of various meteorological environment factors should be considered when ships enter or leave the port. The accurate monitoring and forecast of port weather directly affects the safety of ship navigation and cargo loading and unloading.

At present, more and more scholars are pursuing the effects of port meteorological effects. Gupta studied the influence of wind factor and TSP concentration on port operation in Nehru port, India, and established the correlation between port operation, wind factor and air pollutant concentration. McIntosh studied 22 major meteorological and extreme meteorological vulnerability indexes in the northeast of the United States, and established an open data expert evaluation system for port meteorological impact. Qian applied the anomaly-based weather analysis method to the integrated forecasting system of the port, and uses the abnormal temperature pressure model and wet wind model...
to forecast the low visibility process related to the heavy fog along the coast several days in advance. At home, Qingdao port\[^9\] is actively exploring the new mode of port meteorological service, establishing a port meteorological monitoring and early warning platform, and constantly improving the service evaluation system of meteorological risk indicators. Ma\[^10\] analyzed the main factors affecting the navigation safety of the Three Gorges Reservoir area, and evaluated the navigation safety of the Three Gorges Reservoir Area based on FCE. Wang\[^11\] Based on the alternative sparse self-coding network model, constructed the prediction framework of the influence of marine meteorology on ship speed, and mined the influence factors of Meteorology ship speed and their implicit relations by using association rule method.

Most of research focus on port construction, anchorage planning and function adjustment, whereas few of them apply mathematical methods to deeply explore the influence of meteorological factors on ships’ navigation in and out of the port. This paper is based on the fuzzy comprehensive method Evaluation(FCE), which is the mathematical model of port weather on ship navigation restrictions is constructed, and the sensitivity of meteorological factors on navigation influence is analyzed. The validity of the model is verified by comparing the calculation results of 2010-2015 port navigation ban model with the test results, and the quantitative influence results of wind, fog and thunder factors on ship navigation restrictions are obtained.

2. Materials and Methods

2.1. Navigation restriction model

Port navigation often involves several meteorological factors, which together affect the navigation of port ships. As to accurately predict and evaluate the impact of future meteorological conditions on ship navigation, port units generally rely on the experience of meteorological departments and personnel to analyze and evaluate, and make decisions on navigation schemes. In this process, it is very important to analyze and quantify the fuzzy concepts such as experience, requirement and determined. FCE is a feasible measure to deal with this kind of problems.

2.1.1. Navigation decision set

Based on the navigation control requirements of the main domestic ports and the regulations of the maritime department, the decision set is composed of several navigation impact results:

\[ D = \{ \text{none, slight, severe, no navigation} \} \]

The port meteorological factors influencing the navigation decision-making are selected as the fuzzy evaluation basis. According to the meteorological data collection framework, the meteorological primary factor set is formed:

\[ W = \{ \text{air quality, visual weather, temperature} \} \]

Meteorological secondary factor set:

\[ W_1 = \{ w_{11} \} \]
\[ W_2 = \{ w_{21}, w_{22}, w_{23}, w_{24} \} \]
\[ W_3 = \{ w_{31}, w_{32} \} \]

Where, \( w_{11} \) is air quality index; \( w_{21} \) is wind speed, m/s; \( w_{22} \) is rainfall, mm/24 h; \( w_{23} \) is lightning warning level; \( w_{24} \) is visibility, km; \( w_{31} \) is low temperature, °C; \( w_{32} \) is high temperature, °C.

2.1.2. Navigation model index

Through the establishment of fuzzy evaluation matrix, the impact of port weather on navigation is evaluated. The fuzzy evaluation matrix of navigation impact is:

\[ H = A_i H_i \quad (i=1, 2, 3) \]  

(1)

In the formula, \( A_i \) is the weight matrix of meteorological primary factors and \( H_i \) is the membership matrix of meteorological primary factors.
\[ H_1 = (h_{11}, h_{12}, h_{13}, h_{14}) \]  
\[ H_2 = A_{k1} H_1 = (h_{21}, h_{22}, h_{23}, h_{24}) \]  
\[ H_3 = A_{k2} H_2 = (h_{31}, h_{32}, h_{33}, h_{34}) \]

In the formula, \( H_1 \) is the membership matrix of air quality index; \( H_2 \) is the membership matrix of visualized meteorological primary factors; \( H_3 \) is the membership matrix of temperature primary factors; \( A_{k1} \) is the weight matrix of visualized meteorological secondary factors; \( A_{k2} \) is the weight matrix of temperature secondary factors; \( k = 1, 2, 3, 4; j = 1, 2 \).

2.2. Membership degree of meteorological factors
Taking Qingdao port as an example, combining the literature data\(^9\) and the port meteorological data, port navigation control log, maritime data, personnel experience and ship owner data over the years, the membership matrix of meteorological factors at all levels is obtained in Table 1 to Table 3; the influence weight of meteorological factors at all levels on navigation is shown in Table 4.

### Table 1 Membership matrix of \( H_1 \)

| Factor \( w_{11} \) | Range | Nothing | Slight | Serious | No navigation |
|---------------------|-------|---------|--------|---------|---------------|
| <80                 | 0.450 | 0.300   | 0.250  | 0.150   | 0.000         |
| 80–100              | 0.150 | 0.700   | 0.100  | 0.050   | 0.000         |
| 100–150             | 0.050 | 0.100   | 0.700  | 0.150   | 0.150         |
| >150                | 0.000 | 0.000   | 0.200  | 0.800   | 0.800         |

### Table 2 Membership matrix of \( H_{21} \)

| Factor \( w_{21} \) | Range | Nothing | Slight | Serious | No navigation |
|---------------------|-------|---------|--------|---------|---------------|
| <3.3                | 0.350 | 0.250   | 0.250  | 0.150   | 0.150         |
| 3.4–7.9             | 0.100 | 0.500   | 0.250  | 0.150   | 0.150         |
| 8.0–13.7            | 0.000 | 0.200   | 0.650  | 0.150   | 0.150         |
| >13.8               | 0.000 | 0.050   | 0.200  | 0.750   | 0.750         |
| <10                 | 0.350 | 0.250   | 0.250  | 0.150   | 0.150         |
| 11–25               | 0.150 | 0.550   | 0.100  | 0.200   | 0.200         |
| 26–50               | 0.000 | 0.050   | 0.400  | 0.550   | 0.550         |
| >51                 | 0.000 | 0.000   | 0.150  | 0.850   | 0.850         |
| 1                   | 0.450 | 0.200   | 0.200  | 0.150   | 0.150         |
| 2                   | 0.100 | 0.750   | 0.150  | 0.000   | 0.000         |
| 3                   | 0.000 | 0.050   | 0.100  | 0.850   | 0.850         |
| 4                   | 0.000 | 0.000   | 0.050  | 0.950   | 0.950         |
| <0.3                | 0.000 | 0.050   | 0.100  | 0.850   | 0.850         |
| 0.4–1.0             | 0.050 | 0.150   | 0.600  | 0.200   | 0.200         |
| 1.1–10.0            | 0.300 | 0.500   | 0.150  | 0.050   | 0.050         |
| >11.0               | 0.450 | 0.250   | 0.150  | 0.150   | 0.150         |

### Table 3 Membership matrix of \( H_{31} \)

| Factor \( w_{31} \) | Range | Nothing | Slight | Serious | No navigation |
|---------------------|-------|---------|--------|---------|---------------|
| <10                 | 0.250 | 0.450   | 0.200  | 0.100   | 0.100         |
| -10–25              | 0.450 | 0.250   | 0.150  | 0.150   | 0.150         |
| 25–40               | 0.500 | 0.300   | 0.150  | 0.050   | 0.050         |
| >40                 | 0.050 | 0.250   | 0.500  | 0.200   | 0.200         |

### Table 4 Membership matrix of \( H_{32} \)

| Factor \( w_{32} \) | Range | Nothing | Slight | Serious | No navigation |
|---------------------|-------|---------|--------|---------|---------------|
| <10                 | 0.250 | 0.450   | 0.200  | 0.100   | 0.100         |
| -10–25              | 0.450 | 0.250   | 0.150  | 0.150   | 0.150         |
| 25–40               | 0.500 | 0.300   | 0.150  | 0.050   | 0.050         |
| >40                 | 0.050 | 0.250   | 0.500  | 0.200   | 0.200         |
Table 4  Weight of meteorological factors on sail

| Primary factor | Weight value | Secondary factors | Weight value |
|----------------|--------------|-------------------|--------------|
| $A_1$          | 0.150        | $A_{31}$          | 0.200        |
| $A_2$          | 0.600        | $A_{32}$          | 0.150        |
| $A_3$          | 0.250        | $A_{33}$          | 0.300        |

2.2.1 Model simulation verification

In order to verify the feasibility of the model, according to Dagong Island Station (35°57′36.5″N,120°29′31.8″E, monitoring height of 10 m), Fulong mountain station (36°04′11.73″N,120°20′7.82″E, monitoring height of 8.6) in Qingdao port (Fig.1), the coastal area of northern China is affected by the subtropical high over the Western Pacific in summer. The whole year 2019 meteorological data released by the monitoring station were simulated and evaluated, and compared with the port navigation control log test results. Take 8.1 the day meteorological factors (among them, $w_{11} =38; w_{21} =2m/s; w_{22} =6mm/24h; w_{23} =2; w_{24} =9.7km; w_{31} =26℃; w_{32} =30℃$) for example.

![Fig.1  Meteorological monitoring station of Qingdao](image)

From Table 1 to Table 4, Weighting matrix of meteorological primary factors:

$A_1 = (0.150), A_2 = (0.600), A_3 = (0.250)$

The membership matrix of meteorological primary factors is as follows:

$H = (0.450, 0.300, 0.250, 0.000)$

$H_1 = (0.257, 0.488, 0.185, 0.070)$

$H_2 = (0.500, 0.300, 0.150, 0.050)$

The fuzzy evaluation matrix of navigation impact is:

$H = (0.347, 0.413, 0.185, 0.055)$

From the fuzzy evaluation matrix of navigation impact, it can be seen that on August 1, 2019, the weather impact factors $\rho$ on port navigation are 0.347, 0.413, 0.185, 0.05 respectively, and the final evaluation result is: slight impact.

Taking August 2019 as an example, the comparison between the results of fuzzy comprehensive evaluation and the results of navigation control log test is shown in Fig.2 to Fig.3.
It can be conclude from Fig.2 that in August, the navigation non-impact and slight impact curve is generally higher than the serious impact and no navigation curve; when there is no impact or slight impact, the navigation rate to ensure the safety of ships in and out of the port can reach 90.32%. On account of the comparative analysis, it can be seen that the calculation results are basically consistent with the test results, and the number of forbidden spaceflight deviates by one day; the influence of wind, fog and thunder factors on navigation increases in turn; within the same meteorological factor membership, when the wind force is less than level 6, the navigation is significantly affected by fog factors; in addition, the influence of the wind force factor which is less than level 6 on navigation is slightly greater.

2.2.2 Influence degree of Visual Meteorological Factors

In order to further explore the limited influence of wind, rain, thunder and fog factors below level 6 on navigation, according to the results of fuzzy comprehensive evaluation of navigation in August, the single visual meteorological factor change data within the same air quality and temperature subordinate degree is selected for comparative analysis, and the impact evaluation result curve is drawn, as shown in Fig.4, the abscissa is the scheme number of single factor change, and the abscissa is vertical sitting. It is marked as the influence factor of navigation.

Fig.4  Influence curve of visual meteorological factors

Fig.4 demonstrated that the wind force below level 6 and a small amount of rainfall have little impact on the port navigation; compared with the thunder factor, the navigation restriction changes from slight to serious, and the fog factor causes no impact to jump to no navigation state, indicating that the
navigation restriction is more sensitive to the fog factor, at this time, the navigation influence factors of both can reach 0.31 and 0.24; in addition, due to the incomplete separation of the thunder factor, the slight shadow in (c) is caused. The response curve is higher than the no effect curve.

3. Results and Discussion

3.1 Wind factor test analysis
The maritime traffic control manual specifies the navigation control measures to be taken when the actual offshore wind force reaches the critical value. This paper studied the results of the influence of meteorological factors on the navigation restrictions when the wind force is less than 6. Due to the particularity of the geographical location of the port and the safety and reliability of the navigation, it is necessary to further consider the influence of wind force factors on the navigation of the port.

3.1.1 Data monitoring source
Based on the annual meteorological monitoring data of 8 monitoring stations such as Dagong Island Station of Qingdao port from 2010 to 2015 and the navigation control data of Qingdao, the wind impact on navigation was analyzed. The test equipment is X-band weather radar and VAISALA automatic weather monitoring system.

3.1.2 Result analysis
Fig. 5 illustrates the radar chart of the number of days with wind force greater than level 6 in Qingdao port from 2010 to 2015, in which the semantic direction represents the wind force level and the trajectory direction represents the month.

![Radar charts of days with wind greater than level 6 in Qingdao port from 2010 to 2015](image_url)

Fig. 5  Radar charts of days with wind greater than 6 in Qingdao port from 2010–2015.

Take gale as an example, make a fuzzy comprehensive evaluation of the number of banned spaceflight from 2010 to 2015, and compare the calculation results with the results of navigation control test of Qingdao port, as shown in Fig.6, in which the abscissa represents the month and the ordinate represents the number of banned spaceflight days.
Fig. 6 Comparison curve between evaluation value and test value from 2010~2015.

Fig. 6 shows that the curve of the fuzzy comprehensive evaluation results in this paper is in good agreement with the curve of the test results, and the curve trend is basically the same. It is found that the wind force greater than level 6 mostly occurs in October to December, and the navigation ban mostly occurs in May to July, and there is a significant deviation between the two. The reason for the analysis is that Qingdao port is located in Jiaozhou Bay, and the ships are two-way navigation from southeast to Northwest (as shown in Fig. 1), and the wind force from May to July is more than one-way navigation. The wind direction is mainly southerly, and the sea is relatively calm; from October to December, the wind is mainly northerly, and the sea surface is relatively calm; in addition, the number of spaceflight bans reaches a maximum in July every year, with a maximum of 21 days of bans. The main reason is that in summer, Qingdao is mostly affected by the subtropical high and tropical gyration of the Western Pacific Ocean, and the sea conditions are complex and changeable[12]. In addition, due to the influence of the weather, all kinds of ships navigate separately. It is strictly restricted.

According to the fitting calculation method of non-linear curve, the fitting index (\(R_{New}\)) of the model calculation results of navigation ban in each month from 2010 to 2015 and the navigation control test results of Qingdao port is as follows:

\[
R_{New} = 1 - \left( \frac{\sum (y - y^*)^2}{\sum y^2} \right)^{1/2}
\]  

Where, \(y\) represents the test value and \(y^*\) represents the calculated value.

The calculation results of fitness index (\(R_{New}\)) are shown in the Table 5:

| Year | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|------|------|------|------|------|------|------|
| \(\sum(y - y^*)^2\) | 18 | 19 | 44 | 23 | 21 | 17 |
| \(\sum y^2\) | 402 | 856 | 1316 | 913 | 598 | 537 |
| \(R_{New}\) | 0.79 | 0.85 | 0.82 | 0.84 | 0.81 | 0.82 |

From Table 5, it can be seen that the consistency between the calculation results and the test results is about 80%, and the maximum is 85%. That is to say, the fuzzy comprehensive evaluation model established in this paper can meet the requirements of port ship navigation meteorological evaluation.
4. Conclusions
In this paper, by establishing the fuzzy evaluation model of the influence of meteorological factors on the navigation, the influence of meteorological factors on the navigation restrictions is analyzed, and compared with the port navigation control test, the conclusions are as follows:

(1) The fuzzy comprehensive evaluation model established in this paper has a good fit between the calculation results and the test results, which proves that the model is feasible and effective, and meets the engineering needs of ship safety navigation evaluation under the future meteorological conditions;

(2) Within the same air quality index and temperature subordination degree, the influence degree of wind, fog and thunder on the navigation limit increases in turn; considering the influence of weather conditions on the navigation of port ships in the whole year, wind and fog are the most important factors affecting the safe navigation of ships.

This paper focuses on the influence of wind, fog and thunder on the navigation of ships in the port area, which is limited by the meteorological conditions of the geographical location of the area and the existing data. In view of the influence of meteorological factors such as air quality index, rain and temperature on the navigation of ships in the port, further research is needed. In the foundation of summarizing and appraising the influence of wind, fog and thunder on the navigation of ships in the port area, this thesis put forward the coming direction of research in the future.

Acknowledgments
Major projects of Qingdao science and technology(20-3-2-2-2-hy); National Natural Science Foundation of China（60970130, 61672475）

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