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RESEARCH ARTICLE

Modeling of Safe Distance Between Ship Routes and Offshore Wind Farm Based on Tolerable Collision Probability

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ABSTRACT With the continuous increase of offshore wind farms and other offshore regional buildings, the contradiction between them and the navigation safety in the densely distributed areas of offshore ship tracks is increasingly obvious. It is urgent to build a safe distance model based on the actual sea condition to reduce the mutual influence. Based on the drift distance of ships in the boundary water areas of the wind farm under the actual meteorological and hydrological conditions, as well as the tolerable collision probability, reliability model and the normal distribution trend of ships in the ship routes, and the probability model of safe distance between ship routes and wind farm is built in the end. Based on the example and the tolerable collision probability of ships, the safe distance is analyzed, the analysis results show that the calculation model can determine the safe distance according to the control requirements of the collision probability between the ship and the offshore wind farm. In addition, the collision probability and the safe distance obtained are basically consistent with the safe distance published by the local maritime authority in combination with the changes of the output results caused by the velocity difference of the ship. The model lays a theoretical foundation on offshore wind farm site selection optimization, route boundary demarcation, ship safety and maritime supervision.

INDEX TERMS Safe distance, tolerable collision probability, modeling, offshore wind farm.

I. INTRODUCTION

With the reform of energy supply and the development of shipping industry, offshore wind power energy has gradually become one of the most rapidly developed and highly commercialized power generation modes with the largest scale in the field of new energy [1]. At present, offshore wind power has become an important way of energy transformation, and it is also an important means to promote energy and consumption reform and deal with air pollution [2], [3]. However, due to long construction period and complex operating environment, the site selection of offshore wind farm has always been the focus of its study. Existing studies on offshore wind farm site selection mostly consider economy, interest, local environment and other factors, to maximize the potential of offshore wind farms [4]–[6]. However, due to the limitation of water depth required for wind farm construction [5], offshore wind farm construction areas are mostly densely distributed areas of ship tracks, which are mostly distributed on both sides of the route. If the site selection is improper, the risk of collision between ships and offshore wind farms will increase greatly. To ensure more reasonable site selection location of

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offshore wind farms, how to set the safe distance between ship routes and offshore wind farms becomes the first problem to be solved in the process of offshore wind farm construction.

At present, no uniform standard for setting the safe distance is available. For example, Pacific Northwest National Laboratory points out that the distance between ships and offshore wind farms is generally 5 nautical miles [7], while UK NOREL working group stipulates that the boundary and route of offshore wind farms shall be kept at a distance of 2 nautical miles [8], [9]. The above-mentioned regulations are determined according to the relevant risks such as local ship routes, navigation obstacles and navigation environment. However, due to the different executive bodies and great sea area factor differences, they are not completely applicable to the site selection and construction planning of wind farms in various regions, resulting in the weak repeatability and low popularization value of the above-mentioned regulations. When defining the safe distance between ship routes and offshore wind farms, the risk of collision between ships and offshore wind farms is an important index to determine the safe distance. At present, relevant scholars have made a lot of studies on the calculation methods of collision risks. For example, Shuzhe Chen *et al.* established a risk model using the relative speed and relative distance of the ship on the Riemann sphere [10]; Junmin Mou *et al.* established an offshore wind farm operation fault tree analysis system based on data to evaluate many risks of offshore wind farms, including risks of collision with ships [11]; Qing Yu *et al.* discussed the collision mechanism of SOI geometrically by using the mixed risk modeling method. After inserting the risk input data converted into the rule-based Bayesian Networks (BN), they calculated risks of collision between ships and offshore facilities (SOI) and considered factors such as offshore distance and sea velocity [12]. Cheng Xie *et al.* proposed an integrated QRA (quantitative risk assessment) model for analyzing risk, including risk identification, probabilistic calculation, and consequence modeling [13], and also proposes a novel impact index based on the risk theory to improve the risk assessment accuracy [14].

As the distribution characteristics of ships in the route will directly affect the overall collision risks of ships in water areas in the wind farm water areas, some scholars have improved the collision risk model based on the actual distribution characteristics of ships in the route. For example, MP Mujeeb-Ahmed *et al.* considered the distribution characteristics of ships in the route, and estimated the probability of collision with large offshore platforms according to AIS data identifying different types of ships in the database [15]; R. W. Liu *et al.* improve the quality of vessel trajectory records to reduce the risk of ships at sea [16], [17]; Qing Yu *et al.* proposed a mixed risk analysis method for the risks of ships in the route and offshore wind farms. Aiming at the traffic flow in the route, AIS data and subjective judgment are combined in a complementary way to form a new BN risk analysis method based on AIS data [18], which can truly reflect the risks of collision between ships and offshore wind farms in the water; Xie, Haibo *et al.* analyzed the safe distance between offshore drilling platform and passing ships, expressed the safe distance range of offshore drilling platform by circular radius, and determined the safe distance by studying the drift of different ships in the same water environment in combination of AIS data, a drift model for ship out of control and a ship emergency stopping model [19]. Overlarge safe distance will cause water to consider the risk of ship collision and the utilization efficiency of water resources. Son, Woo-Ju *et al.* tested the normality of the safe distance between the pier edge of Incheon Bridge and Busan Harbour Bridge and the ship based on the traffic distribution of the ship. According to Z score, they analyzed the safe distance range by confidence interval, and divided the distance into safe distance and early warning distance, thus avoiding the waste of water resources caused by overlarge safe distance on the premise of ensuring navigation safety [20].

Upon comprehensive consideration of the existing studies, the above methods mostly focus on the calculation method of the risks of collision between offshore facilities and ships, while the studies on the collision risks of offshore wind farms are a few. However, due to the complexity and particularity of the structure of offshore wind farms and the difference of interaction with ships, and Strong winds in the wind farm area often have a strong impact on ships in nearby routes. the applicability of the existing calculation method of the safe distance between offshore facilities to offshore wind farms needs to be verified. At the same time, the offshore wind farm is located in the deep-water area with complicated wind, wave and current, and the track characteristics of existing ships in the route also have a direct impact on the safe distance. Although some domestic and overseas scholars have put forward a series of assessment methods for the risks of collision between ships and offshore wind farms, the comprehensive influence of wind, wave and current, as well as ship routes on the safe distance of offshore wind farms is not considered, causing insufficient estimation of ship collision risk and affecting the rationality and reliability of wind farm site selection. Taking the water areas of an offshore wind farm in China as the object of study, the paper converts the probability of the out-of-control drift of the ship in the offshore wind farm water into the probability of collision caused by out-of-control drift of the ship in the route at a distance from the offshore wind farm based on the a drift model for ship out of control and the occurrence probability of local wind and current at all levels, and establishes the calculation model of safe distance between the ship and the offshore wind farm combined with the tolerable collision probability range of the ship and the offshore wind farm, finally calculates the range of safe distance of the ship in the offshore wind farm water in a quantitative manner. The model lays a theoretical foundation on offshore wind farm site selection optimization, route boundary demarcation, ship safety and maritime supervision.

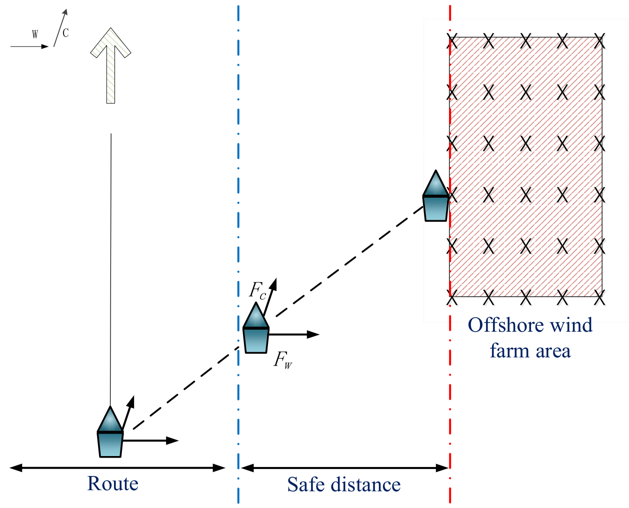

FIGURE 1. Schematic diagram of drift scenario.

II. CALCULATION MODEL OF TOLERABLE SAFE DISTANCE BASED ON SHIP OUT-OF-CONTROL DRIFT

A. MODELING OF SAFE DISTANCE

There is a certain distance between the wind turbines in the offshore wind farm, which aims to facilitate the access of operation and maintenance ships. However, if other ships enter the wind farm area by mistake, they will face great accident risks. Therefore, it is defined that entry of ships into the boundary of the wind farm area can be considered as collision with the offshore wind farm area. In the process of ship out-of-control drift, the ship is under the action of constant wind and current, and longitudinal velocity remains constant. Therefore, it is approximately assumed in the model that the ship will keep rectilinear motion in the process of ship out-of-control drift. Assuming that F_w is wind force and F_w is current force, Fig.1 shows the drift scenario of collision between a ship and an offshore wind farm.

In the process of ship out-of-control drift, under the action of wind, wave, current and other environmental factors, the ship heading is towards the wind farm, thus gradually approaching the wind farm area and colliding with the wind turbine. We established the probability equation for the ship to drift out of control drifting to the wind farm as follows:

$$P_n = N_i \times P_a \times P_b \times P_c \times P_m \tag{1}$$

where: P_n is the probability that the ship collides with the offshore wind farm area due to the drift of the ship when there is a certain distance between the ship and the offshore wind farm in water areas; N_i is the annual traffic volume of a type of ship; P_a indicates the probability that the ship laterally drifts to the wind farm area of the ship under the action of a specific combination of wind and current; P_b is the probability of the target ship getting out of control in the route; P_c is the probability that the ship is distributed at a position in the ship route; P_m is the probability that the crew cannot take effective emergency measures or obtain external rescue in the process of ship out-of-control drift. When P_n is within the tolerable collision probability range upon calculation, the corresponding input position x of the ship at this time is within the safe distance range calculated.

According to the process of out-of-control drift and the objects involved in the calculation, the calculation model of safe distance of out-of-control drift is divided into five modules: route, ship, wind farm, environment and tolerable collision probability.

Route module. The module input mainly includes route width and route position. The width of the route will have an impact on the ship track, and the distribution of traffic flow sections of the ship will change, thus affecting the collision probability between the ship and the wind farm. Position parameters of the route are usually associated with those of the wind farm. This is used to determine the distance between them. The greater the distance, the smaller the collision probability.

Ship module. The module input mainly includes passsing ship velocity, ship loading capacity and reliability. The velocity of the ship affects the safe distance. When the ship is under the action of wind and current, the larger the loading capacity, the lower the drift velocity, and the longer time for the ship to drift to the wind farm area. Reliability means that the ship may get shore-based rescue or self-rescue by taking effective measures when the drift time of the ship exceeds a threshold.

Wind farm module. The module input mainly includes wind farm position and wind farm boundary length. As mentioned in the route input module that position parameters of the route are associated with those of the wind farm; the greater the distance between them, the lower the probability of ship collision. The boundary length of the wind farm refers to the length of the wind farm near the route area. The longer the boundary length, the longer the ship in the high-risk area of collision with the wind farm, and the higher collision probability between the ship and the wind farm.

Environment module. The factors of the module input mainly include wind and current. The ship drifting out of control is affected by wind-induced drift and current-induced drift, and such impact determines the track of the ship drifting out of control, thus affecting the safe distance of the ship drifting out of control.

Tolerable collision probability module. The module input is tolerable collision probability range specified in the international tolerable collision probability standard or by the allowable collision probability range specified by the local maritime authority in a sea area. It is used to further determine the safe distance range of the ship out-of-control drift.

B. STUDY ON THE A DRIFT MODEL FOR SHIP OUT OF CONTROL

Through the analysis on the process of collision between the ship drifting out of control and the wind farm and consideration of the influence of ship types and ship loading capacity on the collision process, the calculation model of the safe

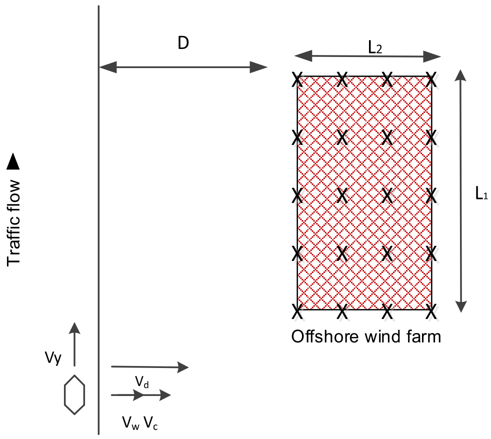

FIGURE 2. Wind, current and velocity model diagram.

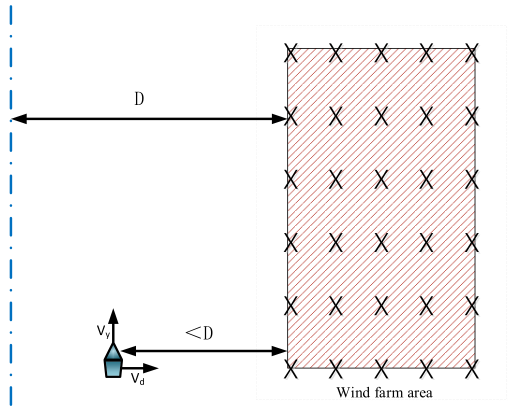

FIGURE 3. Schematic diagram of ship drift.

distance between the ship shifting out of control and the wind farm is constructed as shown below. The resultant velocity decomposition diagram is shown in Fig.2.

In Fig.2, v_y is the longitudinal velocity of the ship in the route, v_w is the wind velocity, v_c is the current velocity, v_d is the actual resultant velocity of wind and current of the ship, D is lateral drift of the ship when passing through the water areas beside the wind farm, L_1 is the length of the wind farm, L_2 is width of the wind farm.

To determine the magnitude and direction of resultant velocity v_d, firstly, it is necessary to know the stress of the ship out of control. The ship out of control is mainly under the action of wind, current and wave. Through the stress analysis of the ship drifting out of control, the following stress equation can be obtained:

$$M \times \frac{dV_d}{dt} + mf = F_w + F_c + F_s \quad (2)$$

$$F_w = \frac{1}{2}\rho_w C_w S_w \left|\vec{v}_w - \vec{v}_d\right| (\vec{v}_w - \vec{v}_d) \quad (3)$$

$$F_c = \frac{1}{2}\rho_c C_c S_c \left|\vec{v}_c - \vec{v}_d\right| (\vec{v}_c - \vec{v}_d) \quad (4)$$

where: M is the loading capacity of the ship; mf is Coriolis force; F_w is the drag force of the wind; F_c is the drag force of the current; F_s is the wave radiation force; ρ_w and ρ_c are the density of air and seawater respectively; S_w and S_c are the hull area above and below the water surface of the ship drifting out of control respectively; C_w and C_c are drag coefficient of wind and current respectively; v_d is the wind current and velocity of the ship; v_w is the wind velocity; v_c is the current velocity.

Assuming that the target ship is always in a dynamic balance condition at sea, that is, $dv_d/dt = 0$ is satisfied at any time and position, and the action of radiation force and Coriolis force of wave is not considered at the same time, equation (5) is obtained:

$$F_w + F_c = 0 \quad (5)$$

v_d equation (6), as shown at the bottom of the page, can be derived.

Assuming that the projected length of the distance between the head and tail of the wind farm in the route is L_1 and the initial velocity of the ship drifting out of control is v_y, the time t spent by the ship passing through the projected length L of the wind farm is:

$$t = \frac{L_1}{v_y} \quad (7)$$

The lateral drift D of the ship out of control is:

$$D = t \times v_d \quad (8)$$

The lateral drift D of the ship can be calculated by synthesizing local wind and current velocities and combining the time when the ship passes through the water of the wind farm.

C. STUDY ON PROBABILITY OF COLLISION BETWEEN SHIP OUT OF CONTROL AND OFFSHORE WIND FARM

When the distance between the ship and the offshore wind farm is less than the calculated lateral drift D, there will be a risk of collision with the offshore wind farm. The schematic diagram of ship drift is shown in the Fig.3.

The ship may collide with not only the side boundary but also the lower boundary of the wind farm. The abscissa of the drift collision point is not fixed and the ship drift is longer in the process, the probability of ship self-rescue or rescue in

$$v_d = \sqrt{v_w^2 + \left(\frac{\left|\vec{v}_w - \vec{v}_c\right|}{1 + 0.036\sqrt{\frac{C_w S_w}{C_c S_c}}}\right)^2 - \frac{2v_w\left|\vec{v}_w - \vec{v}_c\right|}{1 + 0.036\sqrt{\frac{C_w S_w}{C_c S_c}}} \times cos\left(\frac{v_c \times cos\langle\vec{v}_w, \vec{v}_c\rangle}{\left|\vec{v}_w - \vec{v}_c\right|}\right)} \quad (6)$$

the drift process is higher after survey, and the probability of collision with the boundary near the route in the wind farm area is smaller. Therefore, the study only analyzes the ship collision with the boundary of the wind farm near the route. P_a is calculated as follows:

$$P_a = P_{cw} \tag{9}$$

where, P_{cw} is a certain resultant velocity of drift when the ship out of control is under the joint action of environmental factors such as wind, wave and current.

The magnitude of P_{cw} can be determined by comparing the consistency between the direction of the resultant velocity of drift and the orientation of offshore wind farms. Because of different wind directions and wind velocities in different water areas, the position of the ship out of control in the route will also affect the magnitude of P_{cw}. On such basis, the calculation equation of P_{cw} derived is as follows:

$$P_{cw} = \sum_{w=1}^{N_w} \sum_{c=1}^{N_c} P_w \times P_c \tag{10}$$

where: N_w is the number of wind direction types classified; N_c is the number of current types classified; P_w is the probability that the wind direction is the direction of w; P_c is the probability that the current direction is the direction of c.

For a specific water or region, the local meteorological and hydrological conditions can be investigated, the wind velocity and current velocity and their occurrence probability can be counted, and they can be arranged and combined, to calculate the probability of a type of drift of the ship in water areas, and further calculate the probability of collision with the wind farm. The calculation method of the probability P_{b} that a type of ship under normal sailing is out of control in the route is as follows:

$$P_{\mathrm{b}} = P_{i\mathrm{b}} \times \frac{L_1}{v_{iy}} \tag{11}$$

where: $P_{i\mathrm{b}}$ is the average out-of-control probability of this kind of ship in the route per hour; L_1 is the length of the wind farm area; v_{iy} is the longitudinal average velocity of this kind of ship passing through the route.

Generally, the offshore wind farm is built in wide water areas. For ships in wide water areas, the side boundary where the ship may collide with the wind farm is taken as the origin of x axis, and the coordinate system is established with the direction perpendicular to the ship's route as the x axis. Assuming that x is the coordinate of the transverse width of the ship out of control in the route, it indicates the distance between the ship and the wind farm; assuming that B is the average width of the ship out of control, the section of ship traffic flow in the route usually obeys the characteristics of normal distribution [21]. The corresponding position distribution is shown in Fig.4.

Due to different characteristics of ship traffic flow in different water segments, through AIS historical data of specific offshore wind farm water areas obtained by survey from maritime authority. Using $f(x)$ to represent the distribution of ships in routes, it can be obtained by fitting the number of ships in the transverse width direction of the route after collecting the ship traffic flow data in the relevant sea. The corresponding normal distribution is as follows:

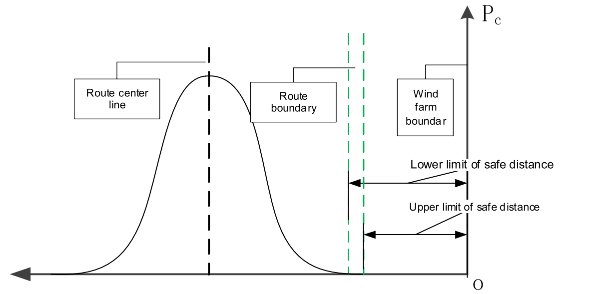

FIGURE 4. Probability density function of ship route transverse distribution.

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{12}$$

P_c is the occurrence probability of ships at corresponding positions, and the calculation method of P_c is as follows:

$$P_c = \int_x^{x+B} f(x)\, dx \tag{13}$$

The crew can obtain external assistance by repairing faults, anchoring, shipping service suspension and other measures to avoid collision with offshore wind farms. Through data analysis for relevant study [22], it can be obtained that the probability $P_m(t)$ of failure to repair the ship's main engine in time depends on the main engine failure time, as shown in Equation (14):

$$P_m(t) = \begin{cases} 1, & t < 0.25h \\ \dfrac{1}{1.5 * (t - 0.25) + 1}, & t > 0.25h \end{cases} \tag{14}$$

According to Equation (14) and combined with the lateral velocity of the ship at this time, it can be obtained that the probability P_m that the crew cannot take effective emergency measures or obtain external rescue. The expression of its distance from offshore is Equation (15).

$$P_m = \begin{cases} 1, & x < \dfrac{1}{4} * \mathrm{v_d} \\ \dfrac{1}{1.5 * \left(\dfrac{x}{v_d} - 0.25\right) + 1}, & x > \dfrac{1}{4} * \mathrm{v_d} \end{cases} \tag{15}$$

After the expressions of variables N_i, P_a, P_b, P_c and P_m are determined, the collision probability between the ship out of control and the wind farm can be calculated.

D. CALCULATION OF TOLERABLE SAFE DISTANCE BETWEEN THE SHIP AND THE OFFSHORE WIND FARM

The tolerable collision probability standard is set with reference to the methods and principles equationted by the acceptable risk standard (As Low As Reasonably Practicable).

TABLE 1. Collision probability standard.

Acceptability of collision probability	Ship collision probability standard/year
Intolerable	$>1\times10^{-5}$
Tolerable	$2\times10^{-6}\sim1\times10^{-5}$
Negligible	$<2\times10^{-6}$

Based on the safe distance calculation model of out-of-control drift, the safe distance calculation model based on tolerable collision probability is established. Theoretically, the greater the distance between the offshore wind farm and the route is, the smaller the probability of collision is. However, the probability of collision between the ship and the wind farm is very low, and setting too large safe distance will cause a waste of water resources.

For equation of tolerable collision probability standard based on ALARP principle, the primary condition is to set the intolerable standard line and negligible standard line. Referring to the requirements of the Maritime Safety Administration of the People's Republic of China for the probabilities of ship collision accidents and ship collision accidents in reality, combined with the subjective willingness and actual risk of risks formulated by relevant departments [23], the probability calculated is set as the standard critical values of intolerable collision probability and negligible collision probability, as shown in Table 1. By drawing the collision probability curve, tolerable range of safe distance can be obtained.

III. CASE STUDY

A. STUDY ON THE DEFINITION OF SAFE DISTANCE OF OFFSHORE WIND FARMS

An offshore wind farm area along the coast of China is selected as the safety study object. The wind farm is in northwest-southeast direction, about 6,000 m long from east to west and 7,000 m from north to south, with large water areas occupied. There are several routes nearby, therefore, it has a certain impact on the safety of ship navigation. One side of the offshore wind farm and the route closest to the wind farm is taken for analysis, and the navigable ships are mainly cargo ships, with an average ship width of 38 m. Based on the actual survey, the solid blue line represents the effective wind force and its intensity, and the dashed line on the outer frame represents the frequency of wind in different directions. The local wind rose map is obtained, as shown in Fig.5.

Among them, the left half is the effective wind force, which promotes the ship to drift towards the boundary of the wind farm; the right half is the ineffective wind force, which offsets the ship away from the wind farm.

In order to simplify the calculation, the effective wind velocity is decomposed to obtain the velocity projection perpendicular to the boundary of the wind farm, which reflects the impact of wind forces of different levels and directions

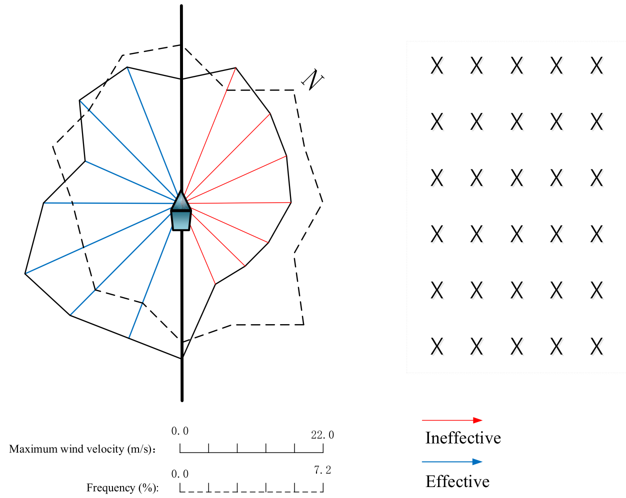

FIGURE 5. Relationship between the wind rose and the route boundary in a coastal area of China.

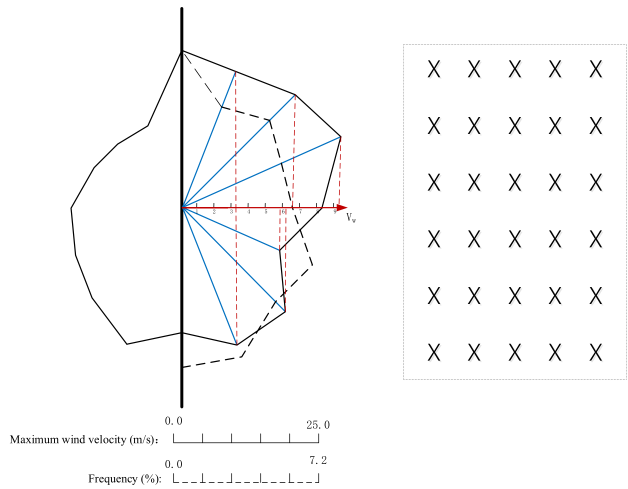

FIGURE 6. Schematic diagram of effective wind decomposition.

on the lateral drift of ships. If the ship heading is parallel to the boundary of the wind farm, the wind velocity acting on the ship in the vertical and horizontal direction will also change. The different wind levels in different wind rose maps are decomposed to obtain the wind velocity projection and gradation that promote the ship to drift to the boundary of the wind farm, as shown in Fig.6.

Survey the current in the water areas, test the current velocity of the surface of the wind farm water areas through experiments, draw the distribution diagram of current velocity and direction, and deal with it (the same as the above wind velocity and frequency treatment process). After projecting the wind velocity and current velocity in the direction perpendicular to the boundary of the wind farm, classify them according to the actual wind and current, and then know the value of wind velocity and current velocity in the water areas after projecting perpendicular to the boundary of the wind farm and its natural occurrence probability statistics, as shown in Tables 2 and 3. Calculate the occurrence probability of different combinations of wind and current, as shown in Fig.7.

Upon the above diagrams of resultant velocity of different wind and current coupling as well as occurrence probability, the limit distance of ship lateral drift under the impact of actual resultant velocity of wind and current as well as the probability of the limit distance can be obtained in different combinations. The calculation results of the above diagrams of resultant velocity of different wind and current coupling as well as occurrence probability are analyzed. The ship navigation model in the water areas is shown in Fig.8.

The left side of the above Figure represents the ship access route, and the occurrence probability in the route obeys the characteristics of normal distribution. v_w and v_c on the right represent wind velocity and current velocity, and the values above numbers 1-9 represent the occurrence probability of wind and current at different levels (consistent with Tables 2 and 3). The final wind and current act on forming the resultant velocity v_d of the ship and determine the lateral drift of the ship.

For beside water areas of the wind farm, local ship tracks and other AIS data are surveyed and analyzed, as shown in Fig.9.

According to Fig.9, the distribution characteristics of section of ship traffic flow in the water areas meet the normal distribution N (4,000, 800). Where, $N(\mu, \sigma)$ and μ represent the position of the center line in the route, which is essentially the distance between the center line in the route and the offshore wind farm area; σ represents the variance of ship distribution in the route, which represents the density of ship distribution and the dispersion of section distribution of ship traffic flow. If σ is larger, the ships are more dispersed in the horizontal distribution, and the probability of its distribution around the center line of route is larger; if σ is smaller, the ships are more densely in the horizontal distribution, and the probability of its distribution around the center line of route is smaller.

Upon the survey of AIS data of ships in local water areas, the fitting shows that the ship velocity distribution meets the normal distribution, as shown in Fig.10.

Taking the average velocity of the ship passing the area of 8.8 m/s, combined with the traffic flow in the water areas and the occurrence probability of local wind and current in Tables 2 and 3, the probability of the ship collision with the offshore wind farm due to out-of-control drift can be calculated through Equation (1); and combined with the tolerable collision probability range in Table 1, the allowable range of safe distance between the ship and the wind farm in the water areas can be calculated.

B. ANALYSISOF SAFE DISTANCE BETWEEN THE ROUTE AND THE WIND FARM

In order to determine the safe distance between the route and the offshore wind farm, the collision probability corresponding to different distances is calculated according to the collision probability calculation model established, and the probability is compared with the tolerable standard, thus judging whether the distance between the ship route and the offshore wind farm is within the range of safe distance, finally further determining the range of safe distance. Combined with Equations (9) and (10), according to the occurrence probability of local wind and current at all levels in Tables 2 and 3, the occurrence probability P_a of the combination of wind and current corresponding to the natural drift of the ship for a certain distance due to the wind and current resultant force under a specific water environment can be calculated preliminarily.

For Equation (1), the analysis of the ship's natural drift process in this paper is based on the ship out of control. According to Equation (11), the probability P_b of ship out of control in the route can be calculated by using the average probability of ship out of control in the route per hour (about 0.0011/h), the length of the wind farm area and longitudinal average velocity of ships passing the route.

Due to the particularity of traffic flow in different regions, the distribution characteristics of ships in the route will also change. According to the route characteristics of the water areas of the wind farm and Fig.9, the section of ship traffic flow obeys the normal distribution of N (4,000, 800). Taking the ship width as the upper and lower limits of the distribution probability integral, the occurrence probability P_c of the ship at a certain position can be calculated.

Due to different drift time during the out-of-control drift, the probability of failing to make self-rescue or obtain rescue will also change for ships. This paper analyzes the reliability of Equation (14) during the ship drift, and transforms the functional relationship between the probability of failing to make self-rescue or obtain rescue and time into the relationship with the distance from the ship to the wind farm, so that the probability P_m that the ship cannot carry out effective making self-rescue or obtaining rescue can be obtained according to the ship's position.

The distribution relationship between the above factors and the distance x is shown in Fig.11.

According to the survey, the ship traffic flow along the wind farm route in the water areas is about 95 ships/day, and the annual traffic flow converted is about 35,000 ships/year, i.e.,. Upon the above calculation result of $N_i, P_a, P_b, P_c, P_m, P_\mathrm{n}$ can be obtained according to Equation (1), as shown in Figure 12.

According to Fig.12, the tolerable section of ship collision probability in Table 1 is $[2 \times 10^{-6}, 1 \times 10^{-5}]$. In the range, there are two groups of corresponding safe distances in Fig.12, and the distance range is [570 m, 1,100 m] and [1,780 m, 1,970 m], The results are shown in Table 4.

C. RESULT OPTIMIZATION ANALYSIS

According to Fig.11, from the macro perspective, the collision probability changes with the distance between the ship and the boundary of the offshore wind farm. With increasing distance between the ship and the wind farm, the collision

TABLE 2. Wind velocity corresponding to all wind levels and its occurrence probability.

Wind level	1	2	3	4	5	6	7	8	>9
Wind velocity (m/s)	1	2	4	6	9	12	15	18	>21
Frequency of natural occurrence	0.01	0.017	0.027	0.083	0.1	0.043	0.043	0.007	0.007

TABLE 3. Current velocity corresponding to all current levels and its occurrence probability.

Current No.	1	2	3	4	5	6	7	8	>9
Current velocity (m/s)	0.5	0.7	0.9	1.1	1.3	1.5	1.7	1.9	>2.1
Natural frequency	0.013	0.02	0.033	0.117	0.083	0.033	0.017	0.01	0.007

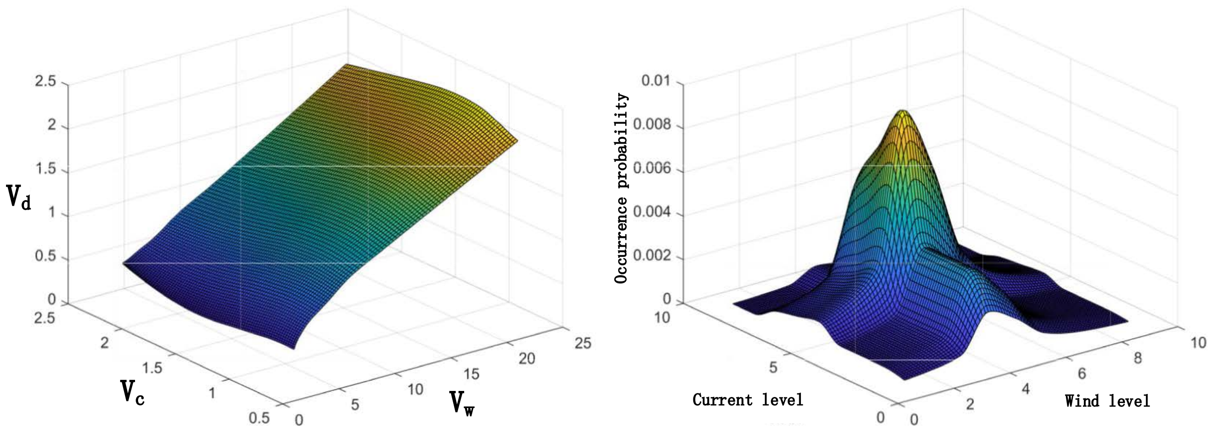

FIGURE 7. Composite diagram of wind and current velocity and occurrence probability in water areas of the offshore wind farm.

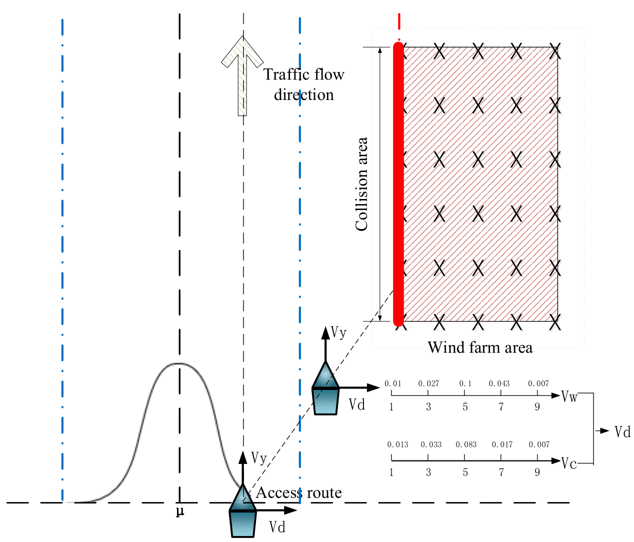

FIGURE 8. Regional model of ship navigation wind farm.

TABLE 4. Safe distance and collision probability range.

Acceptability of collision probability	Ship collision probability standard/year	Safe distance section 1 between ship route and wind farm	Safe distance section 2 between ship route and wind farm
Intolerable	$>1\times10^{-5}$	[1100m,1780m]	[1100m,1780m]
Tolerable	$2\times10^{-6}\sim1\times10^{-5}$	[570m,1100m]	[1780m,1970m]
Negligible	$<2\times10^{-6}$	<570m	>1970m

probability of ships rises first and then declines, and the image fluctuation trend is mainly affected by P_a, P_c, P_m and other parameters. P_b depends on the time ship navigation in the water areas and the probability of ship out of control, and only the amplitude of P_n is affected; N_i is the annual traffic volume of ships passing the route beside the water areas of the wind farm, and only the longitudinal magnification of P_n is affected. Combined with the change trend of P_a along with the distance, when the ship is near the wind farm area, the probability of the wind and current combination making the ship drift to the wind farm area is relatively large, and with the increasing distance between the ship and the wind farm and compared with the close location, the occurrence frequency of the combination of wind and current making the ship drift to the wind farm will decrease, so P_a will decrease with the increase of distance. P_c indicates the distribution

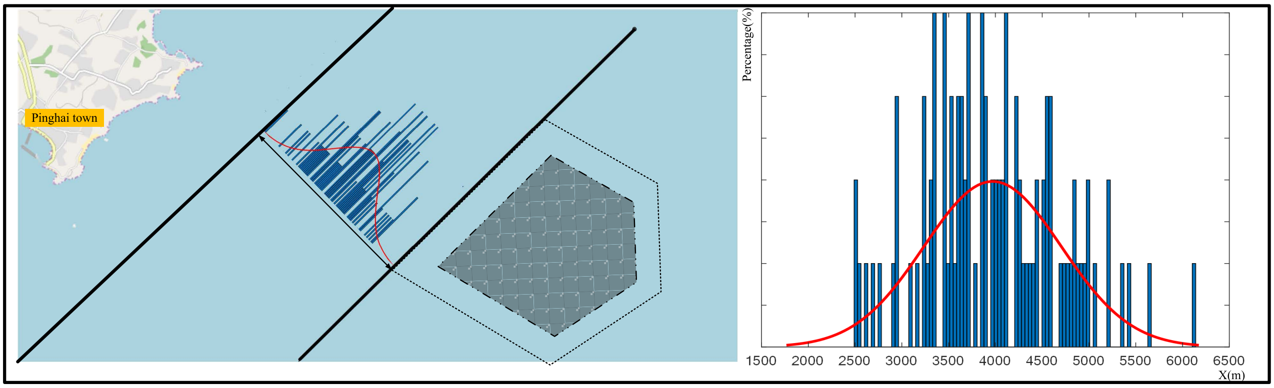

FIGURE 9. Schematic diagram of effective wind decomposition.

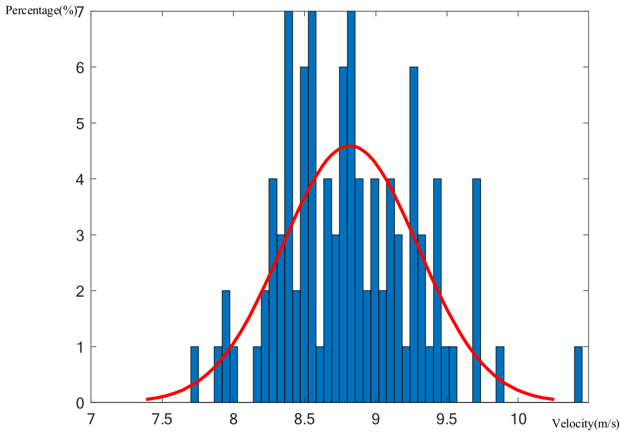

FIGURE 10. Schematic diagram of drift scenario.

probability of the ship in a certain location. According to Fig.9, the ship obeys the normal distribution with a mean of 4,000; therefore, in the water areas within 4,000 m from the offshore wind farm, the occurrence probability of the ship will be increasing with the increase of distance. Combined with Fig.11, when the ship is under the condition of a combination of wind and current and the distance from the offshore wind farm is greater than a threshold, the ship may rescue itself or obtain the rescue.

Combined with the tolerable collision probability range, Sections 1 and 2 mentioned in Table 4 can be obtained. Although they belong to the tolerable collision probability range in the aspect of analysis on the value, the tolerable collision probability range is a comprehensive value in combination with multiple parameters. According to the analysis from the perspective of the probability changing along with the distance in the case that the ship naturally drifts to the water areas of the offshore wind farm, as shown in Fig.13, if normal distribution of the section of ship traffic flow is not considered, when the ship is in Section 1, the occurrence frequency of the combination of wind and current making the ship naturally drift to the offshore wind farm area is relatively large, up to about 0.101; therefore, there is a large collision risk between the ship and the offshore wind farm. While in Section 2, the occurrence frequency of the combination of wind and current making the ship naturally drift to the offshore wind farm area is relatively small, as low as 0.0021, which is 1/50 of the corresponding occurrence frequency of the wind and current in Section 1. Compared with Section 1, the probability that the ship enters the offshore wind farm by the combination of wind and current is relatively small in Section 2. Therefore, it is more reasonable to select Section 2 as the tolerable range of safe distance collision probability.

At the same time, when the ship is out of control in an area close to the wind farm, the relationship between the reliability analysis image Pm and the distance is shown in Fig.14.

When the ship is out of control in the area near the wind farm, the relationship between its reliability analysis image P_m and the distance is shown in Fig.14. When the ship is in Section 1, under different wind and current conditions, the probability that the ship fails to rescue itself or obtain rescue is larger than that in Section 2 on the whole, that is, the ship is too late to make a response or ask for help during drifting. When the ship is under relatively severe wind and current conditions, the probability that the ship fails to rescue itself or obtain rescue is almost the same in two sections, i.e., 1. But in case of the out-of-control drift of the ship in the area with relatively good sea conditions, and combined with the red area and the blue area, the probability that the ship in Section 2 can rescue itself or obtain rescue will increase by 0.13 - 0.4. Therefore, it is more reasonable to select Section 2 as the tolerable range of safe distance collision probability.

In Section 2, with the increase of the distance, the collision probability between the ship and the wind farm shows an overall downward trend. When the distance between the ship and the wind farm is 1,780 m, the probability that the ship naturally drifts to the offshore wind farm area is only 0.0021; when the distance is 1,970 m, the probability is only 0.00055. In brief, under natural conditions, if the section distance is greater than 1,780 m, the probability that the ship naturally drifts and collides with the offshore wind farm area

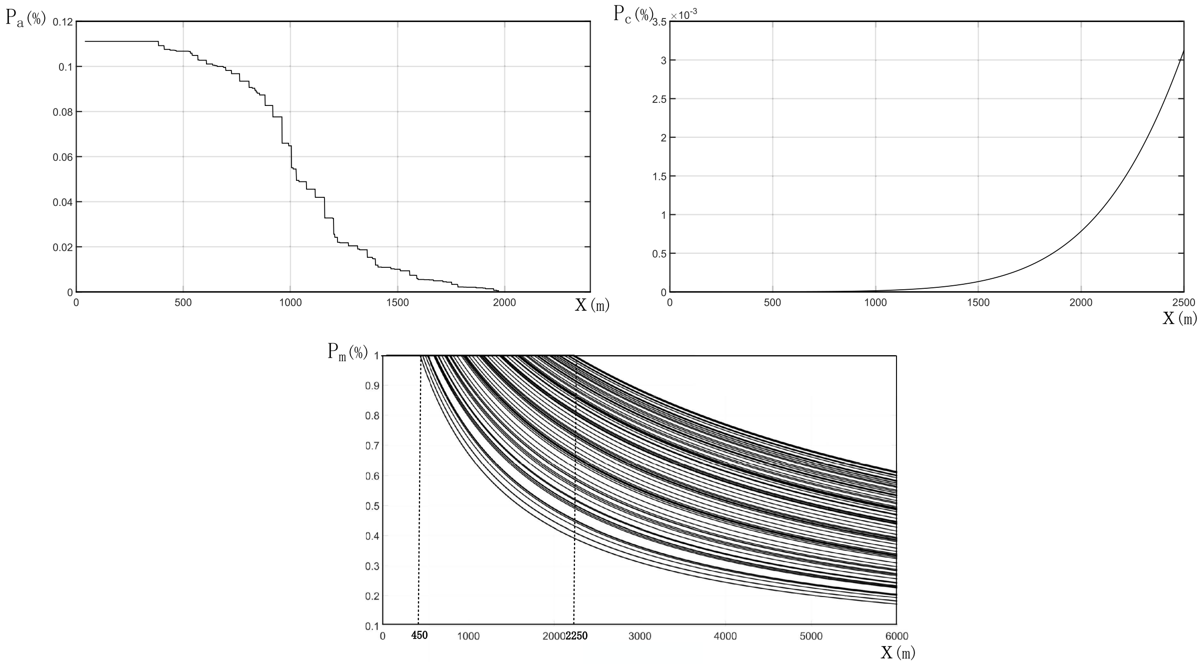

FIGURE 11. Distribution diagram of each influencing factor and distance x.

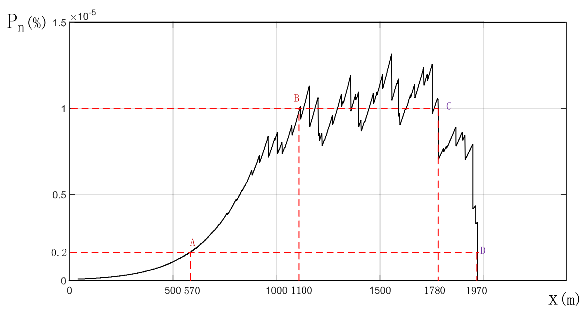

FIGURE 12. Schematic diagram of calculation results of wind farm distance and ship collision probability.

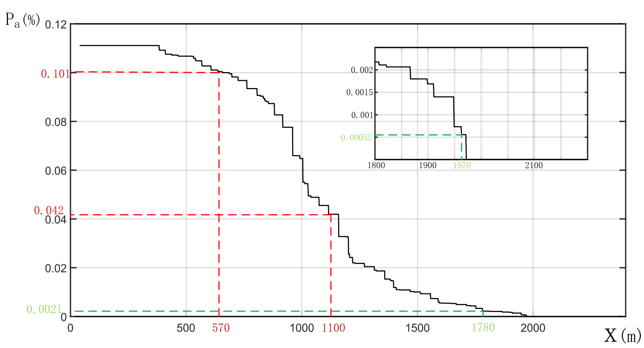

FIGURE 13. Relationship between the drift distances of ships in sections 1 and 2 and the corresponding occurrence frequency of wind and current.

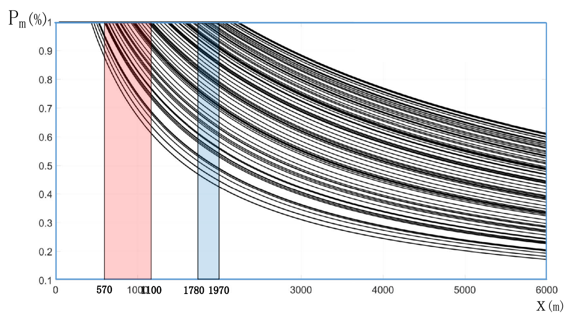

FIGURE 14. Schematic diagram of relationship between the probability of ships in different sections failing to perform self-rescue or obtain rescue and the distance from the wind farm.

is acceptable. In Section 2, the distribution probability of the ship in the area is relatively large, and the collision probability is relatively low at the same time. If the safe distance is greater than 1,970 m, the probability that the ship is out of control and drifts to the offshore wind farm is very low, and the collision probability is close to 0; if the safe distance is set to be very large, the limited route resources will be wasted, thus reducing the traffic efficiency in water areas.

According to the safety evaluation risk report of the local offshore wind farm, the actual distance between the offshore wind farm and the nearby ship route is about 2,500 m, greater than the intolerable distance, indicating that although the calculated safe distance between the ship route and the offshore wind farm belongs to the acceptable range, there is still a certain waste of resources of water areas. If the route boundary is set appropriately near the water areas of the offshore wind farm, the transverse distribution of the ship will be dispersed, thus reducing the collision probability between ships and improving the navigation efficiency of ships in the port.

In conclusion, the output results of the model in this paper comply with the navigation cognition of the maritime authority. Compared with the traditional definition method of the safe distance between the ship route and the offshore wind farm, the traffic flow characteristics of route are combined while considering the out-of-control drift of ships in the model, and the transverse distance of ultimate drift of ships is calculated; therefore, the output of the model better complies with the actual characteristics of the water areas of the wind farm. Simultaneously, the area scope divided by the output of the model can provide a more precise quantitative support for the determination of the safe distance of the offshore wind farm, which is of important practical application value.

IV. DISCUSSION

In this paper, the definition on the safe distance between the route boundary and the wind farm is analyzed from the perspective of the out-of-control drift of ships. During the analysis, the longitudinal (parallel to the boundary of the wind farm) velocity of ships during navigation in the set route is a constant value, which will not change during navigation, and only the transverse (perpendicular to the boundary of the wind farm) velocity of ships is considered. Actually, affected by the wind farm and other offshore buildings, the width of the ship traffic flow will be further narrowed, simultaneously, due to velocity differences in ships, it is easy to have the mutual interference in ships in the route, causing the decrease of the constant velocity of ships and the increase of actual time of ships passing the boundary of the wind farm, as a result, the transverse drift distance of ships under severe wind and current conditions will increase. Simultaneously, because the minimum velocity is lower than the average velocity, there are certain defects in the calculation of the wind and current action time by adopting the average velocity in the water areas, and the model in this paper shall be further optimized.

According to Fig.14, the actual mean velocity in the water areas of the wind farm is 8.8 m/s, the minimum velocity is about 7.7 m/s and the maximum velocity is about 10.5 m/s. If there is a ship at the maximum velocity greater than the average velocity and it is not affected by the ships at a low velocity, its transverse drift distance shall be shorter than the drift distance at the average velocity, which is relatively safer. If there is a ship at the minimum velocity, its navigation time in the boundary of the wind farm will be greater than the time calculated at the average velocity, at this time, its transverse drift distance shall be greater than the drift distance at the average velocity, which shall be paid special attention to. Simultaneously, due to velocity differences, the following ship will slow down when approaching the followed ship, causing that the velocity of the following ship is affected by the followed ship, and at this time, the drift track of the following ship is an arc when approaching the followed ship, and its transverse drift distance is between the drift distance caused by the followed ship and the original velocity of the ship. Whether there is the mutual influence in ships, if the velocity of ships is lower than the average velocity, the time of ships passing through the water areas will become longer, that is, the ultimate drift distance increases, and its drift track is shown in Fig.15.

In the Figure: D_s is the drift distance of the ship at the minimum velocity, D_g is the drift distance of the ship at the velocity greater than the velocity of the followed ship under the condition that the velocity of the followed ship is lower than the average velocity, D is the drift distance of the ship at the average velocity, and D_r is the drift distance of the ship at the maximum velocity.

The calculation result of safe distance under tolerable collision probability in Fig.15 is shown in Table 5.

According to the verification analysis of the data obtained from Table 5, when the ship slows down or its velocity is relatively low under the influence of the followed ship when passing through the water areas of the wind farm, the time of the ship passing through the water areas becomes longer, and the corresponding transverse drift distance when getting out of control accordingly increases. Compared with ships at a high velocity, the occurrence frequency of the combination of wind and current causing collision with the wind farm area affected by wind, current and others will increase for the ships at a low velocity. When the velocity of the ship is greater than the average velocity when passing through the water areas of the wind farm, the time of the ship passing through the water areas becomes shorter, the corresponding transverse drift distance when getting out of control accordingly decreases, and the corresponding safe distance will decrease on the whole. Compared with ships at a low velocity, the occurrence frequency of the combination of wind and current causing collision with the wind farm area affected by wind, current and others will decrease for the ships at a high velocity. Upon analysis, the lower limit value of the safe distance at the minimum velocity of 7.7 m/s is 2,252 m, which is closer to the shortest safe distance of 2,500 m set by the local authority. If it is required to reversely derive the minimum velocity of the ship with a safe distance of 2,500 m, according to Fig.16 and equation (1), when the minimum velocity is about 6.94 m/s, the safe distance can reach 2,500 m. According to the model in this paper, the maritime authority defines the safe distance with the more conservative minimum velocity, and its safe distance has a lower collision risk on the basis of the velocity surveyed in this paper.

In general, the following points should be paid attention to when using the safe distance model between the ship route and the offshore wind farm in this paper.

- The study on the safe distance model in this paper is performed in certain water areas, the parameters affecting the safe distance model output are mainly related to the local wind, current, annual traffic volume, distribution of the section of traffic flow in the local route and other factors. The probability of the ship drifting to a certain location depends on the strength of the resultant velocity that a local specific combination of wind and current projects on the ship drift direction and the occurrence frequency of the combination of wind and current of the

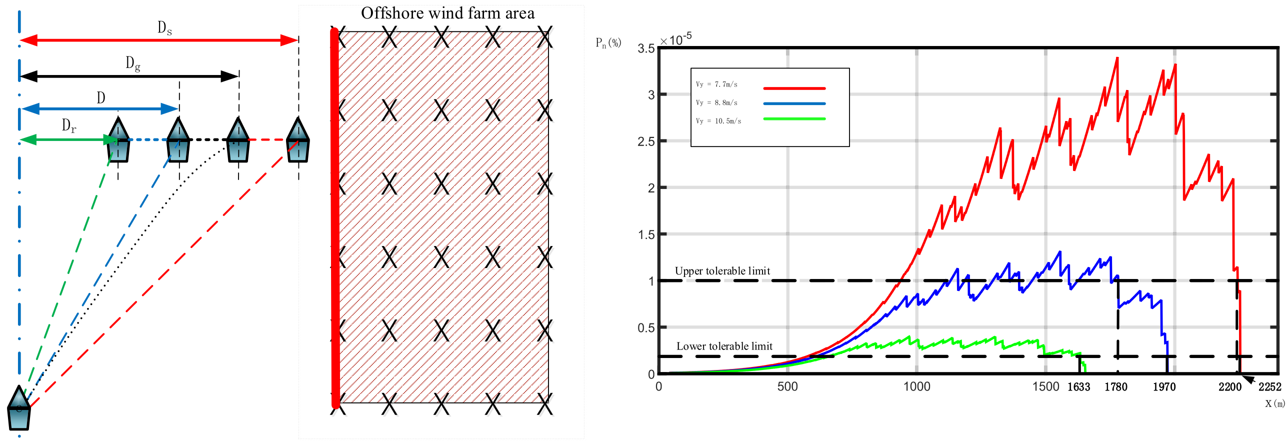

FIGURE 15. Schematic diagram of drift model of ships along with velocity and comparison of safe distance model output under different velocities.

TABLE 5. Schematic diagram of changes of safe distance range.

Safe distance / Input velocity	Upper limit of safe distance	Lower limit of safe distance	Remarks
Minimum velocity: 7.7 m/s	2200m	2252m	There are upper and lower limit sections of tolerable probability for the model output results.
Average velocity: 8.8 m/s	1780m	1970m	There are upper and lower limit sections of tolerable probability for the model output results.
Maximum velocity: 10.5 m/s	——	1633m	All model output results are under the lower limit of tolerable probability.

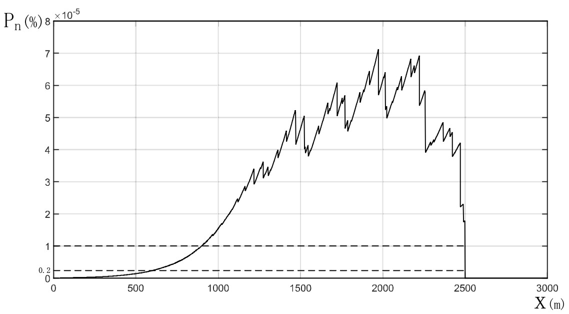

FIGURE 16. Schematic diagram of safe distance model output result at a velocity of 6.94 m/s.

corresponding resultant velocity of ship drifting. During the model calculation, the detailed survey and analysis on the local wind rose map, current rose diagram and other environment information of local water areas is required. The distribution of the section of ship traffic flow in the route can reflect the distribution probability of the ship in a certain location in the route, the different navigation obstacles in the water areas or the planning of local relevant departments on the ship route can affect the distribution of the section of ship traffic flow, and also the change of ship traffic flow can affect the model calculation results. Therefore, the detailed survey on the local ship traffic flow and the section distribution is required for the definition on the safe distance of the model.

- The velocity differences in ships are finally analyzed in this paper, and according to the discussion, there is a significant difference of the safe distance model varying with the change of the mean ship velocity and section. In general, the higher ship velocity will cause the shortening of the safe distance; therefore, the theoretical average velocity of ships shall be firstly considered as the calculation basis. In case of large difference of actual ship velocity, the condition that the slow ship may block the fast ship will occur, causing that the actual average velocity of the ship passing through the wind farm is lower than the theoretical value; therefore, there are certain defects when taking the mean ship velocity into consideration, and the lower velocity can be appropriately considered as the calculation basis, and its minimum theoretical limit value is the minimum velocity of the ship, although its actual occurrence probability is relatively low. Therefore, when calculating the safe distance with the model, it is relatively reasonable to determine the safe distance with a certain value between the average velocity and the minimum velocity. As for the actual maritime authority, the more conservative safe distance can be adopted according to the minimum velocity in the history to publish the actual rules of the water areas.

- As for the tolerable ship collision probability, the extreme values of tolerable probability of ship collision referred in literatures are combined in this paper to define the section of extreme values of the annual collision probability as $[2 \times 10^{-6}, 1 \times 10^{-5}]$, but the ship collision probability in different water areas has its different characteristics, and the upper limit of the tolerable probability is mainly considered for the safe distance of the model to determine the minimum distance; therefore, the upper limit of the tolerable probability can be adjusted according to the actual conditions and the requirements of the maritime authority. As for the lower tolerable limit, it is manly used to protect the navigation resources of the water areas. Under the condition that the probability of ships colliding with the wind farm corresponding to a certain distance from the wind farm in the water areas is lower than the lower tolerable limit, it is basically considered that the ship does not have the conditions to collide with the wind farm, and generally, the combination of the extreme wind and current loads of the water areas can be appropriately considered for the overall consideration.

V. CONCLUSION AND PROSPECT

Through the calculation of the out-of-control drift model of ships under the coupling influence of wind, wave, current, distribution characteristics of the section of ship traffic flow and other factors in this paper, and combined with the tolerable collision probability model, a new definition method of the safe distance between the ship route and the offshore wind farm is proposed. Simultaneously, the example of a coastal wind farm in China is selected for case analysis. The regional average velocity of ships in the wind farm is 8.8 m/s, and the section range of the safe distance obtained by the model in this paper is [1,780 m, 1,970 m], if the minimum velocity of the ship of 7.7 m/s is taken for calculation, the section range of the safe distance can be obtained as [2,200 m, 2,252 m]. According to the calculation result of the safe distance model proposed in this paper, and compared with the minimum safe distance between the actual ship route and the wind farm of 2,500 m published by the maritime authority of the water areas, the difference between the result calculated at the minimum velocity and the result published by the maritime authority is 12%, indicating that the actual safe distance delimited by the maritime authority is more conservative than the safe distance range output by the model in this paper.

In conclusion, the model in this paper has strong universality, and the safe distance calculation model of the wind farm established is of important theoretical value for the actual site selection of the wind farm, route adjustment and others. Simultaneously, its calculation result is of important guiding significance for the improvement of the construction of traffic order in the water areas by the wind farm and the utilization of resources in the water areas.

In the future, we will apply the model to other wind farm waters to further verify the correctness of the model and further improve the ship runaway drift model and the collision probability model.

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