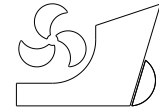


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<http://dx.doi.org/10.21278/brod71201>

ISSN 0007-215X
eISSN 1845-5859

SHIP COLLISION RISK ASSESSMENT MODEL FOR QINZHOU PORT BASED ON EVENT SEQUENCE DIAGRAM

UDC 629.5.051.53:629.5.051.8
Original scientific paper

Summary

Qinzhou Port is one of the most important ports in the “Beibu Gulf” of China. It is also the main hub port of the "21st century maritime silk road" strategy. Based on a basic collision risk assessment approach, an Event Sequence Diagram (ESD) model that explains the four-stage collision avoidance decision-making procedure is proposed from the perspectives of perception, cognition, decision, and execution. Using the historical data derived from collision accident reports from the Qinzhou Port waters from 2013 to 2017, as well as the data elicited from expert knowledge, a quantitative evaluation of probability distributions of different collision failure modes is performed. The results are also compared with relevant results from other types of navigation waters to analyse collision risk level of Qinzhou waters. At the same time, the main failures paths of collision avoidance decision making are identified. The proposed model can provide with an overall collision risk picture from a macro perspective.

Key words: Qinzhou Port; ship collision; Event Sequence Diagram; collision avoidance failure mode

1. Introduction

Qinzhou Port is one of the most important ports in the “Beibu Gulf” area of China. It has many advantages in terms of geographical position advantage, favourable port conditions with wide water area, low frequency of storms, small amount of incoming sand, stable shoreline, and favourable conditions for constructing deep-water berths[1]. In May 2008, the Chinese national government approved the establishment of China's 6th world-connected port in Qinzhou Port. In 2018, the annual cargo handling capacity of Qinzhou Port reached more than 100 million tons. Under the guidance of Chinese "21st century Maritime Silk Road" Strategy (MSR Strategy), Qinzhou Port is also striving for opportunities in the worldwide

supply chain network [2] and actively integrating itself into the development of MSR Strategy.

With the continuous growing ship traffic volume, it is important to keep ship collision risk at acceptable level at Qinzhou Port from risk management and emergency decision making perspectives. Fig. 1 presents a distribution of maritime accident in Qinzhou Port from 2013 to 2017. As can be seen from Fig. 1, collisions/contacts accounts for a large proportion among all types of accidents, and a growing trend is observed during the past years. The vessel traffic flow in Qinzhou Port in the corresponding years is present in Table 1. In view of this, the main objective of this paper is to perform a quantitative analysis on the failure probabilities of collision avoidance decision to present a full picture of collision risk in the water area, and to identify the main causations of collision accidents. Furthermore, measurements of managing and reducing the risk can be formulated by focusing on the most influencing factors. In other words, the study will support the administrators and shipping companies in putting forward effective risk management measures to reduce accident rate.

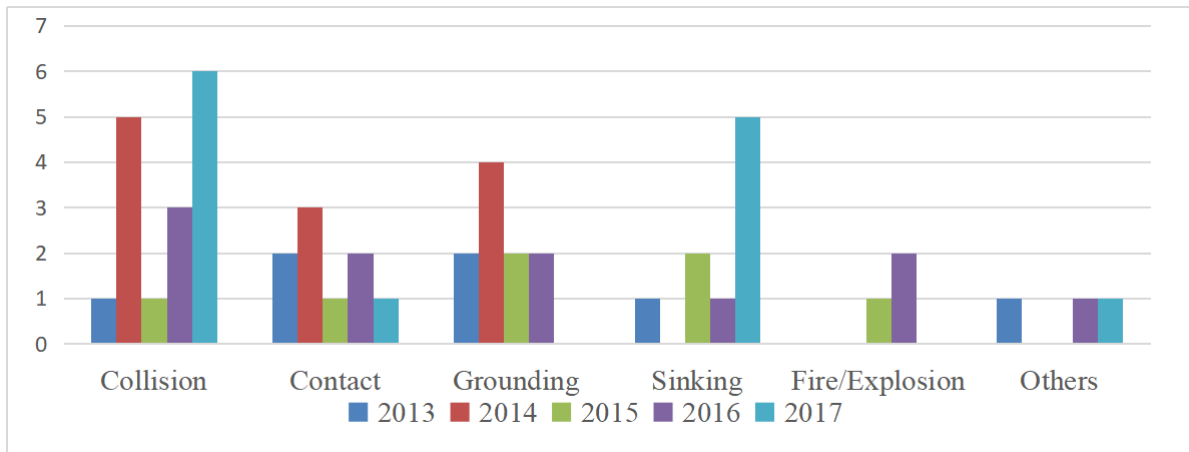


Fig. 1 Distribution of maritime accident in Qinzhou Port

Table 1 Ship traffic volume in the Qinzhou Port

Year	2013	2014	2015	2016	2017	Total
Traffic Volume	21395	14235	11972	27452	29668	104722

The failure modes of collision accidents in Qinzhou Port will be investigated in detail using an Event Sequence Diagram (ESD) model. Different failure modes are quantified using historical data as well as knowledge from experts. The rest of the paper is organized as follows: Literature review in maritime risk assessment and collision risk modelling is discussed in Section 2. In Section 3, the ESD model is constructed, along with the predictions on failure probabilities. Results and analyses are presented in Section 4, followed by discussions in Section 5. Finally, conclusions are made in Section 6.

2. Literature review

2.1 Maritime risk definition

Maritime safety and risk assessment methods have been attracting growing interest for many years. It is a fundamental issue to make a definition on maritime risk. In general, maritime risk is defined as the probabilities of undesired event multiplied by the possible consequences in terms of fatalities, economic loss, and environment pollution [3]. However, such concept may not reflect the full picture for very frequent accidents but with small

consequence, as well as very rare accidents with catastrophic consequences. For example, the risk values for these two types of accidents maybe quite similar, but they have quite different characteristics and should be investigated in different perspectives. In order to overcome this, a scenario-based maritime risk concept was proposed [4], in which the probabilities and consequences are correlated with specific scenarios. Furthermore, some recent researches [5] [6] applied indicator sets, in which contributions of indicator sets to accidents can be quantified. This leads to proposing the most effective measurements in dealing with maritime risks. Goerlandt & Montewka[7] and Lim et al.[8] performed comprehensive literature review on maritime transportation risk assessment from the perspectives of foundation issues and computational algorithms, respectively. They concluded that it is very important to address the issues of uncertainties in dealing with different types of data, including subjective, historical, qualitative and quantitative.

The concepts above tried to express risks from a perspective of undesired events. Comparatively, Resilience Engineering (RE) theory [9] tries to investigate it from the safety perspective. That is to say, it mainly focusses on “what can go right?” instead of “what can go wrong”. One reason for doing this is the fact that undesired events are usually rare, and it is not easy to get enough data to perform in-depth analysis. In general, most of RE models in maritime risk assessment are largely at the conceptual phase and few of them are capable to achieve quantitative evaluation on the risks.

2.2 Collision risk models

A lot of researches have been performed in both maritime and collision risk assessment. Li et al. [10] performed a comprehensive literature review on maritime risk assessment from both frequency and consequence estimation models. The advantages and disadvantages of the models were discussed. They concluded that quantifying the human errors in maritime accidents is the most challenging issue in the future research. In dealing with human factors quantification, Martins & Maturana [11] proposed a Formal Safety Assessment (FSA) approach for the human failure evaluation in the collisions and groundings accident of oil tankers, in which the greatest potentials to reduce the risk are identified. Banda et al.[12] did similar research on the risk management modelling in extreme navigation environment like arctic waters. Collisions between ships are one of the most frequently occurring types of accidents in maritime traffic. Collision risk assessment has been a hot topic for a long time. One of the most widely applied collision risk assessment methods was the Fujii and Macduff model [13][14], which is expressed using the following formula:

$$P = N_A P_C \quad (1)$$

Where N_A is the number of encounters which occur in a specific water area within a certain period of time. If no effective action was taken, collision will occur. This parameter is usually referred to encounter rate. The number of encounters are usually very frequent in some traffic intensive waters [15]–[17]. P_C is the probability of failure of collision avoidance actions when two ships are approaching each other. This paper focuses on the quantitative analysis of ship collision avoidance action failure probability (P_C) in Qinzhou Port.

2.2.1 Encounter rate prediction

The encounter rate between ships within a certain waterway is usually predicted from the perspective of ship traffic flow. Ship Domain (SD) model [17][18] is one of the earliest and the most widely used model to estimate encounter rates. SD is defined as a water area around the own ship, where any violations of other ships are not allowed. The dimensions of a SD is influenced by many factors, including types of waters, navigation environment, a ship's

size and so on. However, most SD models did not consider the manoeuvrability of encounter ships, especially in close-range encounter situations. In order to overcome this, Minimum Distance to Collision (MDTC) model [19][20] was proposed, which is defined as the minimum required distance between two ships to avoid collision with each other using the most effective actions (e.g. performing the largest turning angle with the correct turning directions). The MDTC model was comprehensively applied to the collision risk evaluation in the Gulf of Finland [19][21].

Ship traffic simulation is an effective tool to analyse both safety and efficiency of maritime transportation [22][23][24]. From traffic simulation perspective, Traffic conflict model [25] is another proactive collision risk approach for port areas, in which traffic conflict is defined as a situation that ship collision cannot be avoided if none of them perform effective actions. The degree of collision is measured according to the relative bearings, velocities between them. Such model has been applied to the Port of Singapore[26].

According to the latest research on the encounter rate calculation model, there are various tools to obtain spatial and temporal distributions of different types of encounter situations (head-on, overtaking and crossing). Most of them can estimate the number of ships encounter according to the statistical characteristics of ship traffic flow from the macro dimension, providing a strong basis for collision risk assessment.

2.2.2 Collision avoidance failure prediction

Compared with the encounter rate prediction, the collision avoidance failure estimation is more complex because it is influenced by many factors such as human failures. One intuitive way is to calculate the ratio between the number of collision accidents to the total traffic volume in a specific period of time [27]–[29]. However, it can only present an overall picture on this issue, instead of providing with more detailed knowledge on the characteristics of failure mode. Fault tree or event tree analysis (FTA/ETA) [30][31] is widely applied to representing the logical relationship between different failures and the accident. For example, Uurlu et al.[30] identified and quantified the main causation factors of maritime accidents, including COLREGs violation, communication failure, interpretation failure of the officer on watch. Fuzzy Logic (FL) and Evident Reasoning (ER) [6] are usually used synthetically to express the correlation between factors and risks, as well as some decision making procedures in maritime emergency decision making, considering the uncertainties from the data, the model and so on. For example, ER is applied to the rescue mission optimization for ships that are out of control [27]. The incompleteness of information from different involved organizations are expressed using belief structures. A case study was performed for an accident with main engine failure to validate the model.

FTA/ETA and ER models are tree-structured model and cannot express the correlations among different factors. Bayesian Belief Networks (BBN) [32] are another widely used tools in modelling maritime accidents. A comprehensive literature review is performed in [33], in which the authors highlighted its advantages in expressing complex, weak and uncertain relationships in maritime safety and risk assessment. However, it also has some challenges, especially in different types of uncertainties, as well as validation of the models. Despite this, BBN is a useful tool for safety management and decision making. Zhang et al.[34][35] proposed a relative risk model based on Conjugate Bayesian method. The relative risk model is applied to quantitative evaluation of critical factors of collision risk of Tianjin Port. The model can also identify and quantify key factors of collision accident causations by combining Bayes and least square method. The results indicate that navigational area, ship type and time of the day are among the main causations to the accidents in Tianjin Port.

The researches above are mainly investigating maritime risk from a static perspective. However, maritime accidents are usually characterized with dynamic events. For example, during a collision avoidance decision procedure, ships are performing actions iteratively and the collision risk varies a lot with uncertainties during the whole process. For example, Wang et al. [36] performed a spatial-temporal analysis on an accident under different scenarios. Chang & Mosleh [37] proposed dynamic probabilistic simulation of operating crew response to complex system accident called (IDS-IDACrew). The model can predict the process risk in a real-time mode by quantifying the distance of the present situation to the risk boundaries. This model is largely used in the nuclear sector and has potential to extend its application to maritime sectors.

Based on the related research results, this paper takes collision accident in Qinzhou Port as a case study. A four stage collision decision failure framework, including perception, cognition, decision and action, is proposed. An ESD model is constructed to express collision avoidance decision-making phase. Then, based on historical data on collision accident in Qinzhou waters, combined with experts' knowledge, failure rates under different encounter situations are estimated. Based on this, a quantitative evaluation of the reliability of the collision avoidance decision-making is performed and compared with related research results to verify the proposed method.

3. Collision avoidance failure model

3.1 ESD model for collision avoidance decision making

When performing a collision avoidance action, the navigating ships usually follow similar procedures, no matter they are made by seafarers or by collision avoidance decision support systems. The first step is to identify dangerous targets nearby the own ship. The targets mainly include moving ships which are approaching, static obstacles such as reefs, buoys. An effective watch-keeping by the seafarers. If the seafarers failed in identifying the targets, some advanced onboard sensors can be treated as supplements in alarming the collision risk from the targets. The targets can be identified using on-board monitoring system, such as on-board Radar, Automatic Radar Plotting Aids (ARPA), Automatic Identification System (AIS), etc. However, such systems may fail in identifying obstacles, or make a false alarm under complex environment. If a target ship is not identified in either of the two ways, a collision accident is inevitable.

After the targets have been identified and motion parameters are available with satisfactory precision, the next step is the collision avoidance decision making, in which a safe and effective collision-free path needs to be formulated for the ships. The decisions need to comply with the International Regulations for Preventing Collision at Sea (COLREGs), in which the roles (give-way or stand-on) and requirements of the encounter ships are determined according to their relative location and bearings. The final step is to manoeuvre the ships to follow the planned path. The main risk in this step can be mechanical failure, wind, current and waves, and the manoeuvrability restrictions of the ships.

Based on the above four-stage collision avoidance decision making framework, the ESD model can be constructed, which is shown in Fig. 2. It can be seen from the figure that the starting point is the encounter situation formed by the ships, which mainly includes three encounter situations: head-on, crossing and overtaking. It should be noted that the collision avoidance operations vary a lot for the three encounter situations. For the head-on situation, both two ships need to turn starboard and cross each other in a port-to-port mode. With respect to the crossing situation, the collision avoidance actions are largely dependent on the crossing angles between the two ships. It is more favourable to turn starboard for a large angle

crossing whereas reducing velocity is recommended for a small angle crossing case. In summary, the failure probabilities for different encounter situations will have certain degree of distinctions.

According to Fig. 2, there are two possibilities for the final results, which are success and failure. The final events S1-S3 mean that a collision is avoided, while the final events F1-F7 mean that a collision accident occurs. According to the ESD model, the failures of both watch-keeping and target detection will lead to occurrence of the collision accident. p_1 - p_4 represents the probabilities of failures at each stage, which need to be quantified in order to make quantitative evaluation.

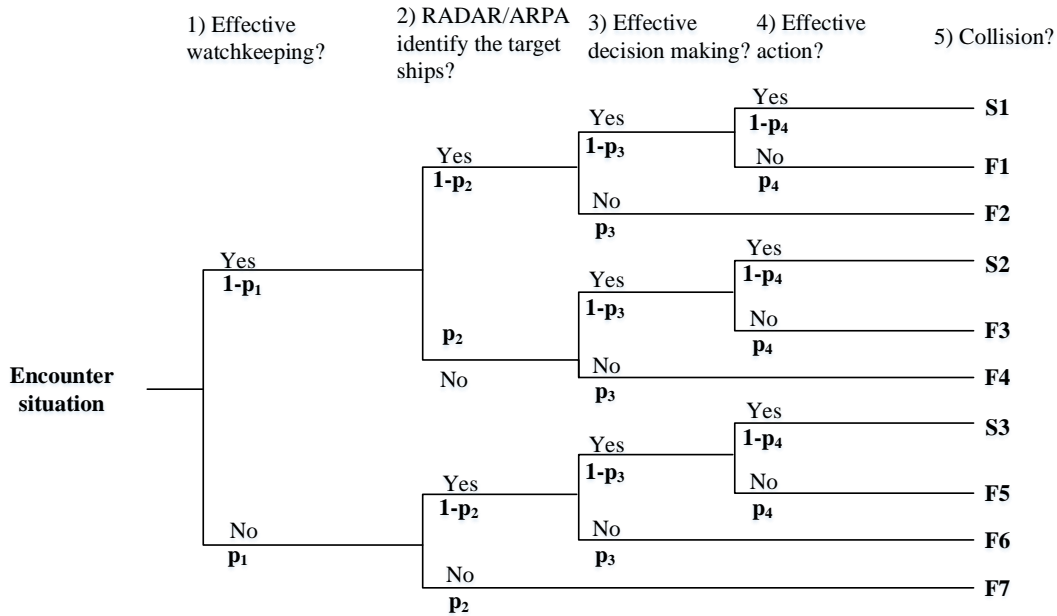


Fig. 2 Event sequence diagram of collision risk in Qinzhou Port

3.2 Failure probability values

Based on the above ESD model for collision risk prediction, it is necessary to estimate the failure probability at each stage, so as to analyse the overall collision risk level. The probabilities can be calculated using the historical data in Qinzhou Port. Table 2 present a sample of the historical accident. According to the collision accident data from 2013 to 2017 as well as the overall traffic flow, the failure probabilities at each stage of decision making can be calculated, which is present in the first row of Table 3. It should be noted that the main causations of collision accidents are recorded in accident reports of Qinzhou Port. According to the report present in Table 2, the causations of each collision accident can be identified. Some accidents are caused by multiple causations. All the causations are counted as one of the failures shown in Fig. 2 and they are all counted in the failure probability calculations. It should be noted that the causation "Not command safe speed" and "Collision avoidance action conflict" are treated as action failure because they are more related with collision avoidance actions.

In order to analyse the failure modes in more detail, the encounter situation is further classified into four categories, which are head-on, large angle crossing, small angle crossing and overtaking. With respect to the crossing situations, the situations with crossing angle larger than 90° is considered as large angle crossing, otherwise it is considered as small angle crossing. It is evident that the degree of difficulty for different encounter situations varies a lot

and they need be evaluated respectively. For instance, in a head-on situation, a very small course alteration will result in an apparent derivation from the present trajectory and keep clearance of the target ship. On the contrary, in a small-angle crossing situation, a small course alteration would not enough to change the direction of the relative velocity with target ships to avoid collision. A detailed graphical explanation on this can be seen in the research by Zhang et al.[40].

Table 2 A sample of the historical collision accident records (From Qinzhou MSA)

Wind	Causations	Ship Type
NW4-5	Negligence watch-keeping; Collision avoidance action conflict	Sand Carrier
		Sand Carrier
NW5-6	Collision avoidance action conflict; Decision failures	Others
		Fishing Ship
E2-3	Mis-operation; Decision failures	Others
		Fishing Ship
SE3-4	Collision avoidance action conflict; Not command good seamanship	Sand Carrier
		Others
SE4-5	Negligence watch-keeping; Not command safe speed; Decision failures	Others
		Oil Cargo Ship
SW5-6	Negligence watch-keeping; Not command safe speed	Fishing Ship
		Others
SE2-3	Negligence watch-keeping; Collision avoidance action conflict	Container
		Fishing Ship
SE3-4	Not command safe speed; Collision avoidance action conflict	Fishing Ship
		Others

However, the historical data did not record such detailed data and the failure rates are not directly available. Alternatively, the subjective knowledge of experts in Qinzhou Maritime Safety Administration (MSA) was introduced. In order to do this, we invited 10 experts, including three managers in Qinzhou MSA, five captains of the ships navigating in the waters, and two safety and security officers from shipping companies. They are all males and they have 5-20 years of experience in maritime transportation risk management in the Qinzhou Port. They are all familiar with the navigation safety situation in the water area from a macro perspective. The experts in Qinzhou MSA are working in the VTS centre, who are familiar with the ship traffic behaviours. The captains are very familiar with the navigational environment in the port. The experts from shipping companies have advantage in safety culture and safety management practices and skills. They are required to estimate the failure possibilities in the four stages. Due to the fact that the probabilities are rather small values and it is difficult for them to estimate, the questionnaire survey simplified the problem by the following questions: What are the maximum and minimum number of failures in each stage of collision avoidance procedures in 10, 000 encounter situations? It should be noted that the failure probabilities may vary a lot under harsh and good navigation environment. For example, the probability of failure in identifying target ships by watch-keeping should be higher in poor visibility than in good visibility. Therefore, the experts are required to give an upper and lower bounds on the failure probabilities. Based on their subjective knowledge, the failure probabilities under different situations is present in lines 2-5 of Table 3. The left values in the brackets are the average of the minima whereas the right values are the maxima of the failure probabilities from the ten experts.

Table 3 Failure probability values under different situations

Encounter situations	p1	p2	p3	p4
Collision rate calculated from historical data	4.77 E-5	1.91 E-5	1.05 E-4	1.43 E-4
Head-on	[4.37E-5, 7.04E-5]	[5.05E-6, 6.23E-6]	[2.19E-5, 4.87E-5]	[6.51E-5, 9.26E-5]
Large angles crossing	[1.35E-5, 5.51E-5]	[2.38E-5, 4.21E-5]	[1.02E-4, 1.47E-4]	[1.04E-4, 1.56E-4]
Small angles crossing	[1.24E-4, 3.07E-4]	[1.04E-5, 1.77E-5]	[4.69E-4, 7.14E-4]	[5.07E-4, 7.30E-4]
overtaking	[5.63E-6, 8.71E-6]	[7.43E-6, 8.25E-6]	[5.04E-5, 8.26E-5]	[8.47E-5, 1.22E-4]

4. Results and analysis

According to the four-stage ESD model for collision avoidance decision making, the occurrence probabilities of different failure modes can be calculated using the following formula:

$$\begin{aligned}
 F1 &= (1-p_1)(1-p_2)(1-p_3)p_4 \\
 F2 &= (1-p_1)(1-p_2)p_3 \\
 F3 &= (1-p_1)p_2(1-p_3)p_4 \\
 F4 &= (1-p_1)p_2p_3 \\
 F5 &= p_1(1-p_2)(1-p_3)p_4 \\
 F6 &= p_1(1-p_2)p_3 \\
 F7 &= p_1p_2
 \end{aligned} \tag{2}$$

Where $F1$ means action failure, $F2$ means decision failure, $F3$ means action failure with RADAR/ARPA detection failure, $F4$ means decision failure with RADAR/ARPA detection failure, $F5$ means action failure with watch-keeping failure, $F6$ means decision failure with watch-keeping failure, and $F7$ means target detection failure. Based on the above formula and the probability distribution in the first row of Table 3, the average probability distribution of different failure modes in Qinzhou Port is calculated, which is present in Fig. 3. As can be seen from the figure, $F1$ and $F2$ is much higher than other failure modes and they are about 4 orders of magnitude higher. Therefore, it can be concluded that the main causations of ship collision mainly include the failure of collision avoidance decision and action failure. It is found from the accident report that such two failure modes are mainly caused by improper ship handling, conflicts between different collision avoidance actions and unfamiliar with the navigation environment. Therefore, it can be concluded that these human errors are the main causes of collision accidents in Qinzhou Port.

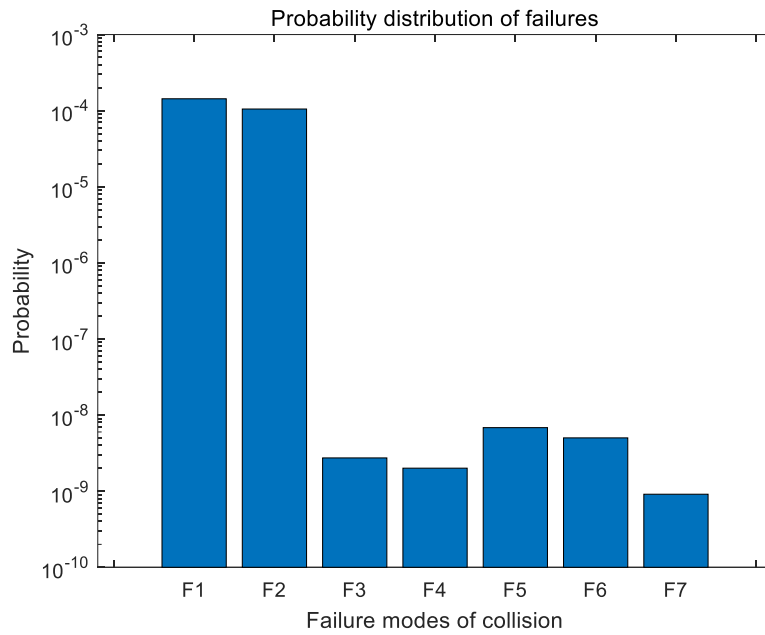


Fig. 3 Probability distribution of different failure modes

Fig. 4 shows the probability distributions of failure modes under different encounter situations. The upper and lower limits of each probability distribution are marked in the figure, correspondingly. As can be seen from the figure, F1 and F2 are also the main failure modes of collision accidents, which are in general higher than other failure modes by 4-5 orders of magnitude. When comparing the four subfigures, the probabilities of collision avoidance failure in small-angle crossing situation is the highest, which is one order of magnitude higher than other scenarios. Such result is in general in agreement with our intuitions. When ships are encountering each other with small crossing angle, it becomes more difficult to identify the target ships because they are navigating in very close direction, where the watch-keepers usually pay less attention to. Moreover, the collision avoidance for such situations is also very complex. It is not clear in such cases whether to avoid collision by course alteration, speed change, or by using both. And it usually takes a long time to keep clearance to each other. Due to the above reasons, the failure probabilities tend to be higher than other encounter scenarios.

It can also be seen from the figures that the probabilities of failures in overtaking are the lowest among the four encounter situations, but with the largest degree of uncertainty. The main reason may be that the front targets are more easily to be identified and collision avoidance decisions are clear under such situations. Both ships should turn to starboard and traverse each other in a port-to-port mode. One issue that needs to be considered is that the head-on situation may be confused with large crossing angles. If so, only one of the ships may take actions, rather than both of them. This may be the reasons for large uncertainty of the results. As a result, the performance of communication and coordination between them become one of the most important factors for collision avoidance.

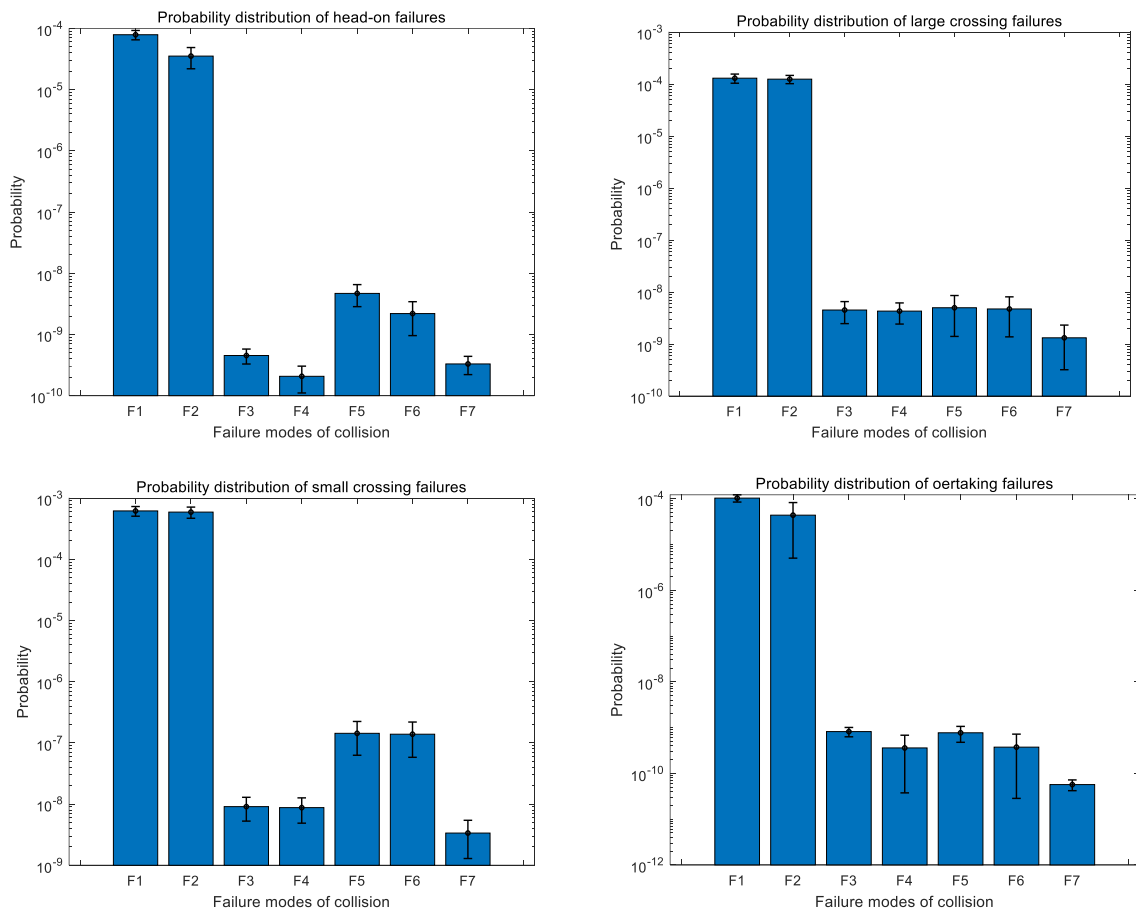


Fig. 4 Probability distribution of failure modes under different encounter situations

Table 4 Comparisons of collision avoidance failure probabilities in different water areas

Navigation waters	Encounter situations	Prob. of collision avoidance failures
Common waters ([10][38])	Crossing	[8.48 E-5, 5.80 E-4]
	Head-on	[2.7 E-5, 5.18 E-4]
The gulf of Finland ([33][39])	Crossing	[5.1 E-4, 6.0 E-4]
	Head-on	[5.1 E-4, 6.0 E-4]
Qinzhou Port waters (This paper)	Overtaking	[8.97 E-5, 2.05 E-4]
	Large angle crossing	[2.06 E-4, 3.03 E-4]
	Small angle crossing	[9.76 E-4, 1.4 E-3]
	Head-on	[8.7 E-5, 1.41 E-4]

In order to further analyse the validity of the calculated results and make a crosswise comparison with the failure rates in other similar water areas, Table 4 lists the results from some other existing researches, including the common waters, the Gulf of Finland, as well as the Qinzhou Port calculated in this study. As can be seen from the data, the current research is limited to cross encounter and opposite encounter, which is generally within the range of 10^{-4} - 10^{-5} . The calculated results in this paper are relatively consistent with the results of these studies. However, the probability of collision avoidance failure is higher under the condition of small Angle cross encounter in Qinzhou Port waters, which is on the order of 10^{-3} . Therefore, it is necessary to focus on how to reduce the reliability of collision avoidance decision in such encounter situations. In general, the probability of collision avoidance failures is relatively low compared with other waters.

5. Discussions

The paper presents a general picture of collision risk in Qinzhou Port using quantitative analysis of the proposed ESD model. The results indicate that the failure rates of collisions in Qinzhou Port are in general similar with other types of navigable waters, but with certain degree of variations for different encounter situations. The accident rates under small crossing encounter situations are much higher than others. Recalling the expert data in Table 3, it can be seen that the failure rates of p2 and p4 are much higher for small crossing situations. This indicates that collision risk is largely derived from the failures in the process of watch-keeping and ship handling. As a result, special attention needs to be paid to enhancing the seafarers' attention to the targets in lateral direction, especially small targets like fishing vessel and tug boats. The ships' officers are encouraged to continuously re-examine the performance of the action they have made in reducing collision. They should also keep effective communication with the target ships, so that they can make adjustment in time when the actions are ineffective.

The results from expert knowledge carry certain degree of uncertainty. This is mainly derived from the inconsistency among different experts, which seems to be a common phenomenon in subjective risk analysis. One possible way to deal with such issue is to get more historical accident data with more detailed information. By doing this, a more comprehensive statistical analysis would become possible. From this point of view, it is meaningful to formulate a detailed report for each accident.

It should be noted that the proposed ESD model is a static mode. However, the collision avoidance procedure is usually in a dynamic mode. When a ship officer is making a decision and performs actions, he will keep monitoring the situation and made new decisions based on new information. By doing so, the procedure is performed in an iterative way. From this point of view, the proposed model can be extended into a dynamic ESD model in the future research. In order to realize this, the collision risk need to be modelled in a real-time mode. And a probabilistic model for quantifying the effectiveness of collision avoidance actions should also be proposed.

6. Conclusions

In this paper, based on a four-stage decision making model, an ESD model for collision avoidance decision-making for Qinzhou Port was constructed. According to historical data and expert knowledge, the occurrence probabilities of different failure modes under different encounter situations are calculated. The results indicate that collision avoidance decision failures and action failures are two main causations leading to collision. The main factors leading to these failure modes include improper ship handling, action conflict, and unfamiliar with the navigation environment. Compared with related researches in other waters, the failure probability of collision avoidance decision in small angle crossing situations in Qinzhou Port is at a relatively higher level, while it is at a lower level in the situation of crossing encounters. These findings can provide with good reference for developing effective collision risk management strategies in the Qinzhou Port waters.

Acknowledgement

The authors would like to thank the two anonymous reviewers for their comments on improving the paper. The authors would also thank the experts for their valuable knowledge in maritime safety management. This research was supported by the National Natural Science Foundation of China (51609194), Guangxi Natural Science Foundation (2018JJB160093), Qinzhou Science Research and Technology Development Project (20198521), and Project

supported by Guangxi Engineering Technology Research Center of Ship Digital Design and Advanced Manufacture (2018SDDAMRC14).

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