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Proposed Measures to Prevent Maritime Collision Accidents—Analysis Combining the SHELL Model with Predictions

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Abstract: We analyzed accident factors in a 2020 ship collision case that occurred off Kii Oshima Island using the SHELL model analysis and examined corresponding collision prevention measures. The SHELL model analysis is a framework for identifying accident factors related to human abilities and characteristics, hardware, software, and the environment. Beyond assessing the accident factors in each element, we also examined the interrelationship between humans and each element. This study highlights the importance of (1) training to enhance situational awareness, (2) improving decision-making skills, and (3) establishing structured decision-making procedures to prevent maritime collision accidents. Additionally, we considered safety measures through (4) hardware enhancements and (5) environmental measures. Furthermore, to prevent accidents, implementing measures grounded in (6) predictions is deemed effective. This study identified accident factors through prediction alongside the SHELL model analysis and proposed countermeasures based on the findings. By applying these predictions, more countermeasures can be derived, which, when combined strategically, can significantly aid in preventing maritime collision accidents.

Key words: Maritime collision accidents, SHELL model analysis, prediction, situational awareness, decision-making ability.

1. Introduction

The expansion of the global economy has driven the continuous development of the shipping industry, which is responsible for international transportation as nations increase their trade activities. Notably, Japan, an island nation surrounded by the sea, relies heavily on shipping, with 99.6% of its trade conducted by weight [1]. However, maritime accidents, including collisions and capsizes, remain a persistent issue. In 2023, the Japan Coast Guard reported handling 1,798 vessel accidents, marking the lowest number in the past decade [2].

Among vessel accidents, the most prevalent was operational failure, followed by collision and grounding, with maritime collision accidents representing approximately 20% of all incidents. For cargo vessels specifically, maritime collision accidents are the most frequent type, constituting about 38% of all accidents. Inadequate lookout is identified as the leading cause of maritime collision accidents, accounting for roughly 36%, followed by improper ship handling at 31% [2]. Consequently, reports indicate that human error contributes to approximately 80% of all maritime accidents [3-5].

Methods for analyzing human error include the human factors analysis and classification system, the Swiss cheese model, and the 4M analysis of human behavior. This examines a recent case of a maritime collision accident through the lens of the SHELL model, emphasizing human factors and the interplay between various elements. Additionally, it integrates a prediction perspective to evaluate strategies for preventing such accidents.

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2. SHELL Model Analysis

The SHELL model, developed by Frank Hawkins of Dutch Airlines, serves as a framework for analyzing human capabilities and characteristics, as well as accident factors within surrounding elements and the environment. Initially designed for the aviation industry, it has since been adopted across various domains, including medicine, manufacturing, and education, for accident analysis and prediction verification. The SHELL model analyzes how four factors (S: software, H: hardware, E: environment, and L: people other than the parties concerned) influence the human beings concerned (L: liveware in the center) in maintaining an optimal state. The model specifically highlights the relationship between the persons concerned and these factors [6]. Fig. 1 presents a conceptual diagram of the SHELL model.

This model provides a straightforward framework to categorize and organize the various elements that contribute to human factors. It is particularly useful for the specific study of measures aimed at preventing maritime accidents. It is also important to determine in advance the various risks behind the causes of accidents and to develop countermeasures to eliminate them. Through the application of the SHELL model, underlying accident factors can be elucidated, leading to the establishment of more effective safety measures.

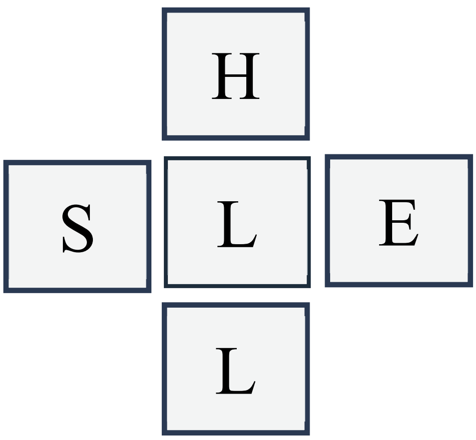

Fig. 1 Conceptual diagram of the SHELL model.

3. Cases of Collision after Maneuvering to Avoid a Collision

3.1 Overview of the Accident

This collision occurred off Kii Oshima, Kushimoto-cho, Wakayama Prefecture, at approximately 02:02 on August 20, 2022. According to the Ship Accident Investigation Report [7], Ship A's Navigation Officer A and Helmsman A were on watch, positioned behind the starboard side radar and automatic steering gear, respectively. Navigation Officer A observed Vessel B's port light on the starboard bow and, recognizing a collision risk, ordered Helmsman A to steer hard a port. Despite this action, the starboard stern of Ship A collided with the bow of Vessel B at around 02:02, resulting in a maritime collision between the two vessels.

Vessel B's Navigation Officer B was navigating with a heading of <076°> at a speed of 11.1 kn while monitoring the planned course line on the GPS plotter and maintaining a visual lookout. At approximately 01:56, he noticed Vessel C displaying her starboard light on the port bow and considered passing port to port. Navigation Officer B anticipated Vessel C to turn right, revealing its port light. However, based on the visibility of the light, he concluded that Vessel C was instead turning left. Concerned about a potential collision if the current course was maintained, he adjusted the course setting dial on the automatic steering gear at approximately 01:58. He executed a right-turn maneuver twice, at 15°-20° each, effectively initiating the avoidance action. At approximately 02:00, Vessel B crossed the bow of Vessel C, moving from starboard to port. Shortly afterward, Vessel C passed the stern of Vessel B at about 140 m. By 02:01, after completing avoidance maneuvers and monitoring the port wing until Vessel C had cleared Vessel B's stern, Navigation Officer B looked to the bow of the vessel and noticed Vessel A's lights on the port bow when Vessel B was heading southeast at about 120°. Navigation Officer B initially believed he could cross the bow of Ship A and adjusted the course setting dial to the right rudder. However, recalling the rudder angle limitations of the course setting dial, he activated the manual steering mode and attempted to steer the hard port rudder to switch to manual control. Despite this action, he was unable to achieve any rudder effect. Upon inspecting the steering mode switch, Navigation Officer B found that it was set to the Non-Follow-Up position. He subsequently adjusted the switch to manual steering and steered to the port. However, at approximately 02:02, the bow of Vessel B collided with the starboard stern of Vessel A. Fig. 2 illustrates the navigation tracks of Vessels A, B, and C, along with the site of the collision.

3.2 Shell Model Analysis with Navigation Officer A as the Concerned Party

The SHELL model was employed to examine a maritime collision accident that occurred off Kii Oshima Island following an avoidance maneuver (referred to hereafter as “this case”). Table 1 presents the findings of the SHELL model analysis, focusing on Ship A’s navigation officer as the liveware (human) concerned party. The authors incorporated the element of prediction to enable the exploration of a wider and more comprehensive array of countermeasures. Additionally, they identified accident factors stemming from failure to predict, as presented in this section.

As illustrated in the table, a greater number of accident factors are attributed to the liveware (human) concerned party, specifically Navigation Officer A. This outcome is inevitable, as human factors are the primary cause of most maritime collision accidents. While preventive measures predominantly aim to address human factors, it is crucial to consider comprehensive strategies that also account for the relationship with

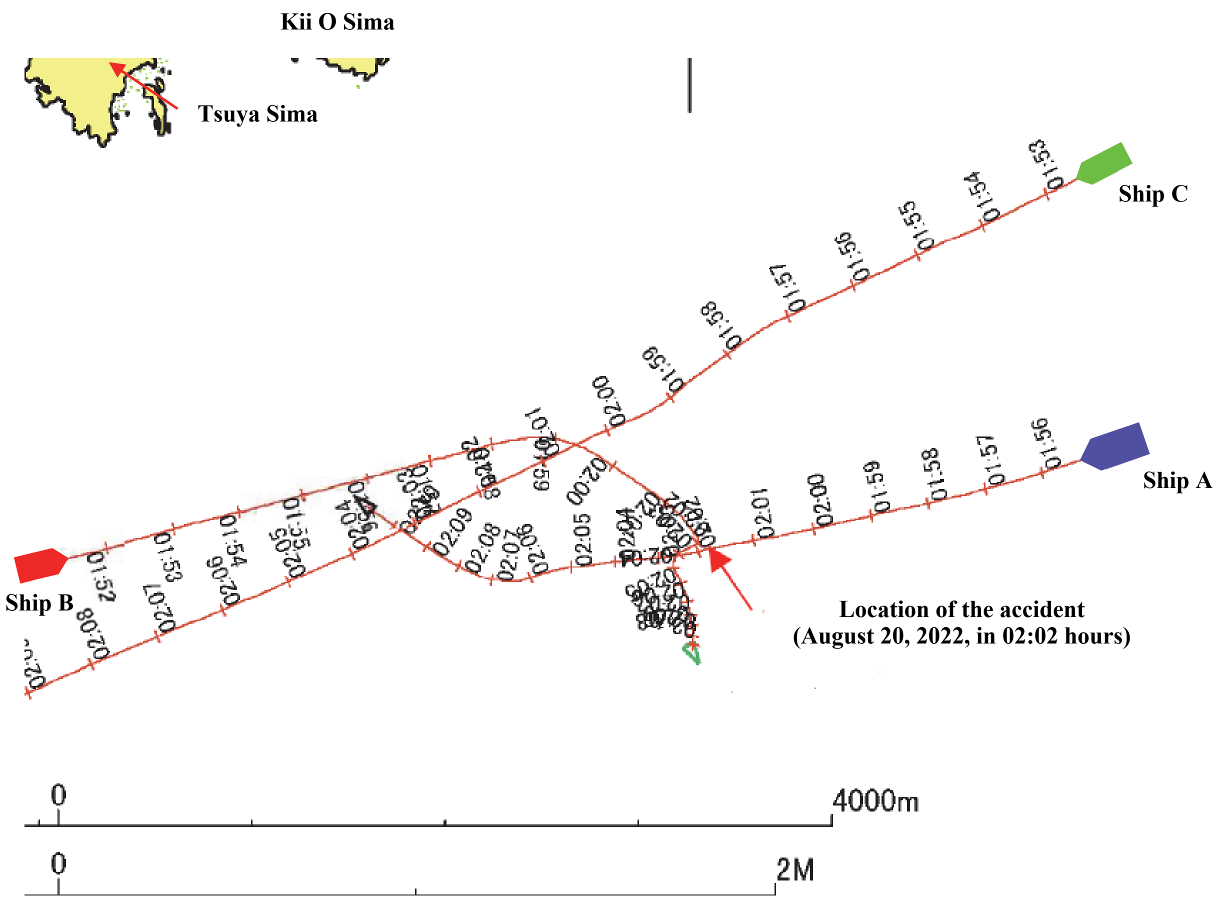

Fig. 2 Sailing routes and location of the accident.

Table 1 SHELL model analysis (Navigation Officer A).

Factors	Accident factors
Liveware (Human) concerned party	It is completely possible that Navigation Officer A was too concentrated on his forward lookout and did not keep a wide enough lookout to the left and right, thus delaying the discovery of vessel B. It is possible that Navigation Officer A did not have a wide area lookout and was not fully aware of his surroundings. Although Navigation Officer A was on the lookout behind the radar, they may not have fully used it, which may have delayed the detection of Vessel B and missed its movements. It is possible that the position behind the radar might not have been ideal for a proper visual lookout. While Navigation Officer A ordered a hard port rudder to avoid the collision, a hard starboard rudder with full astern may have been the better option. There may have been a problem with the passage being too close to land, within 2 nautical miles, and in busy waters with domestic vessel traffic.
Software (Procedures Rules)	Navigation Officer A might have made his decision based on the visibility of Vessel B's navigation lights, which may have delayed appropriate evasive action. Navigation Officer A may not have taken enough avoiding action with a hard port rudder and without using the main engine right before the collision. It is possible that navigation officer A's avoidance action was not done at the proper time, even though Vessel A had the responsibility to give way to Vessel B. It is possible that Vessel A (captain of Vessel A) did not give sufficient guidance and awareness to the lookout.
Hardware (Equipment Instruments)	Although Navigation Officer A was standing behind the radar and in a position to easily detect Vessel B, he may have delayed noticing its presence. It is possible that the radar/ARPA and other navigational instruments were not properly configured. The response time of Vessel A's steering system may have been slow, and the turning performance may not be sufficient. There may have been no or inadequate anticollision assistance equipment or systems aside from radar.
Environment	The vessel was navigating at night, which may have made it difficult to make decisions based on the visibility of the lights. Multiple vessels (Vessel A, Vessel B, and Vessel C) were involved, which may have complicated the decision-making process of the situation. The area is heavily trafficked by vessels, requiring not only attention to the immediate situation but also awareness of the wider sea area. Off Kii Oshima Island, the waters were crowded with domestic vessels, creating an environment that required stricter lookout measures than usual.
Liveware (Human) Non-concerned party	Navigation Officer A did not expect that Navigation Officer B would be too focused on avoiding Vessel C and might overlook the movements of Vessel A. Navigation Officer A should have communicated with Vessel B using an international VHF radiotelephone or other means of communication. Navigation Officer A should have alerted Vessel B to the presence of Vessel A using searchlights or other signaling lights.
Prediction	Navigation Officer A may not have anticipated the approach of not only of the vessel on the opposite course but also the crossing vessel and the vessel on the same course Navigation Officer A might not have considered the possibility that Navigation Officer B was too focused on avoiding Vessel C and was not paying attention to the movements of Vessel A. It is possible that the vessel failed to predict the vessel traffic off Kii Oshima and did not set a proper course. Navigation Officer A did not foresee the potential for a new situation arising from their mutual course of avoiding other vessels, as in the case of Vessel B. Navigation Officer A may not have considered the need to use both the steering and main engine in an emergency. It was necessary to anticipate the impact of a course change after the avoidance maneuver and to plan countermeasures in advance.

other factors. Thus, an analysis of accident factors incorporating a perspective of prediction will be performed, and suitable countermeasures will be considered. By anticipating diverse scenarios and devising corresponding countermeasures, it is expected that collisions can be prevented.

3.3 SHELL Model Analysis with Navigation Officer B as the Concerned Party

Table 2 presents the findings from the SHELL model analysis, focusing on Ship B's Navigation Officer B as the liveware (human) concerned party.

Table 2 SHELL model analysis (Navigation Officer B).

Factors	Accident factors
Liveware (Human) concerned party	Navigation Officer B may have been too focused on avoiding Vessel C, which may have delayed the detection of Vessel A. It is possible that Navigation Officer B did not keep a wide lookout and failed to adjust the vessel's course with the other vessels after the avoidance maneuver. Navigation Officer B may have misidentified the switch in the steering mode and delayed the appropriate avoiding action. After switching to manual steering, Navigation Officer B set the ship to the port rudder, when a hard starboard rudder would have been more appropriate. Although Navigation Officer B was focused on steering, it is possible to use the main engine astern in tandem.
Software (Procedures Rules)	Navigation Officer B may have made a judgment based on the visibility of Vessel A's navigation lights, which may have delayed the appropriate avoidance action. It is possible that Navigation Officer B did not take sufficient avoidance action by failing to use the main engine. It is possible that Navigation Officer B did not have adequate procedures for both avoidance and post-avoidance maneuvers. It is possible that Ship B (the captain) did provide clear guidance and instructions to Navigation Officer B. Navigation Officer B may have mistakenly believed there was enough time to cross Vessel A, which may have led to incorrect judgment.
Hardware (Equipment Instruments)	Navigation Officer B may not have been able to effectively use the radar and other navigational instruments. There may have been no or insufficient anticollision assistance equipment or systems aside from radar. Navigation Officer B might have relied too heavily on the GPS plotter's planned course line and lacked a proper visual lookout. Ship B's automatic steering system had a rudder angle limitation, preventing sharp turns. Navigation Officer B could not steer the ship as intended because the steering mode switch was set to "Non-Follow-Up." Navigation Officer B believed the steering had switched to manual mode, but the settings were different, which delayed the avoidance action.
Environment	The vessel was navigating at night, which may have made decision-making more difficult due to reliance on the visibility of the lights. Multiple vessels (Vessels A, B, and C) were involved, which may have complicated the decision-making process of the situation. The area was heavily trafficked by vessels, and it may have been necessary to take action not only based on the immediate phase but also with a broader view of the surrounding sea area. It is possible that the approach of vessels A and B occurred quickly, leaving insufficient time to take timely avoidance action.
Liveware (Human) Non-concerned party	It is possible that Navigation Officer B did not anticipate that Navigation Officer A on Vessel A was not paying attention to the surrounding situation. Navigation Officer B should have communicated with Ship A through international VHF radiotelephone or other communication methods. Navigation Officer B should have informed Vessel B of his intention to maneuver the vessel by using the whistle or other means. Navigation Officer B should have notified Vessel A of the presence of Vessel B using searchlights and other signaling lights.
Prediction	Navigation Officer B may not have predicted the surrounding situation, including the presence of Vessel A, after avoiding Vessel C. Navigation Officer B needed to pre-assess the possibility of a new risk after avoiding Vessel C. It is possible that Navigation Officer B failed to anticipate the vessel traffic off Kii Oshima and did not set an appropriate course. It is possible that Navigation Officer B assumed Navigation Officer A's inadequate lookout and did not consider maneuvering to avoid other vessels with only his ship. Navigation Officer B may not have expected the use of the steering and main engine in an emergency. It is possible that Navigation Officer B was not given proper lookout instruction and directions from the captain.

As presented in Table 2, numerous accident factors can be attributed to human error on the part of Navigation Officer B. The item on prediction suggests that the collision might have been prevented if Navigation Officer B had anticipated the situation and formulated an appropriate response. Additionally, identifying accident factors through the predictions outlined in the lower section of Table 2 allows for the consideration of a broader range of accident preventive measures.

4. Considerations and Accident Prevention Measures

4.1 Situational Awareness Improvement Training

Based on the accident factors from the SHELL model analysis involving Navigation Officer A of Vessel A and Navigation Officer B of Vessel B, enhancing training programs to develop navigation officers' situational awareness emerges as an effective strategy for mitigating human error.

Navigation Officer A was quite focused on the forward lookout that he overlooked the need for a wider lookout and failed to utilize the radar and other navigation tools to accurately assess the situation of nearby vessels. This indicates that Navigation Officer A lacks adequate situational awareness. In areas with heavy vessel traffic on opposing courses, it is crucial to account for ships crossing from both sides and to keep a lookout without preconceived notions. Additionally, anticipating the patterns of traffic in surrounding waters, as well as identifying vessels with unusual movements, is essential. A thorough lookout, covering a wide area and supported by radar and other navigational tools, is also necessary to ensure safety.

Navigation Officer B focused heavily on avoiding Vessel C, which likely delayed his recognition of Vessel A. It was necessary to predict in advance the situation after one's own vessel had avoided other vessels and to keep a wide lookout in a sea area with heavy vessel traffic, such as those off Kii Oshima. Additionally, Navigation Officer B needed to enhance his situational awareness, as he may have mistakenly assumed he had sufficient time to cross ahead of Vessel A, potentially delaying his decision-making. Furthermore, while monitoring the GPS plotter's planned course line, he may have neglected proper visual observation. To achieve accurate situational awareness, Navigation Officer B should have used a combination of navigational instruments, visual observation, and all available resources to perform the most effective lookout.

Based on these considerations, the following training is proposed, including responses to accident factors based on predictions:

(1) Shiphandling simulator training

A practical approach to enhancing the situational awareness of ship operators involves the use of shiphandling simulators. These simulators effectively recreate situations where maritime collision accidents are likely to occur [8]. To improve situational awareness, training can involve the use of a ship maneuvering simulator to practice lookout and navigation skills under various situations. These may include nighttime operations, restricted visibility, congested waters, varying numbers of vessels, and diverse vessel movements. Training in information processing within multitasking environments is essential to develop the ability to rapidly prioritize critical information and make timely decisions. This is particularly important in situations involving wide-ranging and continuous lookout and high traffic volumes of vessels. Moreover, incorporating scenario-based training that simulates various predictable situations, including an abrupt change of course by another vessel, can enhance trainees' skills in immediately identifying changes and responding effectively to the situation.

(2) Lookout improvement training

Lookout is a fundamental aspect of situational awareness. Beyond visual observation, accurate situational understanding can be achieved by leveraging all available resources, such as radar, navigational instruments, and acoustics. To improve the lookout accuracy, it is also effective to have collaborative discussions about necessary precautions and techniques for an extensive and meticulous lookout. Additionally, reviewing past cases and anticipated situations can help determine optimal lookout positions, enhancing its effectiveness.

(3) Radar/automatic radar plotting aid (ARPA) utilization training

Conduct training sessions to improve radar/ARPA-specific situational awareness using a radar/ARPA simulator. During these sessions, visual information is excluded, and the surrounding vessels, number of vessels, and weather or sea conditions are adjusted. This approach ensures that participants rely solely on radar/ARPA to assess the situation and make appropriate decisions. This training is crucial for mastering the effective use of radar/ARPA as a tool for lookout. However, it is equally important to conduct comprehensive training, such as shiphandling simulator training to avoid overreliance on radar/ARPA.

(4) Communication training

This training focuses on enhancing communication skills with other vessels. Participants will practice using international VHF radiotelephones in various scenarios to ensure clear, accurate, and efficient exchanges within limited time frames. Additionally, the training will incorporate other methods, such as using whistles and lights, to effectively convey navigational intentions.

(5) Case study training

Aims to cultivate the ability to analyze real-world examples of maritime collision accidents and devise strategies to prevent them. By reviewing past accidents, participants can discuss possible avoidance actions, advance predictions, and enhance appropriate avoidance operations.

(6) Understanding the human factors

Understanding cognitive biases, including "overconfidence," "selective attention" (focusing too much on specific information), and "confirmation bias" (focusing only on information that aligns with one's views), is essential. Additionally, having an awareness of how to avoid them is equally important. To foster this awareness, participants will engage in discussions about past accidents influenced by cognitive biases to deepen their understanding.

4.2 Improvement of the Decision-Making Capacity

To strengthen the decision-making capacity as a measure to prevent maritime collision accidents, we focus on three critical aspects: (1) improving situational awareness (information gathering and analysis); (2) strengthening decision-making (risk assessment and decision-making); and (3) ensuring swift and appropriate responses (action execution and teamwork).

Navigation Officer A instructed the vessel to steer a hard port rudder as an avoiding operation. However, alternative actions, such as a hard starboard rudder and full astern on the main engine, were available and necessitated better decision-making capabilities. Additionally, navigation officer A's focus on maintaining a forward lookout in heavily congested waters needs improvement, even though he needed to make decisions not just in sequential phases but also over a broader area of the sea.

Furthermore, Navigation Officer B opted for steering with a port rudder after switching to manual steering mode. However, other options, such as steering hard to starboard or combining a hard starboard rudder with full astern engine operations, were also possible. The complex situation involving Vessels A, B, and C called for more refined decision-making. Moreover, Navigation Officer B should have anticipated an independent maneuver for the vessel to avoid potential collisions, considering the possibility of an inadequate lookout from Navigation Officer A. These factors highlight the need for Navigation Officer B to further improve his precision in decision-making. Consequently, drawing on the SHELL model analysis and predictions, we propose the following specific training and countermeasures for each aspect:

(1) Improving situational awareness (information gathering and analysis)

As most maritime accidents stem from delays in decision-making, often due to insufficient information gathering, it is essential to enhance information gathering and analysis capabilities. The concrete measures were outlined in Section 4.1.

(2) Strengthening decision-making (risk assessment and decision-making)

To ensure effective decision-making, it is significant to cultivate the ability to accurately assess the situation and promptly choose the best course of action. Therefore, we propose the following training:

a) Decision-making capacity training

This training aims to equip participants with the ability to quickly analyze situations and decide on the best course of action, thereby enhancing decision-making. The focus is on repeatedly practicing the cycle of observation, situational awareness, judgment, and action. Concretely, the following training will be conducted:

i) Situational awareness training while on the lookout: Describe the movement of the ship around it within 10 seconds.

ii) Avoidance action selection training: after the lookout, state the choice of avoidance action within 3 seconds.

These will enhance their situational awareness and decision-making skills.

b) Avoiding collision judgment scenario training

This training involves creating concrete cases to help trainees evaluate multiple alternatives. For instance:

i) "In case of the Vessel A and Vessel B's courses intersecting, and there is a duty to avoid, what is the possible method of avoidance?"

ii) "Depending on the situation, is steer hard a starboard, hard a port, or a combination of decreasing speed and steering rudder the best option?"

Through such training, the ability to quickly assess a situation and identify the most appropriate avoidance action is developed.

c) Decision-making exercises with case studies

This training involves analyzing past maritime collision accidents to explore alternative decision-making. For example, participants will discuss various avoidance maneuvers related to the accident off Kii Oshima, as discussed in this paper. They might consider the following questions:

i) "What would have happened if, at this point, he had taken the steering starboard rudder?"

ii) "Can you think of any other alternatives?"

Through these exercises, participants develop practical decision-making capabilities by analyzing the effects of decision-making while performing simulations.

(3) Responding quickly and appropriately (action execution and teamwork)

Even with appropriate decision-making, accidents cannot be avoided if there are delays in execution or if crew coordination is lacking. Therefore, it is crucial to strengthen both the execution capability and teamwork through the following:

a) Very high frequency (VHF) communication training

Proactive information sharing must become a habit. To achieve this, training should focus on fostering communication between navigation officers of different vessels using VHF to convey collision avoidance intentions. This training is designed to keep communication concise and clear while developing skills to detect and prevent communication errors.

b) Training to enhance teamwork

As part of the bridge teamwork exercise, roles such as lookout, shiphandling, and decision-making will be defined, and drills will be performed to ensure seamless coordination. Additionally, emergency response role-plays will simulate scenarios such as "the case of another vessel suddenly changing course," "the case of radar failure," and "the case of poor visibility," prompting teams to strategize effective responses to these scenarios. In instances like the mentioned case study, where Ship B operated with a single officer on duty, training will address the necessary actions to ensure the ability to navigate and respond appropriately even when working alone. Furthermore, the effective use of equipment as an alternative to human resources will be discussed, enhancing the ability to employ auxiliary means.

c) Emergency response training

This training is designed to improve immediate response, including the ability to execute prompt and effective emergency operations such as "decelerate immediately," "switch to manual steering and make a sharp turn," and "take avoidance maneuvers while adjusting engine power output." Additionally, training centered on "using searchlights to alert the presence of the vessel" and "using the whistle to communicate navigational intentions" will strengthen the ability to act promptly and appropriately during critical situations, thereby significantly increasing the chances of collision avoidance.

4.3 Establishment of Decision-Making Procedures

The SHELL model analysis based on this case study identified delayed emergency decision-making and unclear decision-making criteria as key factors in the collision. To prevent such issues, clear emergency procedures and decision-making criteria should be established. That is, defining rules for quick and appropriate action in advance is essential. The following responses may serve as examples of effective emergency decision-making:

(1) Establishing emergency decision-making procedures

Develop clear procedures for swift and precise decision-making in emergencies, ensuring responses adhere to these protocols to prevent accidents.

a) Preparation and thorough implementation of the standard operating procedures

Create a manual outlining emergency decision-making procedure, specifying in advance when to reduce speed and stop when a collision risk arises. Additionally, establish clear guidelines for avoidance maneuvers, including the appropriate rudder angle, steering direction, and the timing of steering. Furthermore, the timing of VHF communication should be specifically defined.

Clarifying decision criteria for handling unexpected vessel movements also enhances emergency response effectiveness. Moreover, structuring the decision-making process enables quick and accurate actions. For instance, a streamlined flow such as "lookout → hazard prediction → initial response (rudder or speed adjustment) → confirmation → additional response (reassessment)" could be structured concisely.

b) Introduction of the emergency checklists

Creating a checklist for emergency responses at the navigation bridge is an essential tool for enhancing safety and efficiency. The checklist could include the following items:

i) Situational awareness (lookout, radar, ARPA, electronic chart display and information system (ECDIS), other instruments)

ii) Selection of avoiding action (avoidance duty or not, appropriate rudder angle, and main engine operation)

iii) Communications (information sharing through VHF, use of lights, and sound signals)

iv) Response based on various predictions (consideration of commensurate relationships, changes in course and speed, relationships with multiple other vessels)

v) Post-action assessment (to confirm that collision avoidance was properly performed)

(2) Clarification of decision-making criteria

To minimize inconsistencies in judgment and enable uniform actions, it is beneficial to establish the following criteria in advance:

a) Establishing priorities for avoidance actions

To prevent confusion in judgment, the priority order of avoidance measures must be clearly defined. The priority is to reduce speed or steer to quickly increase the closest point of approach (CPA) with other vessels. Subsequently, communicate with nearby vessels through VHF and searchlights. Finally, implement emergency measures such as a full stop or full astern. Additionally, posters outlining these priorities will be displayed on navigation bridges to ensure constant awareness, promoting calm and appropriate responses in emergencies.

b) Criteria for VHF communication

Set a predefined timing for VHF communication with other vessels. For instance, establish the following criteria:

i) If the CPA is 0.5 nautical miles or less, communicate intentions through VHF.

ii) If another vessel's movements are unpredictable, assess the situation on the VHF.

iii) Standardize phrases to avoid confusion when performing VHF communications. Examples include:

- "This is vessel A, altering course to port to avoid vessel B."
- "Vessel B, confirm your course alteration."

c) Rudder angle and speed reduction criteria for avoidance

Define clear criteria for rudder angle and speed adjustments in emergencies. For steering, establish the optimum rudder angle (e.g., 10°-20°) and the speed to be maintained. For speed reduction, standardize the timing and extent of engine output reduction.

(3) Reflection and feedback system

Implement a system to review past decisions and determine areas for improvement to prevent accidents.

a) Implementation of post-verification

When an accident or near miss occurs, the team will analyze "where judgment was delayed" and "what can be improved" to enhance the accuracy of emergency response. Additionally, the SHELL model analysis will be reapplied during post-event verification to address specific corrective measures.

b) Comprehensive briefing and debriefing

Before the voyage, confirm the roles in an emergency and review the decision-making criteria. After the voyage, allocate time for reflection on the "appropriateness of decisions" and "improvement points" to refine the decision-making process.

4.4 Hardware Countermeasures

Upgrading existing systems and introducing new equipment can prevent maritime collision accidents.

(1) Installation of high-performance radar/ARPA

Equipping the vessel with high-performing Radar/ARPA integrated with automatic collision avoidance support can provide timely alerts about potential collisions and guide the crew to take necessary avoidance measures. This is expected to prevent maritime collision accidents.

(2) Effective use of ECDIS

The International Maritime Organization (IMO) mandates that vessels be equipped with ECDIS to avoid maritime accidents, such as collisions and strandings, by enhancing accident prevention and navigational assistance. ECDIS helps prevent such accidents by accurately displaying real-time vessel movements and integrating automatic identification system (AIS) and radar/ARPA data with nautical chart information.

(3) Effective use of the AIS

AIS is a system that continuously transmits and receives data on vessel position, speed, heading, identification, and other information. Its primary purpose is to create an identification network among vessels, between vessels and shore, and between shore stations to avoid collisions at sea. By employing AIS, vessel movements can be tracked in real time, enabling immediate collision risk alerts.

(4) Enhanced acoustic and visual warning systems

Install a system that automatically emits sound and light alerts when nearby vessels are detected.

(5) Improved responsiveness of the steering system

To facilitate quick evasive maneuvers, consider reducing steering response time and installing an auxiliary rudder.

(6) Introduction of maritime autonomous surface ships (MASS)

The adoption of MASS with automated systems to aid human awareness, judgment, and response plays a vital role in minimizing maritime accidents due to human factors. Specifically, integrating MASS with automated assistance for the steering, course changing and keeping, posture control, thrust control, lookout, and navigation planning can mitigate human error and help prevent maritime collision accidents.

4.5 Navigational Environment Measures (Optimization of the Navigational Environment)

(1) Review of the route setting

When planning a voyage, it is necessary to prioritize safe navigation by establishing an appropriate route. In areas with heavy domestic vessel traffic, strict compliance with navigation rules is crucial. When traffic separation schemes adopted by the IMO are designated, they must be adhered to. In waters without such schemes, actively utilizing the recommended routes enhances navigational predictability, clarifies vessel-to-vessel intentions, and minimizes collision risks. To further optimize the navigational environment, avoid unnecessary course changes, and strive for operations that promote mutual understanding with surrounding vessels.

(2) Setting routes to avoid congested waters

Leverage vessel information systems such as AIS and radar/ARPA to assess traffic conditions in areas with heavy maritime activity. This approach helps congested waters ahead of time, ensuring a safer navigational environment. In areas where shipping routes intersect or near ports and harbors, where vessel movements are more complex, prioritize offshore routes whenever feasible to maintain a smooth flow of navigation. Moreover, adjust the vessel's departure and arrival times based on anticipated congestion periods to enhance navigation efficiency.

(3) Utilization of marine traffic control systems and the Japan Coast Guard

To effectively manage areas with heavy vessel traffic, improve information sharing with control centers and coast guard stations to receive accurate instructions. Additionally, real-time updates on navigational conditions and weather should be incorporated into navigation plans to ensure safe and organized operations. Furthermore, the coast guard's instruction protocols and emergency communication procedures must be confirmed in advance, and a coordination system should be established to enable appropriate action in case of an emergency.

4.6 Prediction-Based Measures

To reduce "unexpected" situations and reduce the risk of maritime collision accidents, it is essential to consider a wide range of forecasts and predictions. Additionally, predictions that identify the approach of a vessel on an opposing course, a crossing vessel, or a vessel on the same course, provide a broader perspective on the causes of maritime accidents.

(1) Optimization of ship operation planning and route determination

A dynamic risk assessment system (DRAS) will be implemented to examine collision risk by assessing traffic conditions, weather, and the movements of other vessels in real time. This AI-based system conducts real-time navigational risk assessment, analyzing vessel AIS data, weather information, and current data to propose optimal routes. Additionally, the system automatically reassesses risks, such as the movement of other vessels and weather changes, while underway, and suggests new collision avoidance maneuvers as needed.

(2) Preliminary simulation

By using past navigational data, potential danger points can be identified and simulated to proactively develop measures for preventing collisions and maritime accidents. This allows for tailored countermeasures to address specific scenarios and supports immediate and informed decision-making during actual navigation.

(3) Establishment of a risk assessment visualization and warning system

In the ship operation plan, a risk score based on predictions is assigned, and an alarm is triggered if the score exceeds a certain threshold. Visual nautical charts will be provided to allow the navigation officer to intuitively assess the level of risk. Additionally, the history of risk assessment will be recorded, and past data will be examined to enhance the accuracy of future risk predictions and identify new risk factors.

The comprehensive application of these strategies will strengthen risk management based on predictions and contribute to the prevention of maritime collision accidents.

5. Conclusions

A collision accident that occurred off Kii Oshima was examined using the SHELL model, and countermeasures to prevent similar accidents were developed. Additionally, we propose various training measures to improve the situational awareness of navigation officers. The following measures, based on predictions, are expected to enhance early detection of collision risks and contribute to the prevention of maritime collision accidents:

(1) Situational awareness improvement training

The goal is to prevent maritime collision accidents by enhancing situational awareness and detecting collision risks at an early stage. To achieve this, we proposed the implementation of simulator training, improved lookout training, radar and ARPA utilization training, communication training, case study training, and training focused on understanding human factors.

(2) Improvement of the decision-making capacity

To prevent maritime collision accidents, it is crucial to enhance the ability to make appropriate decisions. First, improving situational awareness through information collection and analysis is essential, and this will be reinforced by the aforementioned training. Once proper situational awareness is achieved, the ability to assess risk and make optimal decisions is required. For practical training, we proposed decision-making capacity improvement training, avoidance decision scenario training, and decision-making exercises using case studies. Additionally, we recommend conducting VHF communication training, teamwork enhancement training, and emergency response training to ensure prompt and effective action following a decision.

(3) Establishment of decision-making procedures

To ensure prompt and appropriate decision-making during emergencies, it is essential to establish standardized decision-making procedures. To achieve this, we propose developing standard operating procedures, fully implementing them, and introducing an emergency checklist. Additionally, it is significant to define the decision criteria beforehand, including prioritizing avoidance actions, setting guidelines for VHF communications, and determining appropriate rudder angle and speed reductions for collision avoidance. Roles in emergencies should be assigned, and thorough briefings should be conducted before sailing, with debriefings following the voyage to assess the decision-making process and identify areas for improvement, thereby strengthening decision-making capabilities.

(4) Hardware countermeasures

Given that most maritime collision accidents result from human error, it is essential to complement capacity building through education and training with hardware measures that reduce the likelihood of human error. Particularly, we propose installing high-performance radar/ARPA, utilizing ECDIS, optimizing the use of AIS, enhancing both acoustic and visual warning systems, improving steering system responsiveness, and implementing autonomous surface ship navigation systems. While the long-term goal is to develop fully autonomous surface ships capable of ensuring safety without human intervention, realizing this vision will take time. Meanwhile, it is desirable to foster hardware improvements as much as possible.

(5) Navigational environment measures (optimization of the navigational environment)

On June 1, 2023, at 9:00 a.m. JST, the IMO recommended route became operational in the waters of this case study. While cost-effective route selection is important when preparing voyage plans, the highest priority should always be given to ensuring safe navigation. Particularly, in areas with heavy domestic vessel traffic, strict adherence to navigation rules must be enforced to ensure compliance with recommended routes. Even in areas without designated navigation, efforts should be made to align vessel routes with the traffic flow. Additionally, avoiding congested waters and strengthening cooperation with the vessel traffic system and the Coast Guard Department will ensure safe navigation while receiving appropriate instructions. Furthermore, we propose actively gathering information on vessel navigation conditions to inform the selection of safer routes.

(6) Prediction-based measures

The SHELL model was utilized to analyze this case study, and countermeasures to prevent maritime collision accidents were explored. To implement multifaceted and effective strategies, we propose countermeasures based on predictions. To enhance ship operation planning and course selection, a DRAS will be introduced for AI-based navigational risk assessment. In this system, AI evaluates the vessel's AIS data, weather conditions, and current data to recommend the most optimal route. Additionally, potential risks will be simulated in advance, and a risk assessment visualization and warning system will be established. Moreover, a risk score based on predictions will be incorporated into the ship operation plan, triggering an alarm if a predetermined threshold is exceeded, thereby increasing the awareness of the navigation officer and prompting them to avoid collisions.

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