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COMPARISON OF NAVIGATION RISK BETWEEN THE SETO INLAND SEA ROUTE AND OPEN SEA ROUTE BY ACTUAL SHIP BEHAVIOR ANALYSIS

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ABSTRACT

Generally, a ship is required to navigate the shortest route in order to reduce the operating costs. However, this route is often crowed by many ships and thus difficult to navigate, especially when it is narrow and has complex currents, such as the Seto Inland Sea. The Seto Inland Sea is a primary traffic route for this transportation. Many ships move frequently through this area, especially those departing and arriving from China and South Korea. A Seto Inland Sea route has been developed and stabilized, and is now responsible for the trade between Japan, China, and South Korea, and thus, for their economies. Therefore, understanding the actual navigation situation of ships navigating in this route is very important.

The focal point of this study was to analyze the actual situations of ships navigating in the Seto Inland Sea and the open sea. The navigation risk of ships during passage were evaluated according to the encounter situation, navigational speed, and veering. A dynamic analysis based on real ship-movement data was performed. The results can be applied to ensure safe navigation and the development of an efficient and economic navigation schedule.

Keywords: AIS data, Ship behavior analysis, Encounter situation, Avoidance behavior, Navigation risk

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1. INTRODUCTION

In recent years, with the frequent transportation of substantial amounts of goods and materials between countries, ship voyages have increased. However, the profits of ship-operating companies have decreased owing to the escalating price of oil. Therefore, reducing operating costs has become the most important issue in ship navigation. Consequently, ships are required to navigate the shortest route. The Seto Inland Sea, located in the western part of Japan, has a navigation route that is used as a primary traffic route for transporting goods and materials in Japan. A Seto Inland Sea route has been developed and stabilized, and is now responsible for the trade between Japan, China, and South Korea, and thus, for their economies. Many ships move frequently through this area, because it is the shortest route between Osaka and Kanmon to travel between China, South Korea, and Japan. However, it is difficult for ships to operate in this area because the route is narrow and always crowded by many ships, and the currents are very strong. Thus, maritime accidents occur frequently. It is very important to enable safer and more efficient operations. Although the ships pass through a short route, there may be latent risk and inefficiency in the voyage.

The focal point of this study was to clarify the actual navigation of ships. The target was a ship navigating the Seto Inland Sea route and Pacific Ocean route. In previous years, studies on maritime traffic were performed by dividing the Seto Inland Sea into small areas of each strait (Tanaka et al., 2004). However, to our knowledge, no study has analyzed the entire ocean area of the Seto Inland Sea and the navigation for the entire ship voyage on the routes therein. Previous studies analyzed the traffic of ships using statistical methods. In this study, we analyzed a wide ocean area of navigation for the entire ship voyage and conducted a dynamic analysis of ship navigation using real ship movements. Moreover, we analyzed the navigation risk for these routes.

2. DATA

We analyzed real ship movements according to automatic identification system (AIS) data. An AIS is installed aboard all international voyaging ships of 300 gross tonnage (GT) and all non-international voyaging ships exceeding 500 GT. In recent years, the installation of AISs in small ships such as fishing boats and pleasure boats has gradually increased. Many studies in fields such as port management (Murai, 2003) and traffic control have used AIS data. Thus, the analysis of ship navigation using AIS was expected to be reliable. The primary information contained in AIS data is presented in Table 1. The advantages of using AIS data is the ability to obtain data over a long period and easily and accurately measure the position, course, and speed of ships. Using this accurate and quantitative ship-navigation data, dynamic analysis is possible, and the ship behavior can be understood in detail.

Table 1 Contents of AIS data

Data category	Contents
Dynamic data	Ship's position, coordinated universal time, speed over ground (SOG), course over ground (COG), heading, navigational status, etc.
Static data	Vessel's Maritime Mobile Service Identity (MMSI) number, ship name, type of ship, length, and breadth
Voyage-related data	Draught, destination, estimated time of arrival (ETA), etc.

The research area is from 134°53′25″E, 34°44′10”N to 135°27′52″E, 34°15′30″N, as shown in Fig. 1. The blue dots in the figure indicate the trajectories of ships on one day according to the AIS data regarding the positions of the ships. The trajectories were obtained using a geographic information system (GIS). Traffic exits in the Kanmon Strait on the westernmost side of Japan, as the portals direct these ships to pass through and into the port of Japan. In particular, numerous ships navigate from China and South Korea. This area also contains two main ports—Kobe and Osaka—that are located in the center of Japan in Osaka Bay. In the bay, there are many large container berths and coastal industrial complexes, and most voyaging ships stop at these ports. As shown in Fig. 1, there are two general routes route for ships sailing between Kanmon and Osaka Bay. One is used by ships passing through the Kanmon Strait and the Akashi Strait to sail through the Seto Inland Sea and is always congested

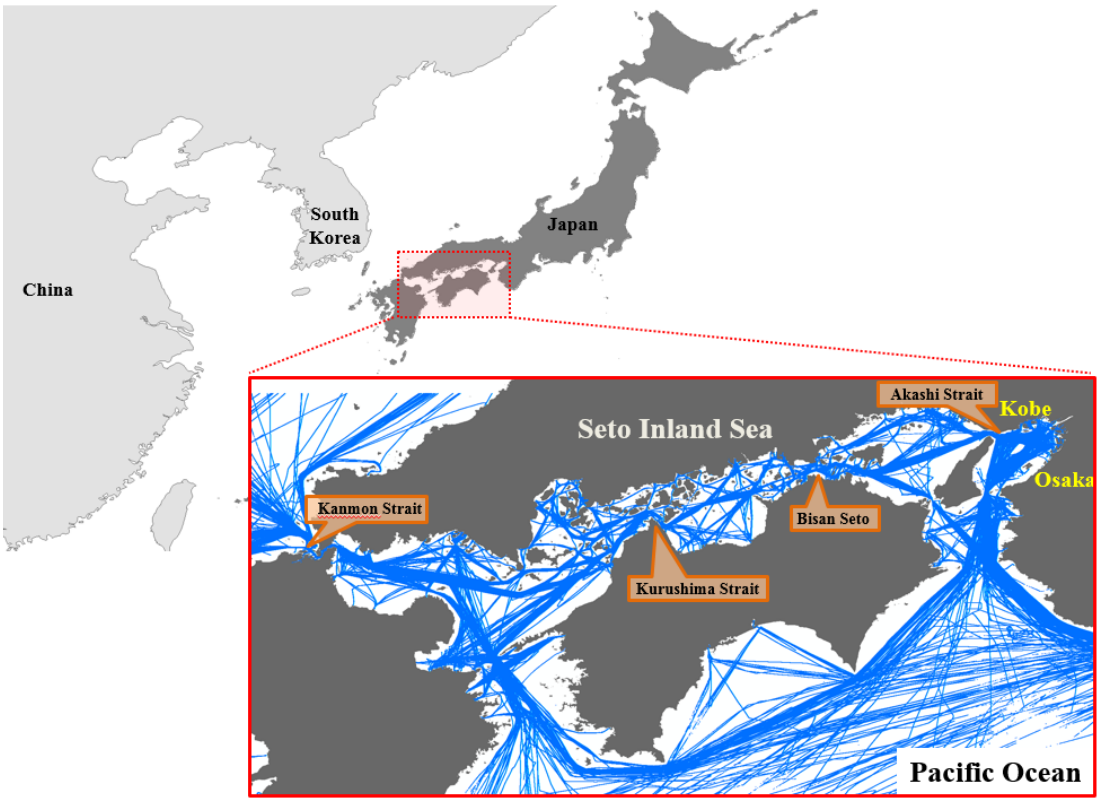

Fig. 1 Map and ship trajectories in the research

by many crossing ships, including fishing boats and ferries. The other route is used by ships passing through Kanmon and sailing the Pacific Ocean to arrive at Osaka Bay. Compared with the inland sea route, the Pacific Ocean route is shorter.

The research period was between March 1 and 7, 2012. According to data provided by the Japan Meteorological Agency, during the investigation period, the weather conditions were zero visibility, little rainfall, and wind. Statistics regarding the ship traffic and cargo type of every ship, along with the MMSI number, were included in the AIS data. The total number of ships was 2,589 during the research period, and there were more than 1,000 ships each day. Fig. 2 shows the number of ships passing through the Seto Inland Sea and Pacific Ocean routes. Fewer ships navigated the Pacific Ocean route, i.e., approximately half of the number of ships navigating the Seto Inland Sea route. Classification by ship category reveals that more than half of the ships contributing to the traffic were cargo ships, with tanker ships constituting the second-highest category. Thus, most of the ships voyaging in this area transport goods, materials, and energy resources, and cargo delays may cause issues for the economy and daily life.

3. METHOD

We examined the ship navigational situation using dynamic analysis. The analysis involved exploring the relationship between the navigational situation and ship movements. The analysis was performed using a GIS. According to the dynamic analysis, it is possible to understand the ships behaviors, accurately. Because the AIS data transmission interval depends on the navigational status, the data transmitted was irregular due to the speed of the ship. Therefore, the position was interpolated at a rate of once every second, and the data was analyzed at intervals of 30 seconds.

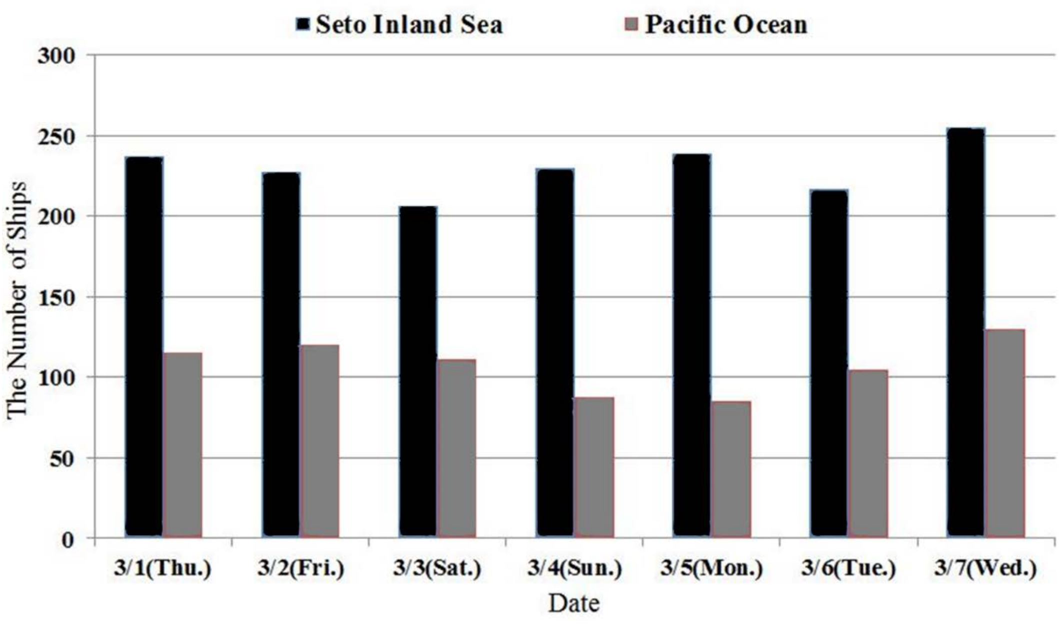

Fig. 2 The number of ships passing through the routes

According to the dynamic calculation and analysis, the navigation situation was understood on the basis of the closest distance and the encounter situation with an approaching ship. These factors are often used to evaluate the collision risk (B.A. Colley, 1984).

To determine the closest distance and the encounter situation, the distance was calculated using Hubeny's formula, which considers the curve of the earth in order to determine the distance between two positions. The formula is given as follows:

$$d = \sqrt{(d_y R)^2 + (d_x N \cos \mu_y)^2} \quad (1)$$

where d_y is the latitude difference between two ship positions, d_x is the longitude difference, μ_y is the average latitude of the two positions, R is the radius of curvature of the meridian, and N is the transverse radius of curvature. The data were projected onto the WGS 84 datum. Thus, the following ellipsoid parameters were obtained: 6,378,137 m for the semi-major a and 6,356,752 m for the minor b.

$$R = \frac{a(1-e^2)}{W^3} \quad (2)$$

$$N = \frac{a}{W} \quad (3)$$

$$W = \sqrt{1-e^2 \sin^2 \mu_y} \quad (4)$$

$$e = \sqrt{\frac{a^2-b^2}{a^2}} \quad (5)$$

Generally, a sailing ship performs an evading action when a target ship within two nautical miles ahead is detected. If a ship enters the domain of one nautical mile, there is a high risk of collision. We developed a program to count the number of ships when a ship approaches within a radius of one nautical mile, and the distance between these ships was calculated simultaneously. The types of encounter situations were based on the Prevention of Collision at Sea Act (1972), which specifies three types according to the angle between the two ships: crossing, head-on, and overtaking. These ship-encounter situations are illustrated in Fig. 3.

The angle between the two ships is indicated by T and was calculated using the ship positions, as follows:

$$\mathrm{T} = \mathrm{t} - (\mathrm{t} - \mathrm{T}) \quad (6)$$

$$\mathrm{t} = \mathrm{Arctan}\frac{\mathrm{d_y}}{\mathrm{d_x}} \quad (7)$$

$$(\mathrm{t} - \mathrm{T}) = -\frac{1}{4\mathrm{m}^2\mathrm{R}^2}(\mathrm{y}_2 + \mathrm{y}_1)\mathrm{d_x} + \frac{1}{12\mathrm{m}^2\mathrm{R}^2}(\mathrm{x}_2 - \mathrm{x}_1)\mathrm{d_y} \quad (8)$$

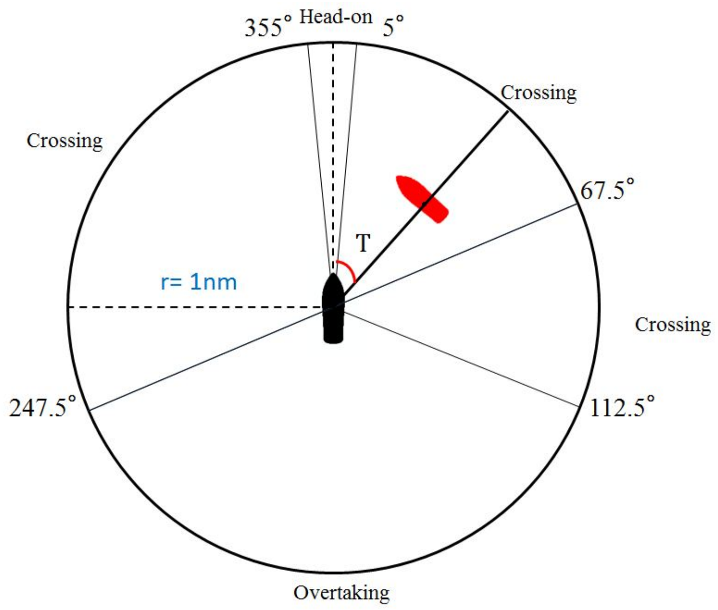

Fig. 3 Ship domain and encounter situation

When a sailing ship entered within one nautical mile, the number of approaching ships increased progressively. A large count number represents heavier ship congestion, and a frequent-encounter situation corresponds to a high collision risk.

The navigational speed and veering during the voyage were analyzed. This information was included in the AIS data. The veering was determined according to the ship heading, as the change of heading means that the helm is taken during ship navigation. Speed and veering are often used to evaluate the navigation environment and maneuvering (Katsuhiro Kuroda, 1993).

4. ACTUAL NAVIGATION SITUATION OF SHIPS

Here, we discuss that the analysis of the ship behavior for an entire voyage in the assessment of safety. The results were explained by two sample ships navigating in Seto Inland Sea route and Pacific Ocean route, respectively. The principal characteristics of the sample ships are listed in Table 2.

Table 2 Principal aspects of the sample ships

Ships	Ship A	Ship B
Route	Seto Inland Sea	Pacific Ocean
Vessels type	Container	Container
Overall length (m)	148	148
Max. TEU	1118	1118
Max. speed (knots)	20	20

Ships A and B are container ships having equal length and GT, making their maneuverability identical. However, these similar ships navigated different routes. Therefore, we used the identical aspects of the ships in order to isolate and compare their navigation situations. Generally, the ships sailed toward the same destination in the area and chose a relatively short distance to navigate. However, ship B sailed the longer route. Fig. 4 shows the ship trajectories, where the red and blue dots indicate the trajectories of ships A and B, respectively. Ship A passed through the Kanmon Strait at 8:00 on March 5 and arrived at the Port of Kobe at 8:00 on March 6, taking approximately 24 hours to navigate 252 nautical miles, and was anchored for 5.5 hours to wait for berth before entering the port. Ship B navigated the Kanmon Strait at 14:00 on March 2 and arrived at the Port of Kobe at 12:00 on March 3, taking approximately 22 hours and traveling 329 nautical miles. Compared with ship A, ship B traveled a longer distance to sail the route.

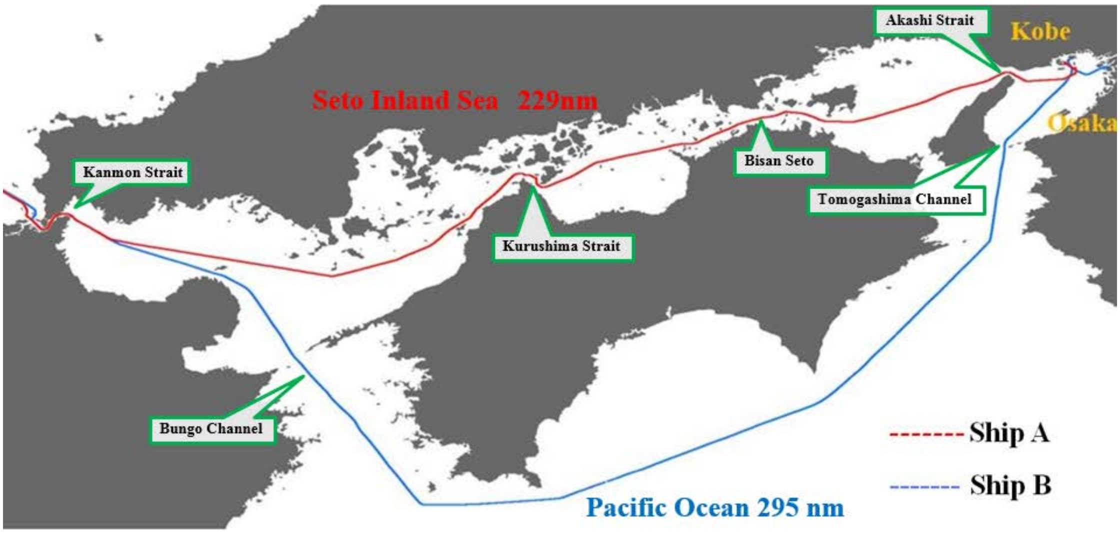

Fig. 4 Tracking of the sample ships

4.1 Encounter Situation of Ships

The encounter situation is a basic factor for evaluating the collision risk of ships. Table 3 shows the results of the encounter situation in the inland sea and Pacific Ocean,

Table 3 Results of risk analysis

Contents / Sample ship	Number of Domain Counts	Number of Approaching ships	Encounter Situation		
			Crossing	Head-on	Overtaking
Ship A	1571 counts	114 ships	10 ships	98 ships	6 ships
Ship B	412 counts	24 ships	2 ships	18 ships	4 ships

which are based on the analysis of the AIS data. The number of domain counts increased when a ship was within one nautical mile. Using the MMSI number, the number of approaching ships was obtained. Clearly, numerous ships navigated close to ship A. The number of approaching ships was about 4 times greater than that for ship B, which sailed the open sea route. The narrow route of Ship A is one of the reasons for this. According to the angle between the two close ships, we found that head-on was the most frequent type of encounter in the research area. This encounter situation occurred frequently in the inland sea. Therefore, there was a high collision risk during operation in the inland sea. Complex encounter situations increase the maneuvering difficulty because of the action constraints on the other ships, causing numerous accidents.

4.2 Speed and Veering

The navigation speed and veering were used to evaluate the ship navigation safety. Figs. 5 and 6 show the changes in ship speed and heading for ships A and B. In each figure, the upper and lower graphs show the speed and ship heading, respectively, during sailing.

The sailing analysis of ship A is shown in Fig. 5. This ship sailed in the Inland Sea and arrived at the Port of Kobe. Navigating the inland sea requires passing through four narrow channels including the Kanmon Strait, the Kurushima Strait, Bisan-seto, and the Akashi Strait. The time zones in which this ship navigated each strait are indicated by green in the graph. The change in speed was frequently checked, and the ship slowed when passing through both straits. The maximum difference in the speed during the voyage exceeded 10 knots. The analytical results confirmed a similar tendency of all ships that sailed in the inland sea. One of the reasons for this is that many routes have speed restrictions, that the ships shall not navigate at a speed exceeding 12 knots. However, the graph indicates that the ship accelerated suddenly after passing through the routes. Compared with ship A, the speed distribution of ship B sailing in the Pacific Ocean was not significantly higher or lower, except in the Kanmon Strait.

The speed of ship A was 0 knots before the ship entered the port. Thus, ship A was anchored offshore while waiting for the berth. The waiting time was approximately 5.5 hours. Ship B entered the port directly. Consequently, ship A had a longer sailing time than ship B. Ships that anchor while waiting is inefficient for fuel consumption.

The blue lines in Figs. 5 and 6 show the heading of the ship. The distribution of the heading indicates that the ship veered frequently, and the heading angle varied considerably in the inland sea, especially when the ship passed through the strait. This phenomenon indicates that the route is very winding. In addition, routes like the Kanmon Strait and the Kurushima Strait have strong currents whereby ships drift. This increases the degree of veering, possibly decreasing the ship maneuverability. Another reason is that it becomes crowded with many ships in the inland sea, and the veering represents avoidance behavior.

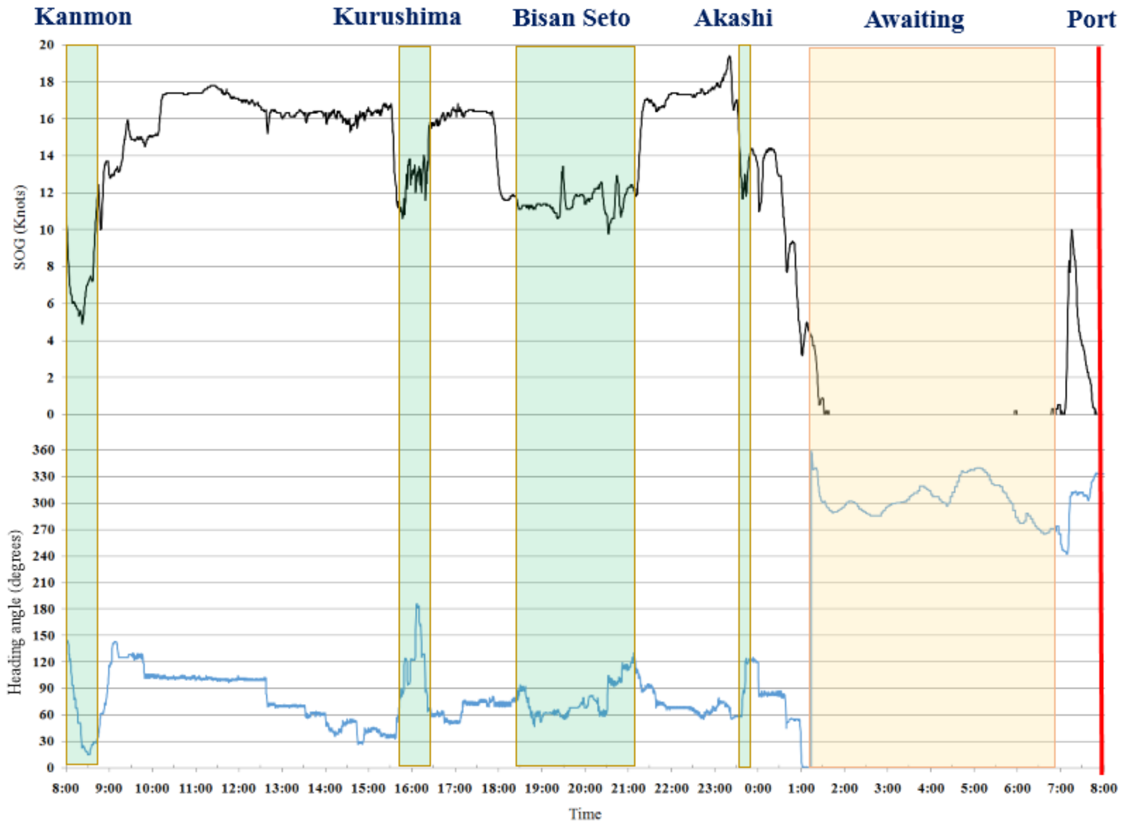

Fig. 5 Speed and heading of ship A in the Seto Inland Sea route

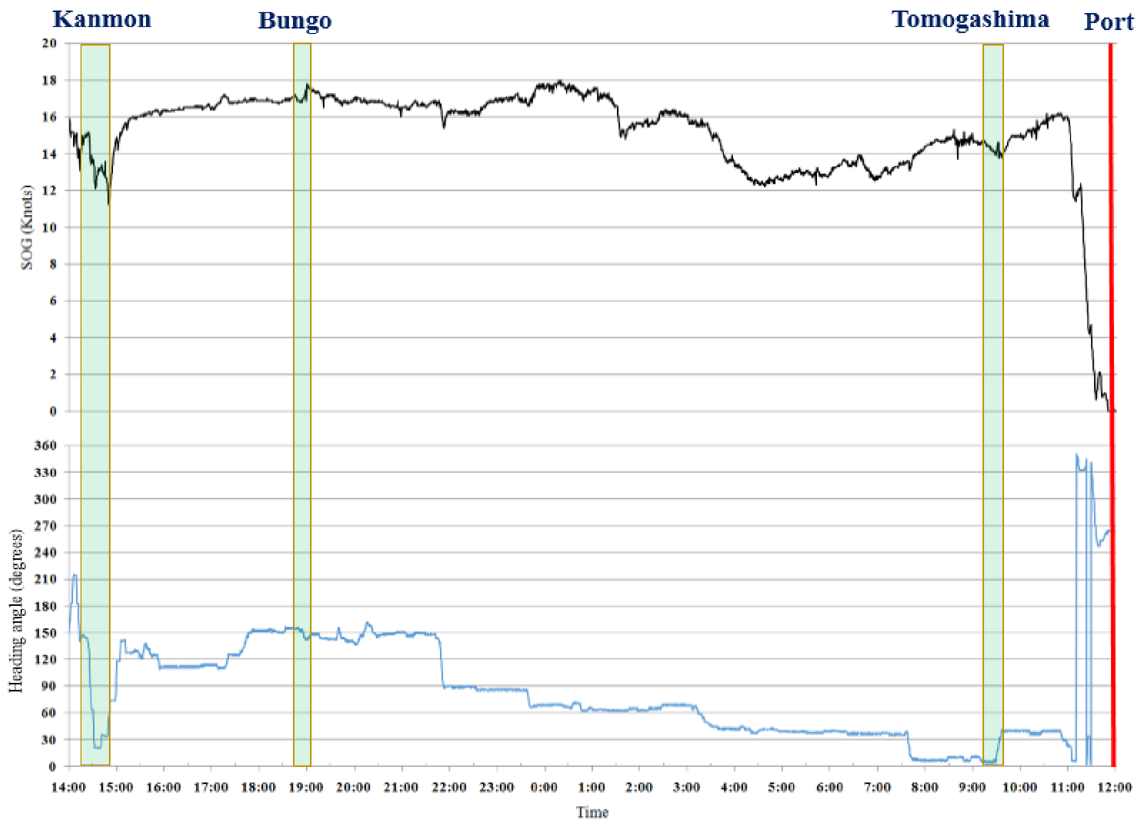

Fig. 6 Speed and heading of ship B in the Pacific Ocean route

4.3 Avoidance Behavior in the Real Voyage

According to the dynamic analysis of the AIS data, we examined the avoidance behavior of a ship in a real navigation situation. Figs. 7 and 8 show examples of the avoidance behavior for navigating in Seto Inland Sea and Pacific Ocean, respectively. The arrows show the ships and their heading. The red arrow represents ship A, and the dots indicate the tracking of the ship for a total of 15 minutes. The yellow region indicates the domain of one nautical mile.

Fig. 7 shows the navigation of ship A in the inland sea. Here, we observe that there were two other ships within one nautical mile. At this time, ship A had just passed through Kurushima Strait and accelerated in order to overtake the target on the port bow. In addition, the head-on ships veered and sailed across. This is because the Kurushima Strait traffic route has a unique rule for navigation: ships should navigate

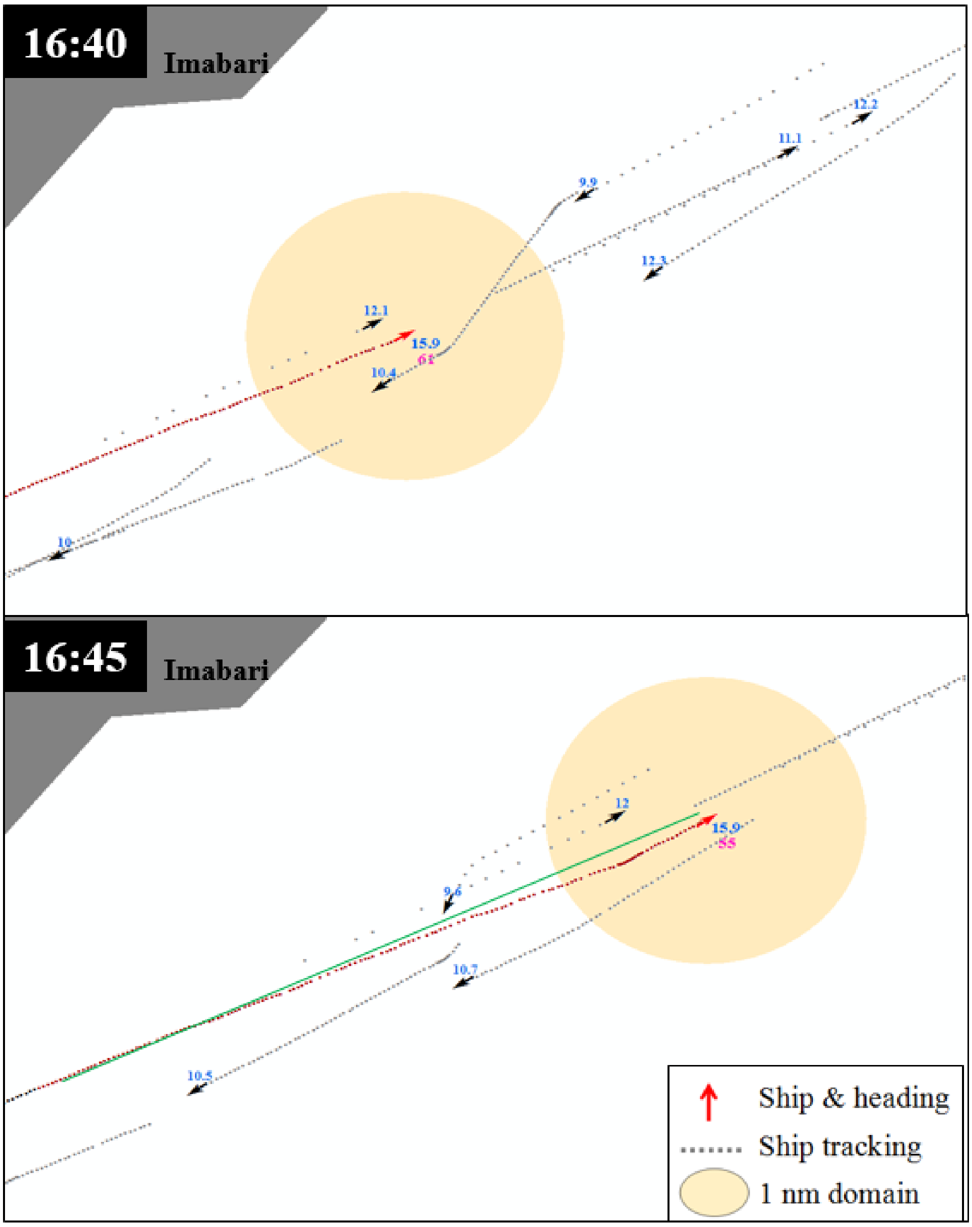

Fig. 7 Avoidance behavior of ship A navigating in Seto Inland Sea

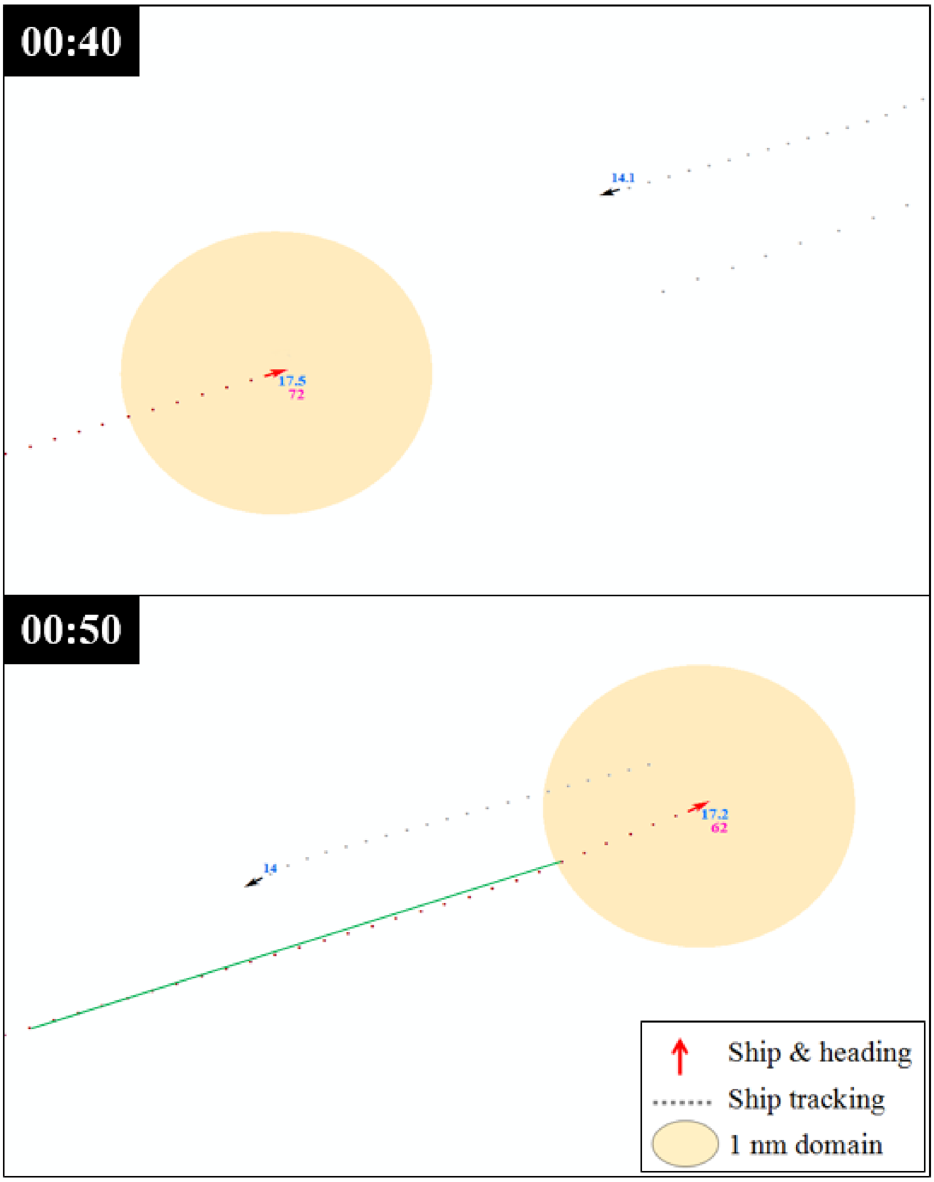

Fig. 8 Avoidance behavior of ship B navigating in Pacific Ocean

the mid-channel with the tidal current and navigate the west channel against the tidal current. At the time, according to the current, many ships changed course before entering the traffic route. This complex situation caused the target ship to list toward starboard in order to avoid the other ships. The green line in the lower illustration shows the scheduled course. The deviation of ship A from the scheduled course was checked according to the trajectory. The difference between the heading before and after veering was about 10°. In addition, another head-on ship sailed on the starboard bow of ship A, presenting a high risk of collision. Avoidance behavior also presents latency risk in complex and congested areas. Fig. 8 shows the avoidance behavior of ship B in the Pacific Ocean route. Compared with ship A, the situation was simpler. Only one head-on ship sailed around ship B. The heading before veering was about 60°, and the ship listed 72° to starboard in order to avoid the head-on ship. The trajectories confirm that ship B had a sufficient width for avoidance. Thus, ship B deviated from the scheduled course in a short distance.

5. DISCUSSION

We compared the navigation risk between the Seto Inland Sea and Pacific Ocean routes. According to the analysis, although the Seto Inland Sea is a shorter route for navigation between Kanmon and Osaka, the route is difficult for ship navigation, and there is a higher collision risk compared with the Pacific Ocean route. The ship navigated at a high speed and passed through a shorter route, but was anchored offshore to wait for the berth. Waiting offshore is inefficient. Considering navigation safety, the Pacific Ocean route is not congested, and there is sufficient distance for avoiding ships. Although it is possible that ship navigation was affected by the Kuroshio current, if the ship rides the current, fuel consumption may be reduced. Navigating the Pacific Ocean route is considered safe and effective.

6. CONCLUSIONS

This study used big data of real ship movements to analyze the navigational situation of ships. According to the dynamic calculation and analysis, the actual navigation situations of ships sailing in the Seto Inland Sea route and Pacific Ocean route were understood. The main results are as follows:

(1) Numerous ships navigated close to the target ship in the Seto Inland Sea. Head-on was the most frequent encounter situation in the research area.

(2) There was a high collision risk during operation in the inland sea. Complex encounter situations increased the maneuvering difficulty owing to the action constraints on the other ships.

(3) Changes in the speed and course were frequent but diminished when the ship passed through both straits. There are latent risks and inefficiency for navigation in the Seto Inland Sea.

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