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Key words: risk assessment, ship behaviour, approaching channel, automatic identification system (AIS), Keelung Harbour.

ABSTRACT

The AIS data is powerful 'Big Data' of marine traffic and can provide critical insights for risk assessment and ship navigation in the congested waterway. In our previous work (Huang et al., 2019), a statistical approach was proposed to explore the information of ship navigation from AIS data. In this study, we extend the previous methods to study navigation safety in the approaching fairway of Keelung Harbour. The AIS data is acquired according to the factors of mooring dock, ship size and seasonal conditions. The statistical method is used to establish a ship behaviour model considering the lateral position, speed and headings for the inbound ships. The probability of potential colliding scenario and probability of colliding are defined. The analysis shows that the colliding risk of the inbound ship with breakwater is quite low, which is consistent with the records from the government. The results of the present study provide valuable information for ship traffic monitoring in the Vessel Traffic Sevice (VTS) station of Keelung Harbour.

I. INTRODUCTION

The Automatic Identification System (AIS) was launched in 2003 with the intent of improving marine safety. Ships above a certain tonnage including cargo and passenger ships are required to install the AIS system. Under the AIS scheme, ships transmit and receive signals containing static and dynamic data to and from other vessels and terrestrial stations at intervals. The amount of real-time and historical AIS data is enormous. This data is potentially a vast source of information once it has been made suitable for statistical use. In-depth analyses of AIS data can potentially ease the lookout and surveillance missions for the watch keeping personnel both at sea and in port.

Real-time and historical AIS data contains useful information for early identifications of ship navigation anomalies and colliding risks. The information is a precious source for navigational risk assessment and has been used in a variety of applications. These include the traffic flow characteristics such as the traffic volume and distributions of ship type and size, ship behaviour analysis in the congested water area (Pallotta et al., 2013; Liu et al., 2017), search, and rescue and maritime surveillance (Vieira et al., 2016; Varlamis et al., 2018; Zhou et al., 2019), the ship collision and grounding risk assessment (Silveira et al., 2013) and recently the intelligent maritime navigation (Tu et al., 2018). In ports, AIS is the most prominent system for monitoring ship activities. The officers monitor ship traffic and identify suspicious activities or potential collisions and raise alerts. The traffic pattern and ship behaviour model based on AIS data would provide VTS or officer of the watch (OOW) with sufficient discriminating knowledge that can be used as a useful reference for regulatory and transportation safety improvement.

In recent years, research using AIS data for maritime transport and maritime safety has gradually increased. A brief review of the use of AIS data to study the ship behaviour and the grounding risk assessment near ports or intricate waterways is as follows. Eide et al. (2007) proposed an intelligent ship traffic monitoring system estimating the risk of individual crude oil tankers for oil spill prevention. Sawano et al. (2011) adopted both the static and dynamic methods to conduct the vessel traffic analysis and safety assessment of Soya Straits. Goerlandt and Kujala (2011) applied the Monte Carlo simulation technique to obtain a meaningful prediction of the relevant factors of the collision events and studied the case of the Gulf of Finland showing a reasonable agreement with the registered accident and near-miss data. Zaman et al. (2015b) and Zaman et al. (2015a) studied navigation safety of tankers in the Malacca Strait. They used AIS data for hazard identification and risk assessment steps of formal safety assessment for the ship collision probability evaluation. Based on the AIS data analysis, Xiao et al. (2012) developed a primary application of multi-agent

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simulation for ship traffic on Yangtze River that provides a realistic representation of the marine traffic. Xiao et al. (2015) used a statistical approach to analyze the ship traffic behaviours and obtained the main characteristics of the traffic parameters for Port of Lisbon. The parameters are important and considered when realistic ship simulations are performed for maritime risk analysis. Mazaheri et al. (2015) utilized the statistical analysis of the maritime traffic to the Gulf of Finland from the AIS data and grounding accidents. The research incorporated the expert elicitation techniques considering the waterway complexity. Wu et al. (2016) investigated the waterway transportation features using AIS data and evaluated the frequency of various types of vessel conflicts in the Sabine-Neches Waterway. In summary, most researchers use data processing and statistical methods to analyze AIS data and establish ship behaviour patterns to study navigation safety in complex water or establish intelligent ship traffic monitoring systems through expert systems or simulation procedures.

The AIS data analysis provides insights in ship traffic and forms a realistic simulation model for confined areas (such as port areas and inland waterways) which can be used for risk assessment of the ship traffic in concerned waterways to improve safety or efficiency. More and more studies utilize AIS data to assess the risk of marine traffic in recent years. The AIS data is powerful ‘Big Data’ for marine traffic and can provide critical knowledge for risk assessment and ship navigation in the congested waterway using artificial intelligence algorithms. The previous research by the authors (Huang et al., 2019) adopted a statistical approach for extracting AIS data to derive the features of the ship traffic behaviours in the waterways of Kaohsiung Harbour. The information is essential and contemplated when realistic ship simulations are performed for maritime risk analysis.

In this study, we extend our previously proposed methods to study the ship behaviours and navigation safety in the approaching fairway of Keelung Harbour. Based on the AIS data, the statistical method is used to establish a ship behaviour model of the inbound ship and to discuss the colliding risk and navigation safety. The results of the present study provide useful information for the ship traffic monitoring and risk alert system in the VTS station of Keelung Harbour. Section 2 investigates the geographical environment, climate and the Sailing Directions of Keelung Harbour. The AIS data and processing method are presented thoroughly in Section 3. The statistical analysis of the route data on crossing-lines and along the inbound fairway was shown in Sections 4 and 5. The risk assessment for the breakwaters is presented in Section 6. Finally, the conclusions are drawn in Section 7.

II. KEELUNG HARBOUR

Keelung Harbour is located at the north-east of Taiwan and sheltered by mountains on the western, southern and eastern sides and by Keelung Island on the north-east. The prevailing wind direction is northeast (NE) to north northeast (NNE) from September to May, and south-southwest (SSW) to south (S) during the period between June and August. In winter, the NE monsoon is extremely windy, sometimes reaching a gale. According to the observations of Harbour and Marine Technology Center of the Ministry of Communications in Taiwan, the wind speed exceeding 10 m/s (force six on the Beaufort scale) accounts for 3.7% of the observation period from 2002 to 2016 (Harbour & Marine Technology Center, 2017). The north and northeast winds create heavy seas in the harbour approaches. The significant wave height experienced in this water area is up to 2.5-4.0 meters. Besides, the typhoon season is in summer, and more intense precipitations occur in winter. The average range of the tide is about 0.92 meters (m). The maximum flood/ebb current speed is about 2-3 knots around the inbound fairway.

According to the Keelung Harbour Vessel Traffic Service Manual (Keelung Harbour Bureau, 2011), all vessels approaching or departing Keelung Harbour are required to follow the Traffic Separation Scheme (TSS). The inbound/outbound waterways are both one-way traffic lanes. Vessels operating in these fairways should maintain a safe distance with vessel ahead according to the maneuverability of each own vessel. For the inbound procedure, vessels sail into the inbound fairway of TSS about 3.5 nautical miles (nm) from the entrance and maintain 7-8 knots to pick up the pilot at the pilot station. The TSS inbound fairway ends at 1 nm from the entrance. The main fairway sector connects the TSS fairway and entrance. There is a strong current causing vessels side shift in the two-way traffic lane, which can be offset by increasing speed. There is a 700 m-breakwater located on the eastern side of the entrance to reduce the current effect. Vessels pass the entrance and alter courses to the starboard side to keep ship position in the main channel and proceed to the berth.

In the port, the area is divided into the main channel and the inner harbour. The main channel contains the two lines located in the outer harbour, one connecting the eastern breakwater and An-Lan light posts whereas the other connecting west breakwater and berth No.19W temporary light posts as shown in Fig. 1. The depth at the centerline of the main channel is 15.5 meters below zero tide level (Keelung Harbour tidal datum). The width of the main harbour channel at the port entrance is 275 meters, the width of the inner harbour between Berth No.19 W temporary light post and An-Lan light post is 355 meters, and the length of the main harbour channel is about 0.8 nm. Once ships proceed into the outer harbour, it is necessary to adjust the heading directions as soon as possible and take the engine astern to stop.

There are two possible risks in the proceeding of the inbound ships. One is the strong current in the main fairway sector where the pilot should increase the speed to keep the course, and the other is the area of the outer harbour where the pilot should run engine astern or emergency stop, especially for large ships under the harsh weather conditions. Therefore, it is vital to study the traffic behaviour and risk assessment in this area.

Table 1. The number of runs acquired from AIS data.

	Small-size ship (LOA under 220 m)			Large-size ship (LOA over 220 m)		
	Total	summer	winter	Total	summer	winter
Inner harbour (IH)	1071	584	487	1017	551	466
Berth west 19 (W19)	296	148	148	794	420	374
West dock (WD)	524	279	245	462	238	224

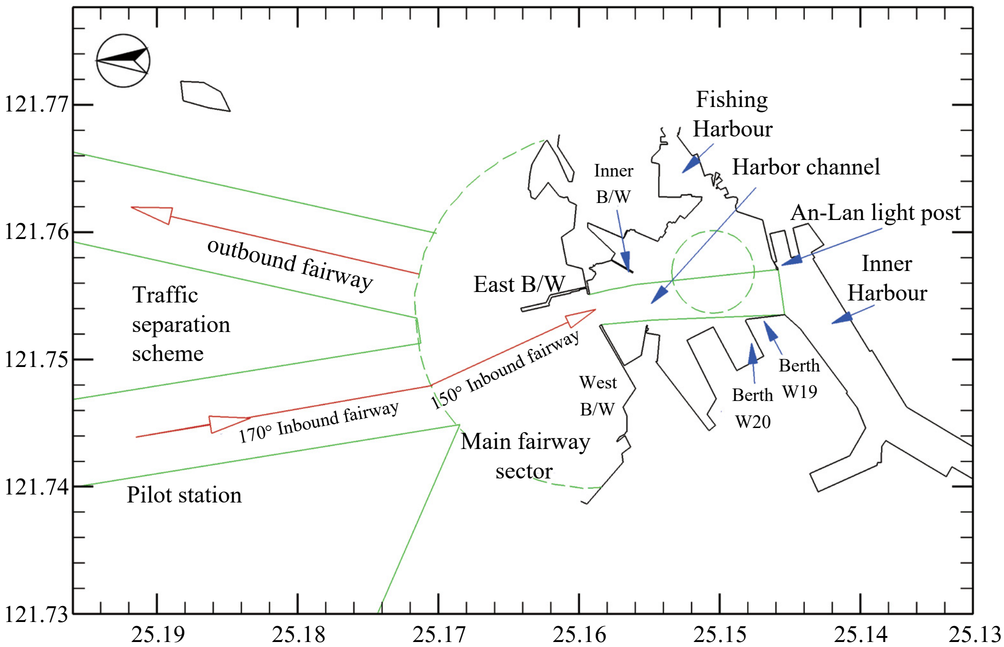

Fig. 1. The layout of Keelung Harbour.

III. AIS DATA

AIS has been operational onboard the ships over 300GT on international voyages since 31 December 2004 (SOLAS chapter V - Annex 17). AIS system is a technology to make ships visible to each other. It transmits the sailing status of ships and exchanges such data with other nearby vessels and onshore stations. The AIS data is sent every few seconds over two dedicated digital marine VHF (Very High Frequency) channels in a limited geographical space. The transmission interval varies depending on ship speed and the turning rate. Faster and turning vessels are updated more frequently. The AIS transponder works in continuous mode regardless of whether the vessel is offshore, within coastal or inland waters, or at anchor. Moored and anchored vessels broadcast their positions less frequently.

AIS data can be divided into two categories: the dynamic information and the static and voyage related information. The dynamic information includes maritime mobile service identity number (MMSI), the AIS navigational status, the rate of turn (RoT), speed over ground (SOG), position coordinates (latitude/longitude), course over ground (COG), heading and UTC seconds. The static information includes international maritime organization (IMO) number, call sign, ship name, cargo type, dimensions, the location of the positioning system's antenna on board the vessel, type of positioning system, draught, destination, estimated time of arrival (ETA). The ship's officer should make sure that they provide the system with the correct information regarding all static and voyage related fields (Harati-Mokhtari 2007).

The gathered data is quite mature and contains a wealth of information, which can be used for studying all segments of the maritime field. For example, in shipping, it is a valuable element optimizing logistics, increasing port throughput, reducing cargo handling costs, enhancing maritime safety, security and efficiency. Furthermore, it could be exploited for the subjects of ship navigation safety, namely, the traffic anomaly detection, route estimation, collision prediction and path planning. In this paper, we use AIS data to study the manoeuvring behaviours and assess grounding risk of the inbound ships on the fairways and entrance of Keelung Harbour.

Since the Keelung Harbour is mostly for container ships, this study only uses the AIS data of the container ships for analysis and is divided into a ship length respectively under and over 220 m according to the size of the ship. The location of the berthing piers will affect the ship's maneuvering strategy, so it is divided into the west dock of berths 20 to 23 (WD), the wharf

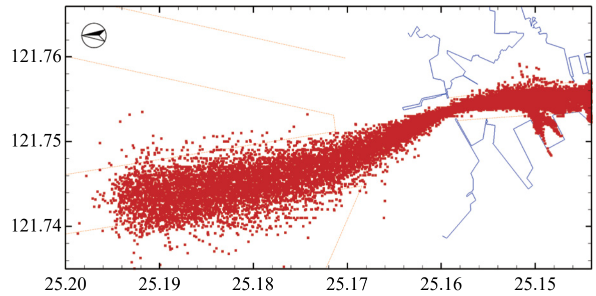

Fig. 2. The data points of container ships LOA over 220 m.

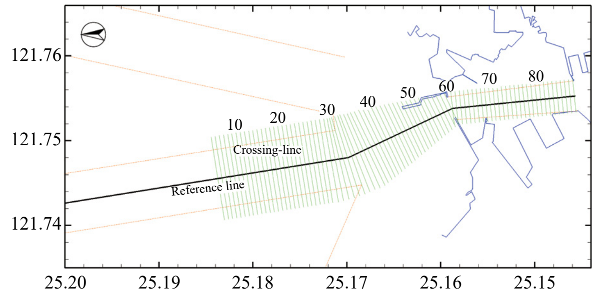

Fig. 3. The layout of crossing-lines and the reference line.

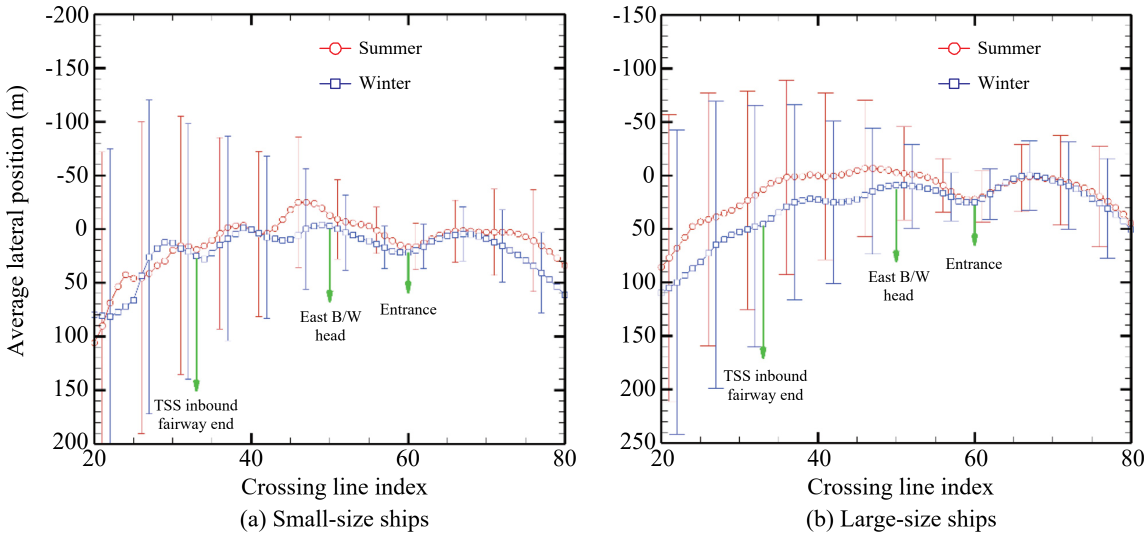

Fig. 4. The comparison of average lateral positions between summer and winter.

of west 19 (W19) and inner harbour (IH) according to the berthing docks. There are 42 months of the AIS data used in this study. The trajectory data acquired from the AIS database for each class with a filter is shown in Table 1. In Table 1, the data of ship length (LOA; length of overall) between 160 m and 220 m, and the LOA between 220 m and 350 m are categorized as the small-size and the large-size ships, respectively. The seasons, summer and winter, refer to the data drawn from April to September and October to March, respectively. Fig. 2 shows the data points for container ships of the LOA class over 220 m.

In this study, a reference track line is defined to analyze the ship's behaviour and assess the grounding risk of inbound ships as shown in Fig. 3. The line extends from the pilot station, through the end of the TSS channel and entrance along the main channel in the harbour. A set of crossing-lines perpendicular to the reference line, shown in Fig. 3, is designed to acquire the trajectory data across the crossing-line. The statistical analysis is usually performed with the crossing-lines to study the changes of those navigating characteristics throughout the inbound traffic lane. The distance between two adjacent crossing-lines is a constant of 50 m. The data of ship lateral position, speed, and head-

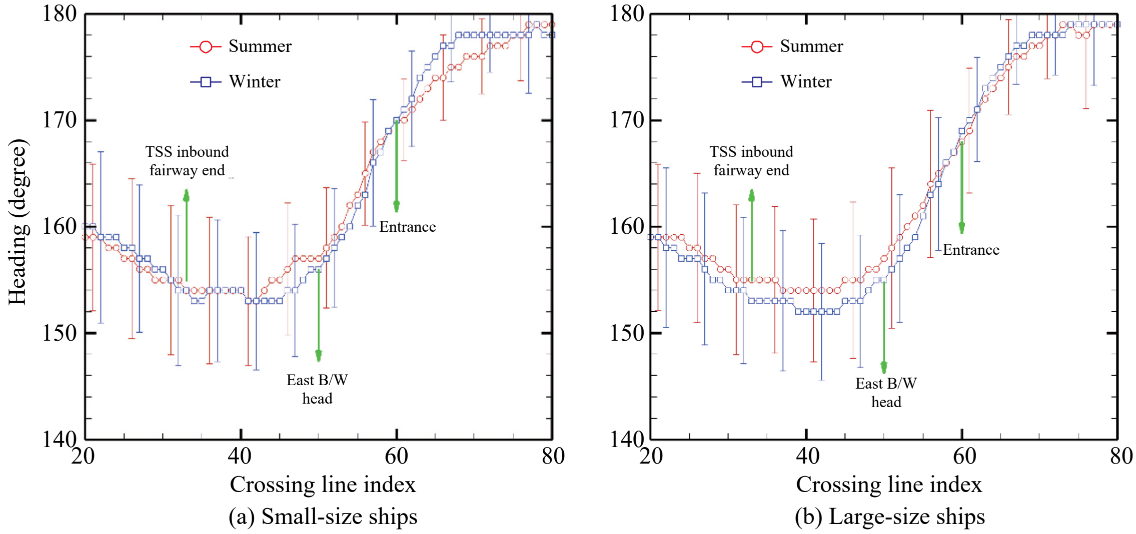

Fig. 5. The comparison of heading between summer and winter.

ing, provided by the AIS information, are recorded at each crossing-line. A total of 89 crossing-lines are named as crossing-line 1 (CL01), crossing-line 2 (CL02), crossing-line 3 (CL03), …, to crossing-line 89 (CL89) from left to right for analysis. Also, CL33, CL50 and CL60 locate at the TSS inbound fairway end, the east breakwater head and the entrance, respectively.

IV. STATISTICAL ANALYSIS ALONG THE INBOUND FAIRWAY

Figs. 4(a) and 4(b) show the comparisons of the average lateral positions along the inbound waterway between summer and winter for the ship berthing on W19 of the small- and large-size ship, respectively. The *x*-axis is the index of crossing-line, and the y-axis denotes the average lateral position. The axis origin is the intercepts of the reference and crossing-lines in which positive is used for the starboard side. The TSS inbound fairway end, breakwater head and entrance are located at the 33rd, 50th and 60th crossing-lines, respectively. The error bars indicate one standard deviation of the lateral position variations. Most of the ships sail on the starboard side, i.e., the downwind side of the reference line, especially in the TSS fairway.

In Fig. 4(a), for the small-size ships (LOA less than 220 m), the average lateral positions in summer and winter conditions are similar to each other. In Fig. 4(b), for the large-size ships (LOA greater than 220 m), the average lateral positions are significantly different in summer and winter. The ship position is biased to downwind side due to the strong northeast monsoon in winter. After entering the breakwater area, the bias of the ship positions by wind and current diminishes. The ship tracks in winter and summer are gradually consistent, indicating that the sailing strategies of the pilots are analogous when entering the entrance regardless of winter or summer.

Figs. 5(a) and 5(b) show the comparisons of the ship headings along the inbound waterway between summer and winter for the ship berthing on W19 of small-size and large-size ships, respectively. The ship headings of the small-size ships are similar in summer and winter. The difference of the heading angles of the large-size ships on the TSS fairways and main fairway sector between summer and winter is about 2 to 4 degrees. The leeway angle of the ships in winter is higher than those in summer due to the ship position is significantly deviated to the downwind side in winter. The difference of the headings between summer and winter gradually decreases when the ship passes through the breakwater whereas it seems almost the same after entering the entrance. The standard deviation is less than 7 degrees, which shows the ship proceeds in a consistent process.

Figs. 6(a) and 6(b) show the comparisons of the SOG along the inbound waterway between summer and winter for the vessels berthing on W19 of the small-size and large-size ships, respectively. Since the pilot station is located at 1.5 nautical miles away from the entrance in which the boarding speed for pilot embarkation is around 7 knots. The pilots accelerate the ship speed to increase the maneuverability. The ship navigates with a speed of 8 or 10 knots on the TSS inbound fairway and main fairway sector in order to overcome the interferences of the wind and current. Due to the heavy weather in winter, i.e., the strong northeast monsoon, the ship speed is slightly lower than that in summer for the large-size ships. The ships start to slow down when they reach about 0.3 nautical miles in front of the eastern breakwater head. The speed of ships navigating across the entrance spanned in a range from 6.5 to 8.5 knots, with a mean of 7.5 knots. The velocity maintained in this range was not too slow to anti-wind-force nor too fast to berthing or stopping. The ships run astern the engine, and the ship speed apace reduced when proceeding in the harbour lane. The eastern breakwater performs beneficial features to help the inbound ships resist the heavy weather. After entering the sheltered area of the eastern breakwater, the weather effects weakened, and the behaviour of the ship in the winter and summer becomes convergent.

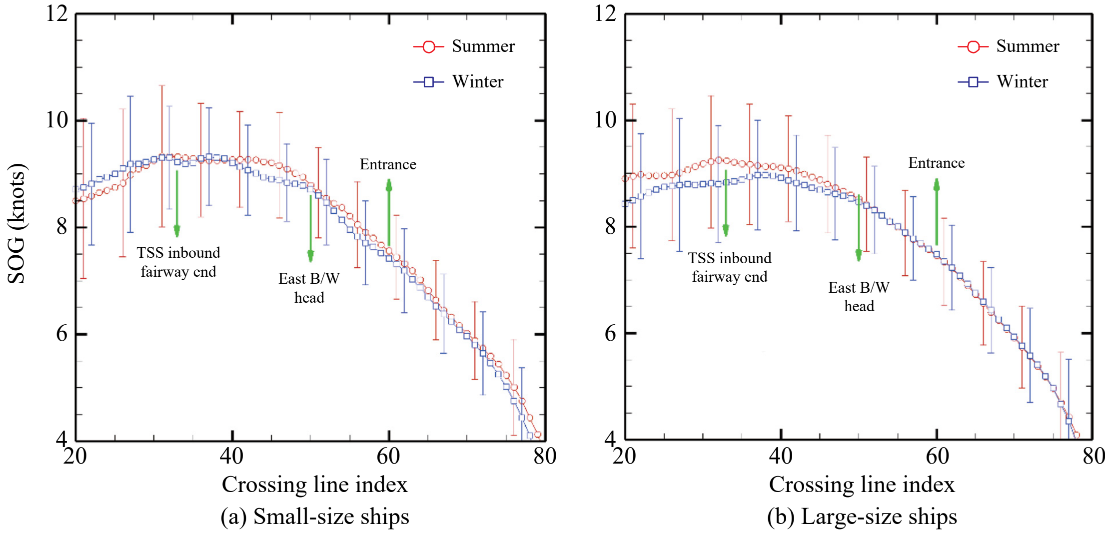

Fig. 6. The comparison of SOG between summer and winter for.

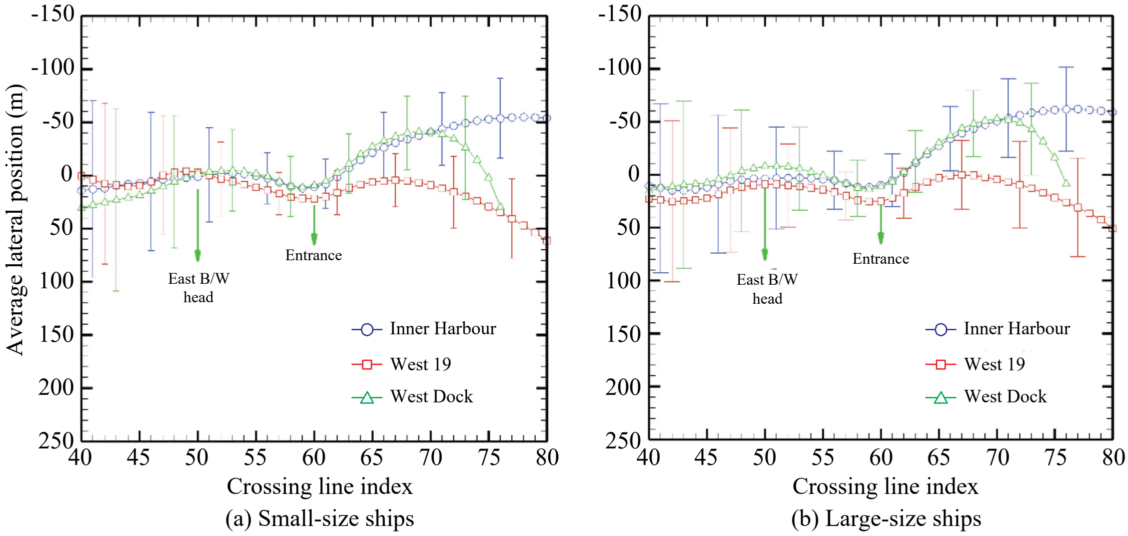

Fig. 7. The comparison of lateral position among berthing wharves for.

Figs. 7(a) and 7(b) show the comparisons of the average lateral positions along the inbound waterway among berthing the wharves in winter for small-size and large-size ships, respectively. When the ships enter the breakwater shelter area, the ship begins to gradually change the navigation trajectory according to the destination (the berthing dock). Since the vessels berthing to WD or IH has a massive starboard turn after passing the entrance, the ship position offsets to the port side of the channel to reserve the steering space. On the contrary, ships moored on W19 wharf proceed alongside starboard, so the ship position biases to the starboard side of the fairway. There is no apparent difference in the average lateral positions between the large-size and the small-size ships.

Figs. 8(a) and 8(b) show the comparisons of the heading along the inbound waterway among berthing the wharves in winter for small-size and large-size ships, respectively. The figures show that the change of the heading is consistent with that of the lateral position. Also, there is a noticeable difference depending on the destination of the berth.

Figs. 9(a) and 9(b) show the comparisons of the SOG along the inbound waterway among the wharf berthing in winter for the small-size and large-size ships, respectively. The ships berthing at wharves of WD and W19 must slow down as soon as possible after passing the entrance because of the channel length limit. Therefore, they proceed at a lower speed meanwhile maintain the sufficient maneuverability in the TSS fairway and main fairway sector. The ships berthing at WD and W19 wharves have already prepared to slow down when entering the main fairway sector. Instead, the ship berthing at IH navigates with a higher speed to reduce the inbound operation

Table 2. SOG of ships passing the entrance.

	Small-size ships			Large-size ships		
	WD	W19	IH	WD	W19	IH
Winter	7.08	7.42	8.76	7.07	7.48	8.68
Summer	6.88	7.56	8.56	6.92	7.45	8.58

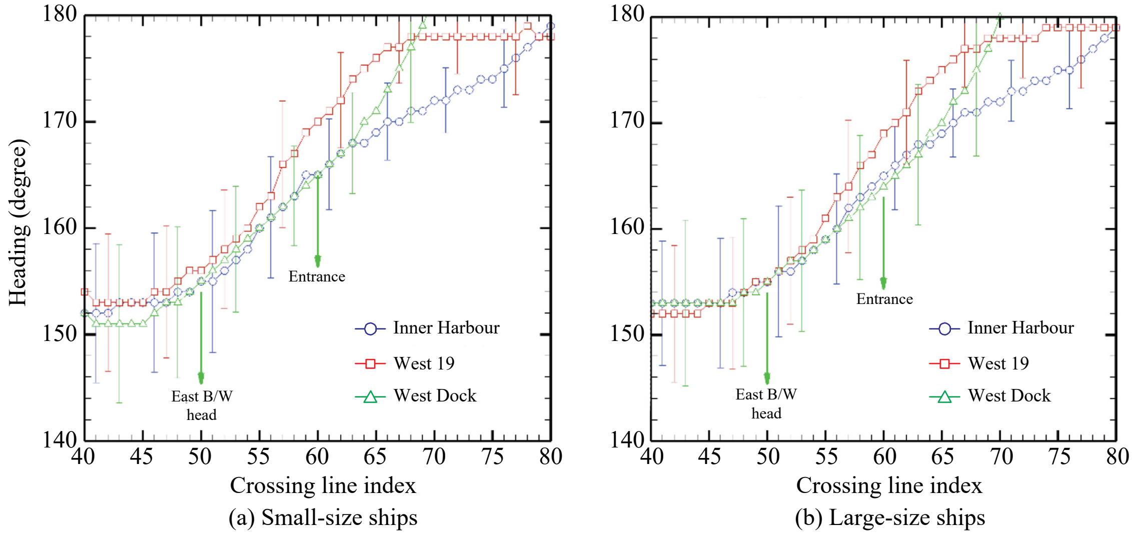

Fig. 8. The comparison of heading among berthing wharves.

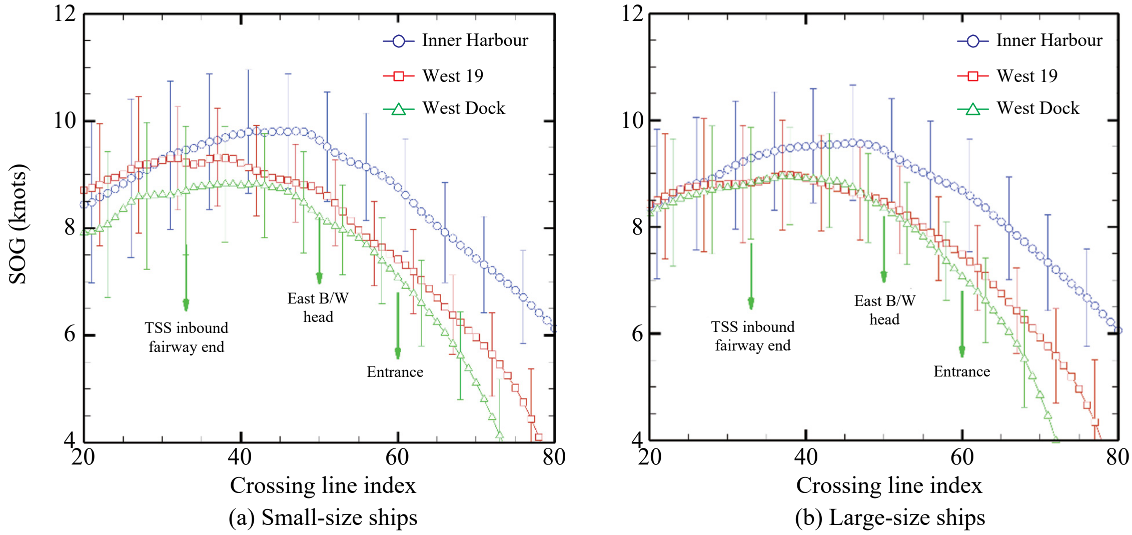

Fig. 9. The comparison of SOG among berthing wharves.

time. Table 2 lists the average SOG of the ships when passing the entrance. The ship berthing at the WD, W19 and IH wharves have the velocities of about 7.0, 7.5 and 8.6 knots. The ship size and weather factors have little effect on the speed of the ship passing through the entrance, whereas the berthing wharf is the most evident element to the ship speed through the entrance.

V. STATISTICAL ANALYSIS OF ROUTE DATA ON CROSSING-LINES

The inbound ship behaviours of Keelung Harbour are analyzed to assess the colliding risk on the breakwater quantitatively. For inbound sailings, pilots embark at the pilot station and navigate vessels through the two-way traffic fairway and main fairway sector to the entrance. Figs. 10(a) to 10(d) show the spatial histogram of the large-size ships berthing at the inner harbour on crossing-lines at the TSS inbound fairway end (CL33), the east breakwater head (CL50), the entrance (CL60) and the inner breakwater (CL66), respectively. The *x*-axis is the lateral

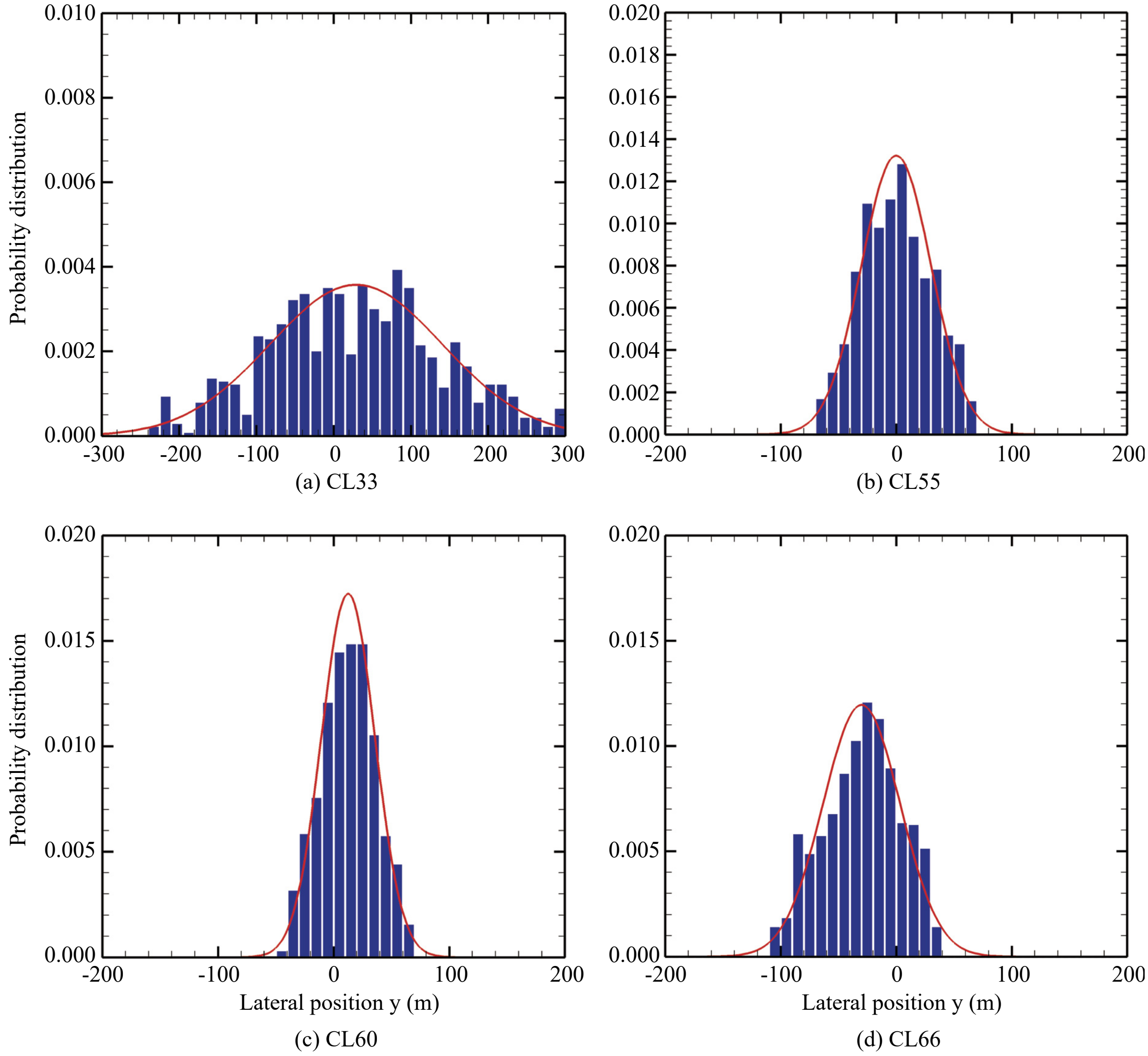

Fig. 10. Spatial histogram of large-size ships berthing at inner harbour.

position from the reference line to the ship middle point, and the *y*-axis gives the fraction of the ship numbers.

We find that most of the ships were navigating along the reference line on the TSS inbound fairway and main fairway sector. However, the ship position deviates to the starboard side of the reference line when approaching the entrance. The average deviation of the lateral positions is 12.5 m. The distribution shows that a normal distribution could well approximate the spatial distribution. In contrast with the entrance, most of the ships were navigating on the port side of the reference line when passing through the inner breakwater to avoid the interference with ships berthing at WD or W19. The shape distribution skews to the left, and the average lateral position is -30 m on the port side of the reference line.

Ship speed plays a vital role in inbound traffic safety. It must be limited within a range. If the ship speed is too slow, it will affect the maneuverability and may increase the inbound time. The tidal window may be missed, which will increase the grounding possibility. On the other hand, if the speed is too fast, the operation time for striking or collision avoidance is reduced, thus compromising the ship safety.

A ship will navigate with a safe speed in the harbour channel. Commonly, the OOW should be able to decide a speed which guarantees the safety of the ship. Such a speed is determined by good seamanship and many factors, such as the experience of the officer, ship position, ship condition, ship dimension, ship type, the waterway characteristic, and the environment. Figs. 11(a) to 11(d) show the ship speed over ground (SOG) histogram of the large-size ships berthing at the inner harbour on crossing-lines at the TSS inbound fairway end (CL33), the east breakwater head (CL50), the entrance (CL60) and the inner breakwater (CL66), respectively. Since the pilot station is located at 1.5 nautical miles away from the entrance and the boarding speed for pilot embarkation is around 7 knots. The pilots accelerate

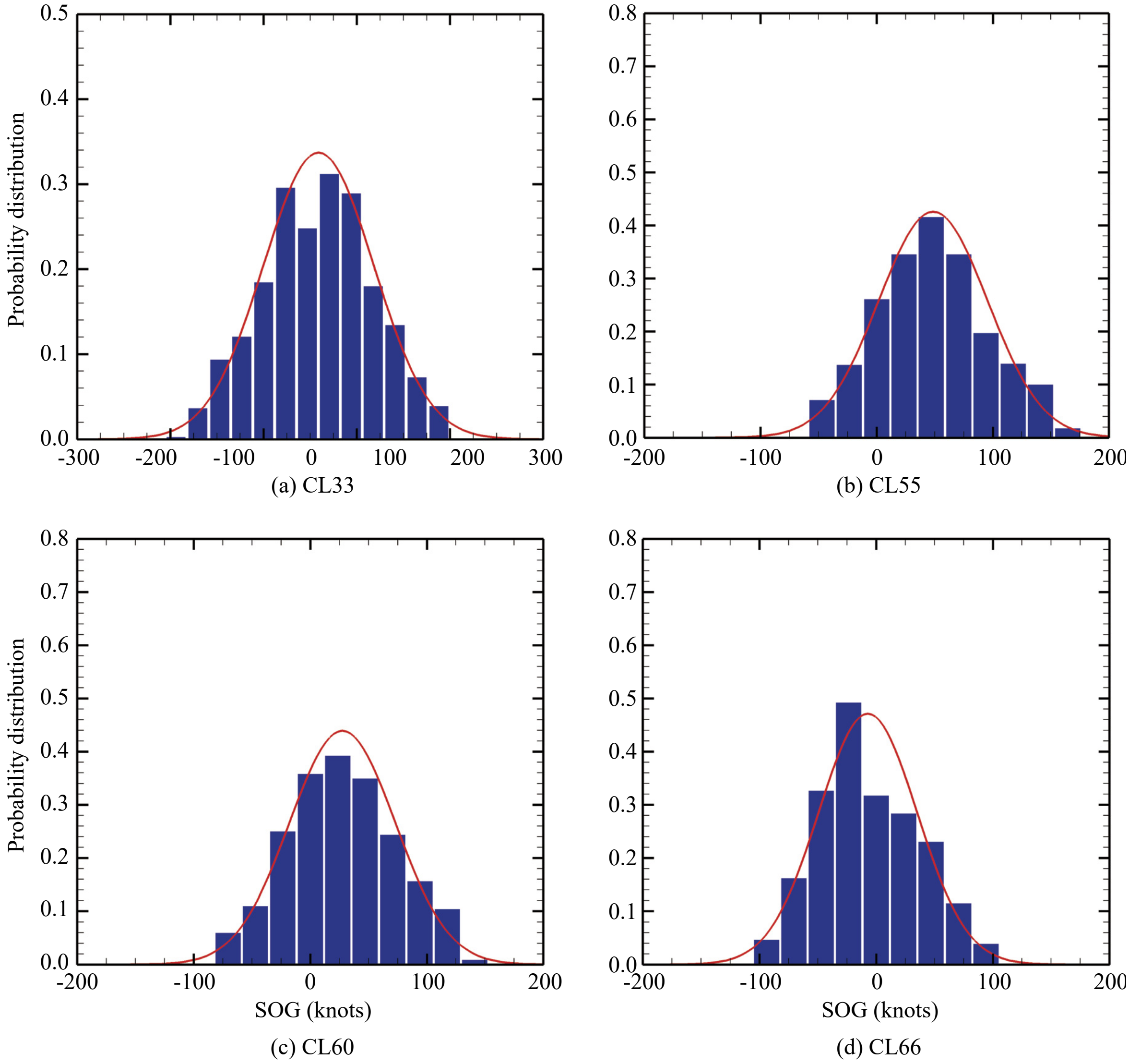

Fig. 11. SOG distribution of large-size ships berthing at inner harbour.

speed to increase the ship maneuverability and then keep the ship course and track to the entrance. The speed of the ships navigating across the entrance spanned in a range from 6 to 11 knots, with a mean of 8.6 knots. A normal distribution function can be well fitted to the speed data as shown in Fig. 11(c). However, after navigating through the entrance, the ship decelerates along the main harbour channel and proceeds to the inner harbour. The shape distribution skews to the right, and the average SOG is 7.7 knots on the port side of the reference line.

Figs. 12(a) and 12(b) show the spatial histogram of the large-size ships berthing at W19 on the crossing-lines at the entrance (CL60) and the inner breakwater(CL66), respectively. Similar results with the case of berthing at the inner harbour are obtained. The ship position deviates to the starboard side of the reference line at the entrance. The distribution shows that the spatial distribution is well approximated by a normal distribution with an average of 26 m on the starboard side of the reference line and a standard deviation of 22 m. In contrast with the entrance, most of the ships were proceeding around the reference line to W19 when passing through the inner breakwater. The shape distribution skews to the left, and the average lateral position is 1.0 m on the starboard side of the reference line.

Figs. 13(a) and 13(b) show the SOG histogram of the large-size ships berthing at W19 on the crossing-lines at the entrance (CL60) and the inner breakwater (CL66), respectively. The speed of the ships navigating across the entrance spanned in a range from 5.5 to 9.5 knots with a mean of 7.5 knots which is less than those berthing at the inner harbour. A normal distribution function can be well fitted to the speed data.

VI. CROSSING-LINE METHOD FOR THE COLLIDING RISK

There are several regions along the inbound waterway that

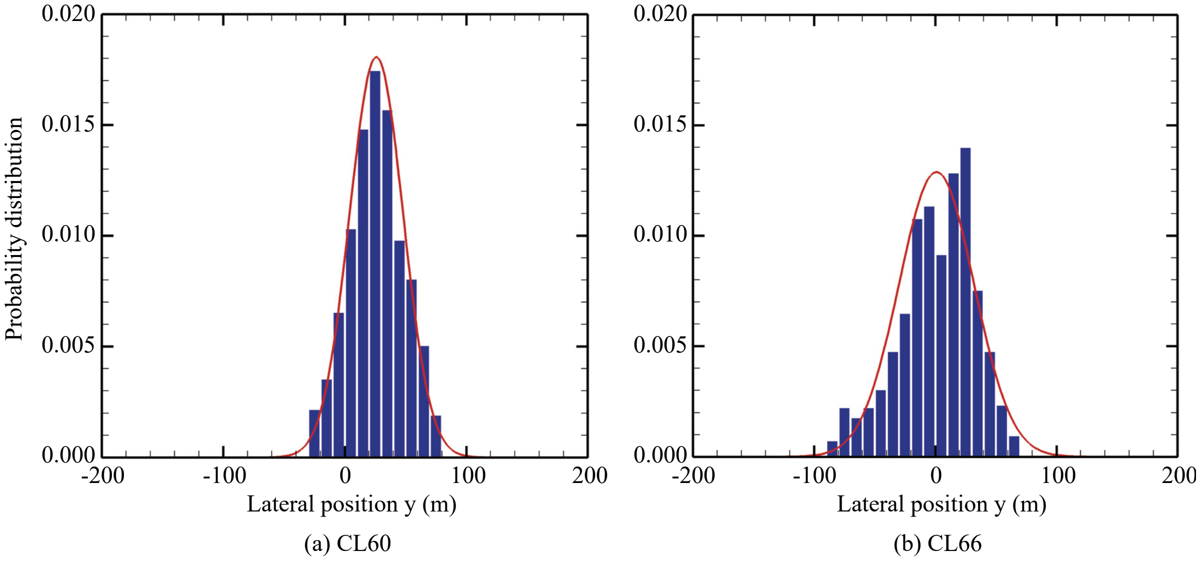

Fig. 12. Spatial distribution of large-size ships berthing at W19.

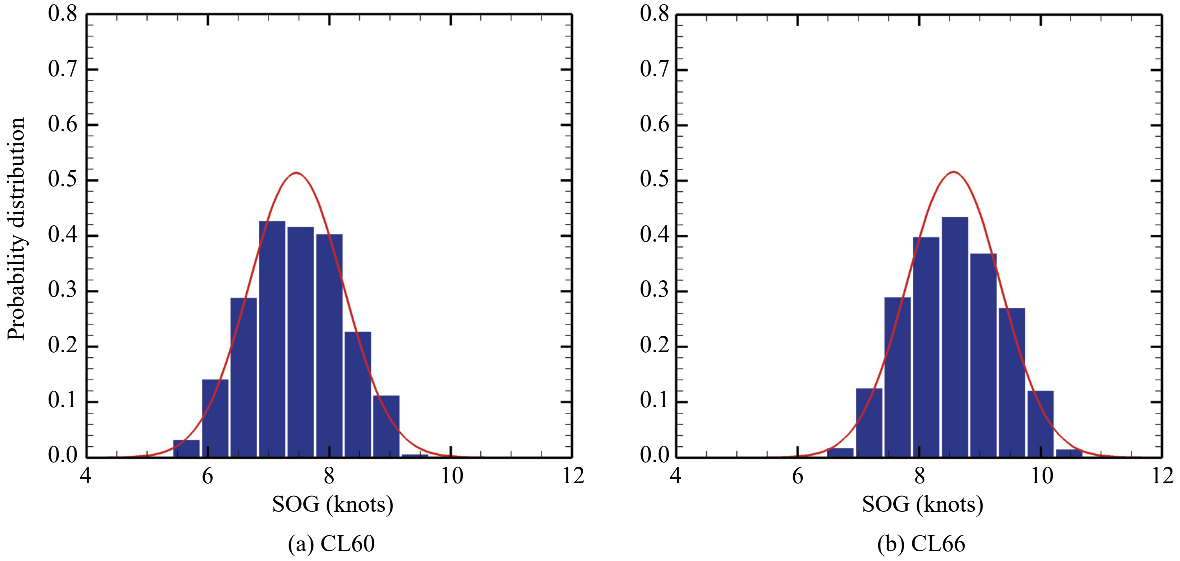

Fig. 13. SOG distribution of large-size ships berthing at W19.

significantly affect the ship navigating behaviours and induce navigating dangers. When ships approach the head of eastern breakwater, the heavy weather and sea conditions may cause position or heading deviations, leading to the risk of grounding or colliding with the eastern breakwater. When the ships pass through the head of the eastern breakwater, the sudden change of the hydrodynamic pressure induced by current results in the heading deviation. It is not easy to correct the deviation before passing the entrance, forming a danger of colliding with the breakwater at the entrance. The pilots increase the speed to reduce the colliding risk as mentioned above. After passing the entrance, ships alter course to the starboard side and sail through the inner breakwater, and then perform the deceleration operation. The inner breakwater is also a region where collisions may occur. In this study, we extend our previous method, the crossing-line method, to assess the colliding risk of the three regions, the head of east breakwater, the breakwater of the entrance and the inner breakwater. We acquired the data on the crossing-line of CL45, CL55 and CL62 where a distance about half to a full ship length in front of the breakwater. We assume that ships cannot avoid the collision with the breakwater within this distance. The colliding risk is evaluated using the statistical analysis of lateral positions and heading angles on the crossing-lines.

In this study, to evaluate the navigation risk of the inbound ships, the potential colliding risk is defined as the probability of the ship's position exceeding the channel borderline that has caused or could have caused the colliding accidents, rather than merely that of the actual colliding events. In order to more clearly

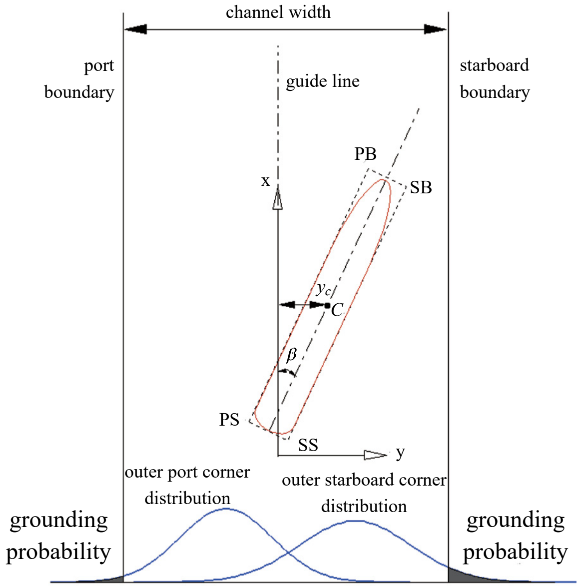

Fig. 14. Sketch definition of ship position in a channel (Huang et al., (2019)).

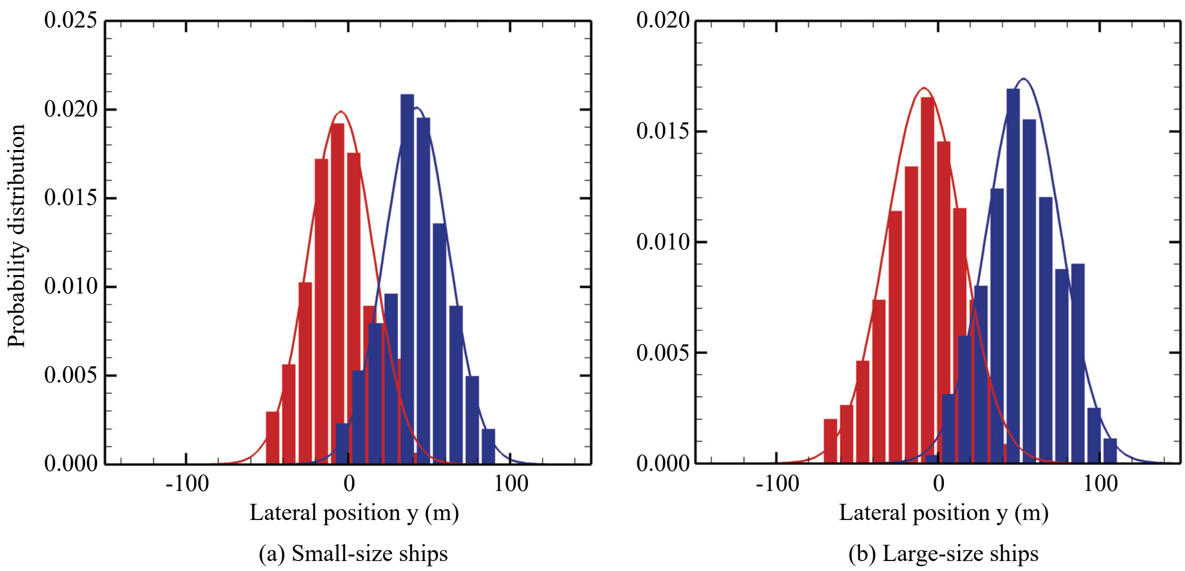

Fig. 15. The distribution of cross-track deviation of the outer port and starboard corners at the entrance, berthing at W19.

illustrate the results of risk assessment, we use the terminology of "probability of the potential colliding scenario" abbreviated as PPCS to denote the probability of exceeding the channel boundary. Moreover, when a ship deviates to the reference line, the pilot tends to correct the heading angle and the ship position back to the reference line to avoid exceeding the borderline. That means the grounding risk is not only dependent on the lateral positions but also the heading angles. The probability of colliding, abbreviated as PC is defined as the events satisfying both the criteria i.e., the ship crossing the channel borderline and continuing moving outside the boundary. That is, the pilot cannot control the heading angles back to the reference line.

1. Single-Variate Analysis for the PPCS

When a ship passes through a crossing-line, the lateral positions and the headings deviating from the reference-line can be calculated based on the AIS data. The lateral positions of the most port and most starboard outer corners denoted y_P and y_S, are easily identified as the values of the bow and stern corner coordinates. They are

$$y_S = \max(y_{SB}, y_{SS}) \tag{1}$$

$$y_P = \max(y_{PB}, y_{PS}) \tag{2}$$

The positions of the four corners of the ships are denoted with the subscript of the port bow (PB), starboard bow (SB),

Table 3. The PPCS of ships berthing at the inner harbour.

Ship size	Season	Head of the eastern breakwater	Entrance		Inner breakwater	
			Port	Starboard	Port	Starboard
Small	Summer	2.22E-04	2.14E-06	8.75E-06	1.49E-08	2.13E-05
	Winter	6.63E-05	6.82E-10	3.15E-07	2.30E-09	2.72E-06
Large	Summer	4.67E-04	1.98E-07	3.32E-06	4.09E-09	2.04E-06
	Winter	1.28E-04	1.20E-08	1.45E-05	7.16E-10	2.54E-08

Table 4. The PPCS of ships berthing at W19.

Ship size	Season	Head of the eastern breakwater	Entrance		Inner breakwater	
			Port	Starboard	Port	Starboard
Small	Summer	4.56E-05	3.32E-11	7.88E-07	2.72E-15	4.86E-06
	Winter	1.52E-05	4.31E-12	2.30E-07	1.01E-16	5.58E-08
Large	Summer	2.05E-04	7.98E-08	2.64E-04	2.78E-12	1.09E-04
	Winter	2.52E-05	8.54E-10	3.53E-05	2.02E-11	6.94E-06

port stern (PS) and starboard stern (SS) as shown in Fig. 14. With the coordinate defined in Fig. 14, the following formulas define the lateral positions of the four corner points.

$$y_{PB} = y_C + 0.5(L\sin\beta - B\cos\beta) \tag{3}$$

$$y_{SB} = y_C + 0.5(L\sin\beta + B\cos\beta) \tag{4}$$

$$y_{PS} = y_C - 0.5(L\sin\beta + B\cos\beta) \tag{5}$$

$$y_{SS} = y_C - 0.5(L\sin\beta - B\cos\beta) \tag{6}$$

In here y_C is the position of the midship point and it is the cross-track deviation from the reference line. The deviation of the heading angles from the reference line β is defined as a positive value in a clockwise direction. L is the ship length, and B indicates the ship beam. The area between the track lines of y_P and y_S resulting from one ship path mostly indicates as the swept path. The lateral positions of the port and starboard outer corners, which are the function of the variables y_C, β, L and B, are evaluated at each crossing-line. In order to assess the risk of colliding with the breakwaters, the PPCS on the crossing-line i at the port and starboard side, $P_{P,i}$ and $P_{S,i}$, are evaluated by the following equations:

$$P_{S,i} = \int_{b_{S,i}}^{\infty} N\left(\mu_{S,i}, \sigma_{S,i}\right) dy \tag{7}$$

$$P_{P,i} = \int_{-\infty}^{b_{P,i}} N\left(\mu_{P,i}, \sigma_{P,i}\right) dy \tag{8}$$

The integral bounds $b_{S,i}$ and $b_{P,i}$ are the starboard and port boundaries of the traffic lane. In this study, the spatial distributions of the most port and starboard corners at each crossing-line, $y_{P,i}$ and $y_{S,i}$, are approximated by the normal distributions $N\left(\mu_{P,i}, \sigma_{P,i}\right)$ and $N\left(\mu_{S,i}, \sigma_{S,i}\right)$, respectively. In the distributions $\left(\mu_{P,i}, \mu_{S,i}\right)$ and $\left(\sigma_{P,i}, \sigma_{S,i}\right)$ are the means and standard deviations of the random variables $y_{S,i}$ and $y_{P,i}$ at the crossing-line i.

Figs 15(a) and 15(b) show the histogram and the approximated normal distribution of the port and starboard outer corners at the entrance for small and large size ships berthing at W19. The lower (port) and the upper (starboard) tails of the distribution will give the probability of navigating outside the safe area in each crossing-line, indicating the approximate colliding risk area and its scope. Tables 3-5 show the PPCS of the inbound container ships at the head of the eastern breakwater, the entrance, and the inner breakwater for the ships berthing at IH, W19 and WD, respectively. Eqs. (7) and (8) evaluate the PPCS of the starboard and port sides. It shows that most of the PPCS of the inbound ships are less than or equal to 10^{-4} order of magnitude. It indicates the colliding risk is not significant in the area of Keelung Harbour. The PPCS at the head of east breakwater are around 10^{-4} to 10^{-5} orders of magnitude, which is higher than those of the entrance and inner breakwater. The PPCS for ships berthing at WD is slightly higher than that of the ships calling at W19 and IH because the pilots adjust the ship positions to port side in advance to prepare for starboard turn into the region of WD. This reason also leads to a higher PPCS value on the west breakwater at the entrance. The PPCS for large-size ships is higher than that of the small size ones, especially for large-size ships that berth at the W19 in summer weather conditions. In this study, we mark the probability of an accident less than 10^{-10} as a safe situation. The PPCS of the port embankment of entrance and inner breakwater for ships berthing at WD are lower than the marked safe situation value, which indicates a relatively low risk in these regions for inbound ships.

Table 5. The PPCS of ships berthing at WD.

Ship size	Season	Head of the eastern breakwater	Entrance		Inner breakwater	
			Port	Starboard	Port	Starboard
Small	Summer	5.16E-04	3.17E-07	1.47E-05	1.50E-09	1.34E-07
	Winter	2.39E-04	4.62E-07	6.21E-05	2.16E-09	7.36E-08
Large	Summer	3.56E-04	5.72E-07	1.23E-05	2.15E-08	1.86E-07
	Winter	6.71E-04	1.86E-06	7.01E-05	7.54E-08	3.96E-08

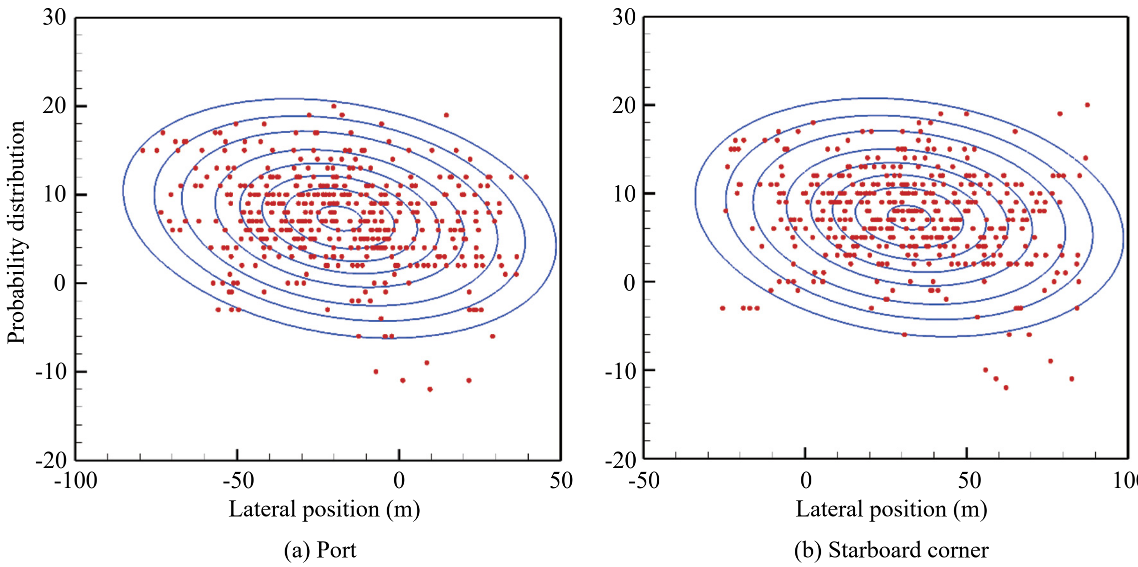

Fig. 16. Sample scatter plot and the contour of the joint normal distribution from the large-size container ships at the entrance for the most (a) port and (b) starboard corner.

2. Two-Variate Analysis for the PC

When an inbound ship is approaching the breakwater of the harbour entrance, if the ship position deviates to the right-hand side of the reference line, the pilot tends to correct the ship position back to the reference line to avoid colliding with the breakwater. Hence the heading angle is negative. On the contrary, when the ship deviates to the left-hand side of the reference line, the heading angle is positive. This means the colliding risk is not only dependent on the lateral position but also the heading angle. In addition to exceeding the width of the entrance, the condition of an event in which the ship strikes the breakwater must consider whether the ship continues to move outside the boundary. That is, the pilot is unable to control the heading angle back to the reference line. To evaluate the conditional probability of the colliding risk with the consideration of the lateral position and heading angle, we introduced a two-variate joint normal distribution to model the relations, of which the density function is as follows,

$$N(\boldsymbol{\mu}, \Sigma) = \frac{1}{2\pi|\boldsymbol{\mu}|^{1/2}} \mathrm{Exp}\left\{-\frac{1}{2}(\mathbf{x}-\boldsymbol{\mu})^T \Sigma^{-1} (\mathbf{x}-\boldsymbol{\mu})\right\} \quad (9)$$

Here $\mathbf{x} = (y, \beta)$ is the vector of the random variables of the lateral position and the deviation of the heading angle from the reference line. The mean vector $\boldsymbol{\mu}$ and the covariance matrix Σ are defined as

$$\boldsymbol{\mu} = (\mu_y, \mu_\beta) \text{ and } \Sigma = \begin{bmatrix} \sigma_y^2 & \rho\sigma_x\sigma_\beta \\ \rho\sigma_x\sigma_\beta & \sigma_\beta^2 \end{bmatrix} \quad (10)$$

In order to assess the colliding risk, apart from considering the deviation of ship position, it is also necessary to contemplate whether the ship continuously moves to the breakwater. The probability of colliding (PC) at crossing-line i was defined as

$$\begin{aligned} P_{S,i} &= P(y > b_{S,i}, \beta > 0) \\ &= \int_0^{\pi}\int_{b_{S,i}}^{\infty} N(\boldsymbol{\mu}_{S,i}, \Sigma_{S,i})\, dy\, d\beta \end{aligned} \quad (11)$$

$$\begin{aligned} P_{P,i} &= P(y < b_{P,i}, \beta < 0) \\ &= \int_{-\pi}^{0}\int_{-\infty}^{b_{P,i}} N(\boldsymbol{\mu}_{P,i}, \Sigma_{P,i})\, dy\, d\beta \end{aligned} \quad (12)$$

Figs. 16(a) and 16(b) show a typical sample scatter plot and the contour of the probability density function of a joint normal

Table 6. The PC of ships berthing at the inner harbour.

Ship size	Season	Head of the eastern breakwater	Entrance		Inner breakwater	
			Port	Starboard	Port	Starboard
Small	Summer	1.02E-13	1.65E-07	3.86E-06	8.12E-12	5.32E-09
	Winter	2.96E-16	7.64E-11	1.52E-07	3.77E-12	1.88E-08
Large	Summer	4.89E-14	9.19E-09	1.52E-06	9.50E-15	4.22E-11
	Winter	5.71E-16	5.86E-10	1.28E-05	1.50E-12	4.75E-12

Table 7. The PC of ships berthing at W19.

Ship size	Season	Head of the eastern breakwater	Entrance		Inner breakwater	
			Port	Starboard	Port	Starboard
Small	Summer	1.60E-22	1.83E-14	8.12E-10	2.25E-17	1.62E-11
	Winter	7.95E-21	3.70E-15	6.53E-08	9.49E-30	6.75E-15
Large	Summer	3.98E-15	9.44E-09	1.79E-04	9.97E-16	1.88E-08
	Winter	3.97E-23	1.92E-11	2.68E-05	1.47E-17	4.11E-11

Table 8. The PC of ships berthing at WD.

Ship size	Season	Head of the eastern breakwater	Entrance		Inner breakwater	
			Port	Starboard	Port	Starboard
Small	Summer	2.24E-13	2.62E-09	1.26E-05	2.57E-12	3.94E-08
	Winter	4.01E-17	1.74E-10	2.20E-05	1.47E-11	8.92E-09
Large	Summer	1.54E-13	1.98E-10	4.60E-06	1.75E-11	1.93E-08
	Winter	1.85E-13	1.58E-08	2.94E-05	1.02E-10	2.54E-08

distribution for the most port and starboard corners, respectively. The data is acquired from the large-size container ships berthing at WD in winter at the crossing-line of the entrance. For the most port corner, Fig. 16(a), the means of the lateral positions μ_y and the heading angle μ_β are -14.4 and 8.0, respectively. The standard deviations of the lateral position σ_y and the heading from reference-line σ_β are 25.6 and 5.0, respectively. The correlation coefficient ρ is -0.13. For the most starboard corner, as shown in Fig.16(b), the means of the lateral positions μ_y and the heading angle μ_β are 36.8 and 8.0, respectively. The standard deviations of the lateral position σ_y and the heading from leading-line σ_β are 24.7 and 5.2, respectively. The correlation coefficient ρ is -0.11.

Tables 6-8 show the PC of inbound container ships at the head of the east breakwater, the entrance, and the inner breakwater for the ships berthing at IH, W19 and WD, respectively. Eqs. (11) and (12) evaluate the PC of the starboard and port sides. The results show that the colliding risk is not significant in the area of Keelung Harbour except that of the west breakwater (starboard side) of the entrance where the PC is more evident than the others. The comparison of the results between PPCS and PC shows that the PC at the head of the east breakwater is significantly smaller than PPCS because most ships move towards the reference line when passing through the breakwater head. This reason also leads to a higher PC value on the west breakwater at the entrance. Similar to PPCS, the PC of large-size ships is higher than that of the small size, especially for the large-size ships that berth at the W19 in summer weather conditions. Most of the collision probabilities among the head of the eastern breakwater, the port embankment of the entrance, and the port side of the inner breakwater are less than 10^{-10}, which suggests that these regions are relatively safe for inbound ships.

VII. CONCLUSION

In this study, we extend our previous research methods to study navigation safety in the approaching fairway of Keelung Harbour. The AIS data is acquired according to the factors of mooring dock, ship size and seasonal conditions. A statistical approach is subsequently applied to explore the information of ship navigation. The results show that the mooring dock is the most obvious factor affecting the ship's trajectory and the speed of the inbound ships, followed by the ship size and seasonal conditions. The evaluated colliding risk of the inbound ships with breakwater is quite low which is consistent with the records from the government. The colliding risk is not significant in the area of Keelung port except that of the west breakwater of the entrance where the PC is more evident than the others.

The navigation information obtained from the AIS data is not only useful for early identifications of ship navigation anomalies and maritime surveillance but also for developing a critical knowledge base for the artificial intelligent navigation. The results of the present study, the traffic pattern and ship behaviour model based on the AIS data, will provide VTS or officer of the watch (OOW) with sufficient discriminating knowledge that can be used as a useful reference for regulatory and transportation safety improvement.

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