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Research Article

Research on the Berthing and Unberthing Time Windows for 100000-ton Container Ships at the Luojing Container Terminal

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Abstract

This paper is based on the navigational environment around the Luojing Container Terminal. Five ship traffic flow statistical sections were established in the nearby waters of Luojing Container Terminal, specifically at the Liuhekou caution zone, Buoy No. 81 of the Baoshan North Channel, the Baoshan caution zone, Buoy No.A79, and Buoy No.A81. The study conducted a statistical analysis of the ship traffic flow in the waters near the Luojing Container Terminal and compared these statistics with the tidal conditions of the area. By analyzing the hourly relationship between the ship traffic flow at the forefront of the Luojing Container Terminal and the tidal levels, it was concluded that the ship traffic flow reaches its peak during the period from 2 hours before to half an hour after the Wusong low tide. During this time frame, the safety risks for container ships docking and undocking at the Luojing Container Terminal are significantly increased. Based on the simulated maneuvering tests for docking and undocking of 100,000-ton container ships conducted during the construction of the Luojing Container Terminal, it was determined that the time window for docking and undocking 100,000-ton container ships at the Luojing Container Terminal is available at all times except from 2 hours before to half an hour after the Wusong low tide. The findings of this research can provide technical support for enhancing the operational efficiency and safety management standards of Luojing Container Terminal.

Keywords

Luojing Container Terminal,100,000-Ton Container Ship, Traffic Flow, Tide, Berthing/Unberthing Time Windows

1. Introduction

The Luojing container terminal is situated on the southern shore of the Yangtze River estuary, adjacent to the Baoshan South Channel. It is located in the narrowest part of the approaching waters of Shanghai Port's 100,000-ton container terminal. Due to the large size of 100,000-ton container ships, which have long surge distances, stopping distances, and large turning radii, their maneuvering is challenging [1]. Additionally, the Baoshan South Channel and nearby waterways experience high vessel traffic with numerous intersecting traffic flows [2]. Conducting research on the traffic flow conditions in the front waters of the Luojing container terminal and extending the berthing and unberthing time windows for container ships based on the traffic flow situation at the terminal front is of significant practical importance. This

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will help ensure the safety of ship berthing and unberthing, enhance navigational safety in related waters, and improve port operational efficiency.

Marine traffic flow effectively reflects the overall state of vessel movements within a specific time and space. Analyzing and predicting the traffic flow in busy waterways not only provides a scientific basis for the management and allocation of resources in channels and ports but also assists maritime authorities in obtaining accurate and efficient dynamic information about the entire temporal and spatial distribution of waterways. This supports vessel scheduling and command, enhances navigation efficiency, and aids in the planning of port waters [3]. Chen Ning et al. utilized ArcGIS to generate the AIS trajectory map of ships in the Qiongzhou Strait waters on January 19, 2023, analyzing the traffic flow structure and characteristic parameters of the area. They constructed a simulation model for ship crossing collisions from Xinhaigang to Xuwengang using Arena, and through simulation, identified the time periods with higher collision probability between ro-ro passenger ships and crossing ships [4]. Wang Jinzhao, focusing on the current state of ship traffic flow in the Jiangsu section of the Yangtze River, conducted an in-depth analysis of the reasons behind the current situation and proposed measures for the regulation and control of ship traffic flow [5]. Jia Xiaofei et al., using traffic flow data and composition analysis from traffic control departments, combined with currently applicable traffic control regulations, explored safe navigation operations in warning zones from a regulatory perspective and provided suggestions for organizing traffic flow and maneuvering for collision avoidance in and around warning zones [6]. Li Zhenfu, based on AIS data from the Arctic Northeast Route in 2020, used a GIS spatial analysis platform and traffic flow theory to analyze the temporal characteristics (daily, monthly, and seasonal) and spatial characteristics (ship density and speed) of ship traffic flow on the Northeast Route [7]. Kim J K conducted semi-continuous spatial statistical analysis tests (the normal distribution test, kurtosis test, and skewness test) to reveal the vessel traffic distribution and its characteristics, such as the degree of use and lateral positioning on the fairway, based on the size of the vessel [8]. Choi B, Park Y, Kim N, et al. examined the status of arrivals and departures of vessels in Busan New Port through maritime traffic flow analysis, provided a plan to improve the safety of vessel traffic in the inbound and outbound fairway of Busan New Port, and identified risk factors and safety measures [9]. Liang C presents an analysis and application method of ship traffic flow considering navigation rules in narrow channels based on the on the constraints of navigation safety domain [10]. Jingyao Wang developed a detailed simulation model for the arrival and departure of super-large ships, with a focus on the Ningbo-Zhoushan Port. The model incorporates various special navigation constraints, including berthing and departure time windows, safety separation requirements, tidal limitations, and potential interference from neighboring berths. Based on the simulation results, several improvement measures were proposed to optimize the navigation and operational efficiency of super-large vessels. This research provides valuable insights and practical guidance for the planning, construction, and operation of super-large berths in coastal ports, offering a significant reference for enhancing port management and maritime safety [11].

It is evident that current research on traffic flow, both domestically and internationally, primarily focuses on areas such as ship collision avoidance, risk management, and the analysis of traffic flow characteristics. However, there is relatively little research on the impact of traffic flow in port waters on the time windows for ship berthing and unberthing. With the acceleration of maritime cargo transportation, the density of ship traffic near various port waters is increasing, which in turn raises the risk of accidents during ships' entry, exit, berthing, and unberthing operations. Different ships, considering their own characteristics and the tidal conditions of the port waters, may choose different time windows to enter or leave the port, thus exhibiting certain patterns in the traffic flow of port waters.

The relationship between vessel traffic flow and tidal conditions plays a critical role in the traffic management of container ports. Tidal variations significantly influence the scheduling of large container vessels' arrivals and departures, as high tide periods provide increased water depth, enabling the safe passage of large ships, whereas low tide periods may impose restrictions on their access. By analyzing the correlation between tides and traffic flow, container ports can optimize vessel scheduling, effectively reducing congestion and waiting times, and thereby enhancing overall operational efficiency. Furthermore, the integration of tidal data into dynamic management systems helps mitigate navigation risks, preventing potential incidents such as grounding and collisions.

Therefore, based on a comparative analysis of ship traffic flow during different tidal periods in the waters near the Luojing Container Terminal, this paper aims to identify the distribution characteristics of ship traffic flow in the waters near the terminal and determine the berthing and unberthing time windows for 100,000-ton container ships. This study is expected to provide technical support for enhancing the operational efficiency and safety management standards of the Luojing Container Terminal.

2. Navigational Environment Around the Luojing Container Terminal

2.1. The Channel Conditions Around the Luojing Container Terminal

The waters of the Shanghai section of the Yangtze River encompass multiple inbound and outbound channels, which vary in terms of water depth, width, and navigational function. The shipping routes in this section are consist of main channels, auxiliary channels, small vessel channels, and warning areas. The main channels include the Deepwater Channel of the Yangtze Estuary, the Waigaoqiao Channel, the Baoshan Channel, the North Baoshan Channel, and the South Baoshan Channel. The Luojing Container Terminal is adjacent to the South Baoshan Channel, which stretches from the western boundary of the Baoshan Warning Area to the eastern boundary of the Liuhekou Warning Area. To the north lie the South Baoshan Anchorage, the North Baoshan Channel, and the North Baoshan Anchorage. Both the South and North Baoshan Channels are currently navigable for vessels of 50,000 DWT and above. The South Baoshan Channel has a width of 450 to 700 meters and a natural depth of over 10.4 meters, while the North Baoshan Channel, which has a width of 350 to 460 meters, is an extension of the Deepwater Channel of the Yangtze Estuary and has a water depth of approximately 12.5 meters. This is illustrated in Figure 1.

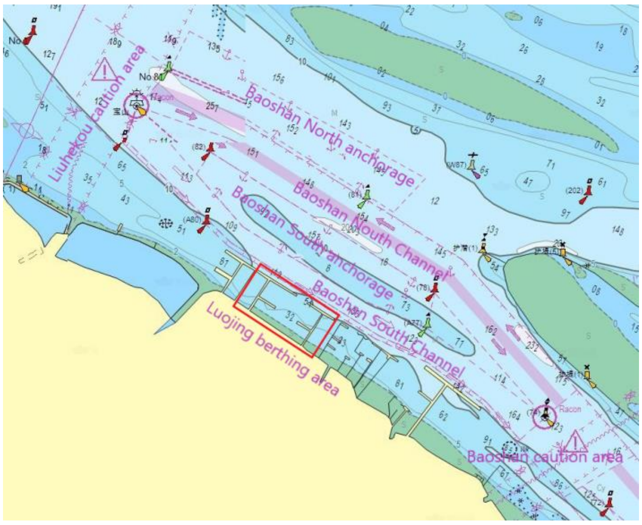

Figure 1. *Schematic Diagram of the Navigational Channels around the Luojing Container Terminal.*

2.2. Vessel Maneuvering Conditions in the Waters of the Luojing Container Terminal

The Luojing Container Terminal is consist of four 100,000-ton-class container berths. The berthing area at the front of the wharf is 91.5 meters wide, with charted depths ranging between 12 and 14 meters. The distance from the wharf front to the northern boundary of the Baoshan South Channel is approximately 650 meters. The turning areas are situated in front of the wharf, arranged in an elliptical shape, with a long axis of 865 meters parallel the direction of the water flow and a short axis of 554 meters perpendicular to the flow direction, as illustrated in Figure 2.

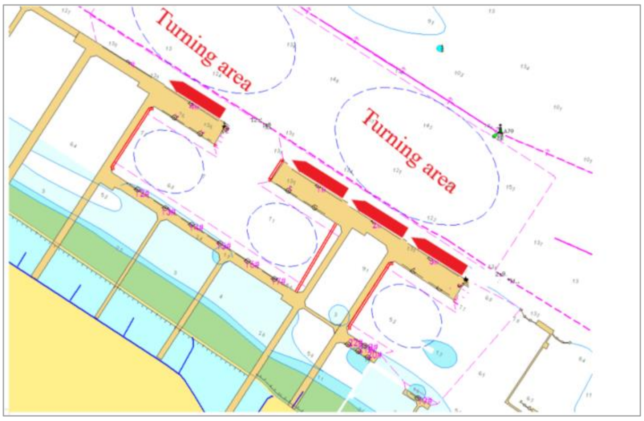

Figure 2. *Diagram of Ship Maneuvering Area in the Luojing Container Terminal.*

2.3. Traffic Flow at the Berth Front of Luojing Container Terminal

Vessel traffic flow refers to the number of vessels passing through a specific point, cross-section, or traffic route within a unit of time. It is one of the three fundamental parameters of traffic flow and one of the most important parameters for describing traffic flow characteristics. The magnitude of traffic flow directly reflects the traffic volume of the traffic route and, to some extent, indicates the level of congestion and risk among the vessels within that route [12]. The statistical model is as follows:

$$\bar{Q} = \sum_{i=1}^{n} Q_i / n$$

In the formula:

$\bar{Q}$ represents the average vessel traffic volume within a certain period;

Q_i represents the traffic volume at a specific moment;

n represents time.

In this study, the AIS system was utilized to statistically analyze vessel traffic flow. However, it is important to note that during the statistical process, factors such as incomplete coverage of AIS equipment on vessels, signal loss or interference, and incorrect initial settings of some vessels' AIS systems may cause deviations between the statistical data and actual vessel traffic flow. To ensure the accuracy of the statistical data, this research fully incorporated radar observation data from the local VTS, thus providing a more accurate representation of the vessel traffic flow at the time.

2.3.1. Vessel Traffic Flow Observation Location

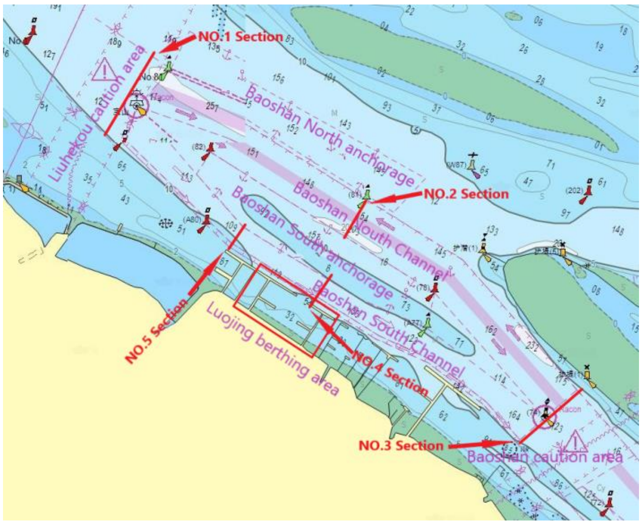

Figure 3. *Schematic Diagram of Vessel Traffic Flow Observation Locations.*

To thoroughly analyze the vessel traffic flow conditions in the Luojing Container Terminal, five vessel traffic flow statistical cross-sections were established based on AIS (Automatic Identification System). These cross-sections are located in the following areas near the Luojing Container Terminal: the Liuhekou warning area, Buoy No.81 in the Baoshan North Channel, the Baoshan warning area, Buoy No.A79, and Buoy No.A81. The locations of these vessel traffic flow statistical cross-sections are illustrated in Figure 3.

2.3.2. Vessel Traffic Volume Statistical Results

The vessel types included in this statistical analysis include all ships passing through the observation cross-sections, such as cargo ships, passenger ships, dangerous goods carriers, fishing boats, engineering ships, and work boats. The vessels are primarily categorized by their overall length, and the statistical period spans from January 1, 2021, to December 31, 2021. Based on the observed vessel traffic data, the total vessel traffic volume at each observation cross-section, the traffic volume of vessels of different lengths, and the traffic volume of different vessel types are illustrated in Figures 4 to 6.

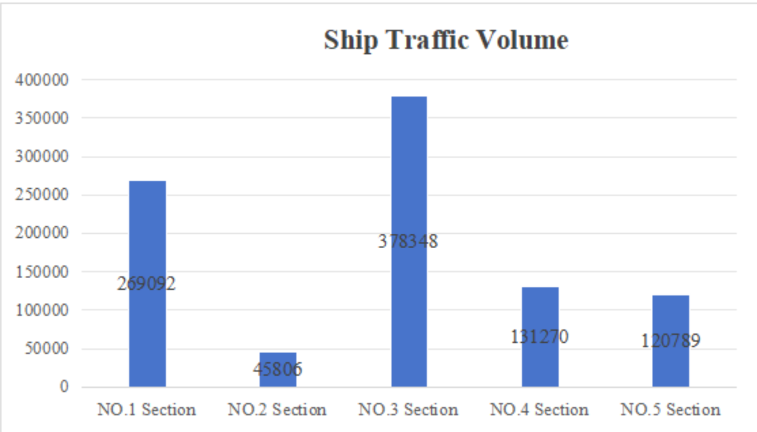

Figure 4. *Total Vessel Traffic Volume at Each observation cross-section.*

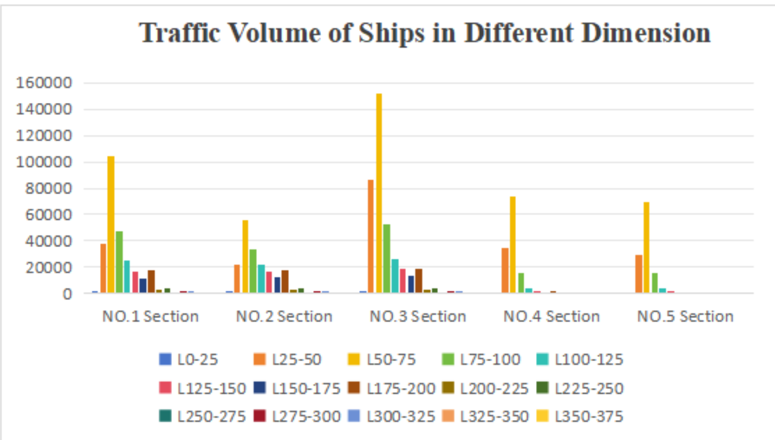

Figure 5. *Traffic Volume of Vessels by Length.*

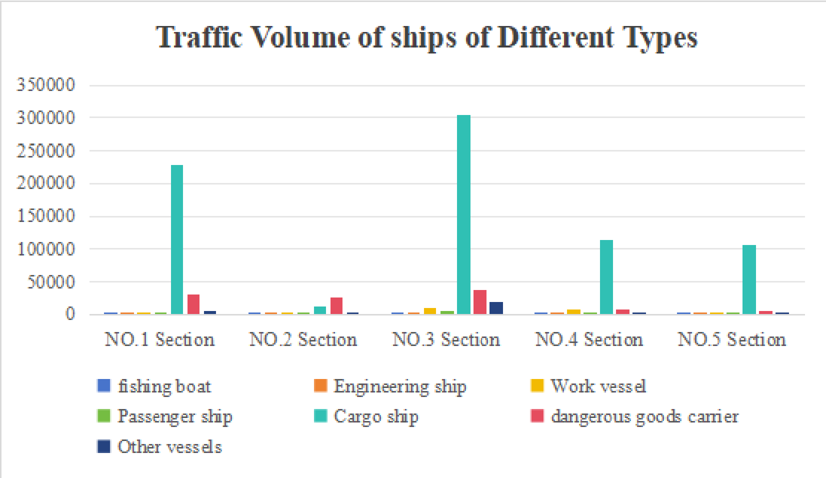

Figure 6*. Traffic Volume of Different Vessel Types.*

From Figures 4 to 6, it can be observed that cargo ships account for the largest proportion when categorized by vessel type. When classified by vessel length in intervals of 25 meters, vessels with lengths between 50 meters and 75 meters are the most prevalent. Among vessels exceeding 100 meters in length, those between 100 meters and 125 meters are the most numerous.

To further analyze the impact of vessel traffic flow on the berthing and unberthing of container ships in the Luojing Container terminal, the traffic volumes of vessels passing through the No.4 cross-section (No.A79 buoy) and the No.5 cross-section (No.A81 buoy) were statistically analyzed. The results are presented in Tables 1 to 4.

Table 1*. Vessel Traffic Volume Observation Statistics for Cross-Section No.4.*

LOA	Fishing Boats	Engineering Ships	Work Boats	Passenger Ships	Cargo Ships	Dangerous Goods Carriers	Other Vessels	Inbound Vessels	Outbound Vessels	Total
L0-25	54	30	678	117	352	15	76	331	991	1322
L25-50	613	455	5690	33	23848	2676	1106	4579	29842	34421
L50-75	381	113	142	94	68474	2226	2022	3563	69889	73452
L75-100	0	18	74	60	14224	702	833	850	15061	15911
L100-125	0	19	2	0	3992	71	100	201	3983	4184
L125-150	0	0	2	0	994	0	31	318	709	1027
L150-175	0	0	0	0	248	3	37	121	167	288
L175-200	0	0	1	6	504	3	14	236	292	528
L200-225	0	2	0	0	109	0	0	59	52	111
L225-250	0	0	0	0	14	0	3	6	11	17
L250-275	0	0	0	0	1	0	0	1	0	1
L275-300	0	0	0	0	6	0	0	3	3	6
L300-325	0	0	0	0	2	0	0	1	1	2

Table 2. *Vessel Type Proportion Statistics for Cross-Section No.4.*

Type	Fishing Boats	Engineering Ships	Work Boats	Passenger Ships	Cargo Ships	Dangerous Goods Carriers	Other Vessels	Inbound Vessels	Outbound Vessels	Total
Volume	1048	637	6589	310	112768	5696	4222	10269	121001	131270
Proportion	0.80	0.49	5.02	0.24	85.91	4.34	3.22	7.82	92.18	100.00

Table 3. *Vessel Traffic Volume Observation Statistics for Cross-Section No.5.*

LOA	Fishing Boats	Engineering Ships	Work Boats	Passenger Ships	Cargo Ships	Dangerous Goods Carriers	Other Vessels	Inbound Vessels	Outbound Vessels	Total
L0-25	55	27	609	29	314	83	13	296	834	1130
L25-50	570	385	2938	26	21759	2577	642	4302	24595	28897
L50-75	367	87	98	81	65252	2334	1463	5991	63691	69682
L75-100	0	18	75	58	14170	933	337	861	14730	15591
L100-125	0	18	2	0	3953	89	54	206	3910	4116
L125-150	0	0	2	0	953	4	16	303	672	975
L150-175	0	0	0	0	204	4	29	100	137	237
L175-200	0	0	0	9	113	1	13	38	98	136
L200-225	0	0	0	0	16	0	0	11	5	16
L225-250	0	0	0	0	1	0	3	2	2	4
L250-275	0	0	0	0	1	0	0	1	1	2
L275-300	0	0	0	0	2	0	0	1	1	2
L300-325	0	0	0	0	2	0	0	1	1	2

Table 4. *Vessel Type Proportion Statistics for Cross-Section No.5.*

Type	Fishing Boats	Engineering Ships	Work Boats	Passenger Ships	Cargo Ships	Dangerous Goods Carriers	Other Vessels	Inbound Vessels	Outbound Vessels	Total
Volume	992	535	3724	203	106740	6025	2570	12111	108678	120789
Proportion	0.82	0.44	3.08	0.17	88.37	4.99	2.13	10.03	89.97	100.00

According to Article 11 of the *Regulations on the Ship Routing System in the Shanghai Section of the Yangtze River*. Large vessels traveling from the Jiangsu section of the Yangtze River towards the Yangtze River Estuary shall proceed downstream via the Baoshan North Channel after passing through the Liuhekou warning area. Vessels berthing at or departing from the Baoshan coastal terminals, proceeding downstream to enter the Huangpu River, or intending to berth at the Waigaoqiao coastal terminals may use the Baoshan South Channel [13].

The term "large vessels" specified here refers to ships of 3,000 gross tonnage or above. However, based on common practices among crew members, outbound ocean-going ships generally proceed via the Baoshan North Channel and outbound river vessels typically use the Baoshan South Channel regardless of their tonnage. In other words, for inbound vessels, regardless of size, both river vessels and ocean-going ships (except those berthing at Baoshan) use the Baoshan North Channel. For outbound vessels, ocean-going ships primarily use the Baoshan North Channel, while river vessels and vessels berthing at Baoshan exit via the Baoshan South Channel. From the above statistics, it can be observed that the traffic volume of inbound vessels using the Baoshan South Channel is significantly lower than that of outbound vessels, with the majority being cargo ships under 75 meters in length.

3. Tidal Characteristics of Luojing Container Terminal Waters

To accurately measure the hydrological conditions of the Luojing Container Terminal, a temporary tidal gauge station was established in the waters near the berth frontage (Latitude: 31°29'57.562"N, Longitude: 121°22'45.293"E), as shown in Figure 7.

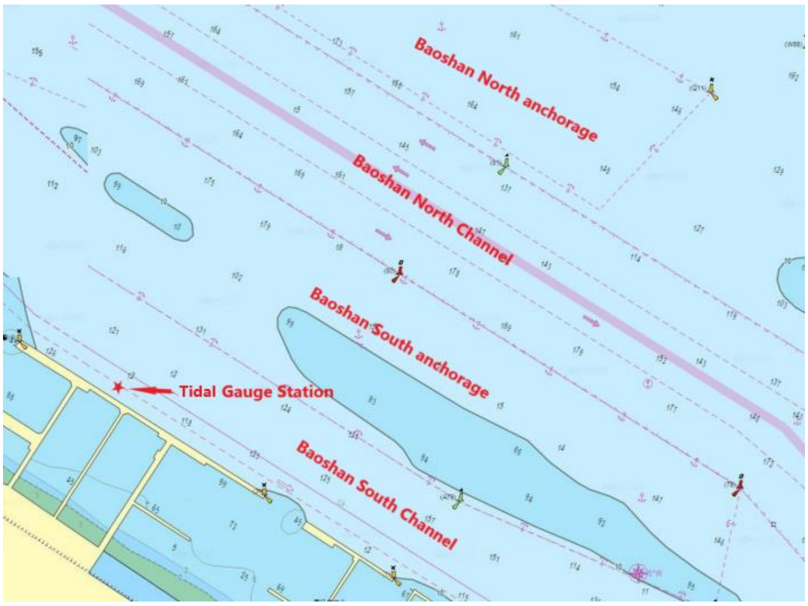

Figure 7. Temporary Tidal Gauge Station.

The temporary tidal gauge station collected hydrological data from May 28, 2022, to June 29, 2022, in the waters near the Luojing operational area. Based on the measured tidal level data, the tidal characteristics are summarized as shown in Table 5.

Table 5. Characteristic Value Statistics of Temporary Tidal Gauge Station.

Characteristics	Max. HW	Min. LW	Mean HW	Mean LW	Max. ranges	Min. ranges	Mean ranges	Mean Flood Duration	Mean Ebb Duration
Value	4.61m	0.95m	3.48m	1.36m	3.57m	0.90	2.11m	4h45m	7h38m

The Luojing Container Terminal is situated in the estuary section of the Yangtze River, where the water flow is significantly influenced by tides. This area experiences an irregular semi-diurnal tide, characterized by two high tides and two low tides each day, with a noticeable diurnal inequality. Typically, the flood tide duration is approximately 4 hours 45 minutes, while the ebb tide duration is approximately 7 hours 38 minutes. The tidal current movement follows a reciprocating flow pattern, with the main direction gener [14] ally aligned along the NW-SE axis. In the channel near the berth front, the ebb current velocity exceeds the flood current velocity. The maximum flood current velocity reaches about 1.5 m/s, and usually occurs around 1 hour before local high tide. The maximum ebb current velocity reaches 2 m/s, and usually occurs around 4 hours after local high tide. The flood current direction near the berth front generally ranges from 305° to 315°, while the ebb current flows in the opposite direction.

4. Analysis of Berthing and Unberthing Time Windows at Luojing Container Terminal

4.1. Hourly Relationship Analysis Between Vessel Traffic Flow and Tide Levels at Luojing Container Terminal

In narrow channels or busy port area, traffic congestion significantly increases the risk of collisions, while the size and maneuvering behavior of different vessels also play a critical role in maritime safety. Large vessels, due to their substantial size and limited maneuverability, are more susceptible to collisions or grounding in confined or congested waterways. In contrast, small vessels are highly vulnerable to wind and wave conditions and have limited collision-avoidance capabilities, further elevating the risk of accidents. Moreover, irregular maneuvering behaviors, such as non-compliance with navigation rules or improper operations, exacerbate safety risks. To address these challenges, it is essential to mitigate safety hazards arising from varying vessel characteristics by implementing intelligent traffic management systems and optimizing navigation rules. By analyzing the relationship between tides and traffic flow, navigation patterns of vessels in specific waters during different time periods can be identified. This enables large vessels to plan and select optimal time windows for berthing and unberthing operations, thereby reducing the risk of accidents and improving operational safety.

To thoroughly analyze the correlation between the peak periods of vessel traffic at the berths of Luojing Container Terminal and tidal conditions, a vessel traffic flow statistical cross-section was established at the berths of Luojing Container Terminal with AIS (Automatic Identification System). This system recorded the precise times at which vessels passed through the cross-section, with the statistical period spanning from January 1, 2021, to December 31, 2021. Subsequently, traffic flow data from a consecutive 10-day period was selected and statistically compared with the corresponding tidal conditions, as shown in Figure 8.

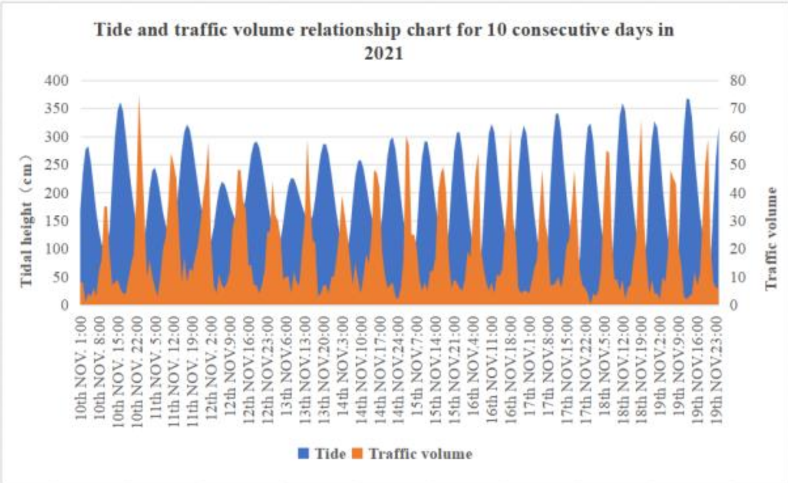

Figure 8. Tide and traffic volume relationship chart for 10 consecutive days in 2021.

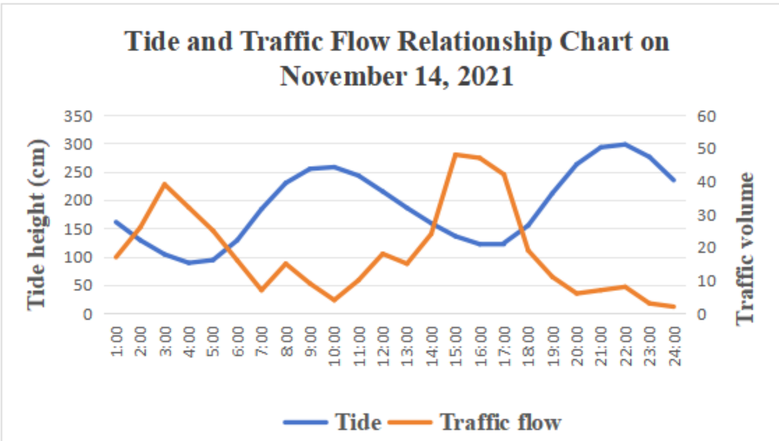

Figure 9. Tide and Traffic Flow Relationship Chart on November 14, 2021.

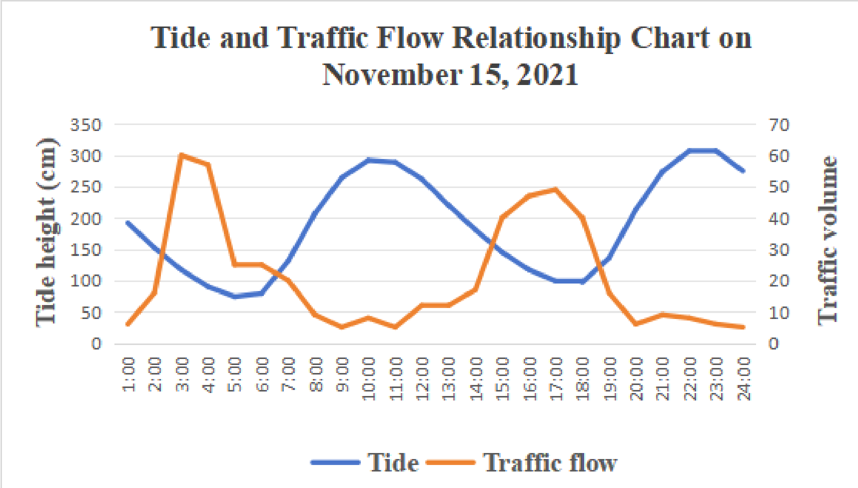

Figure 10. Tide and Traffic Flow Relationship Chart on November 15, 2021.

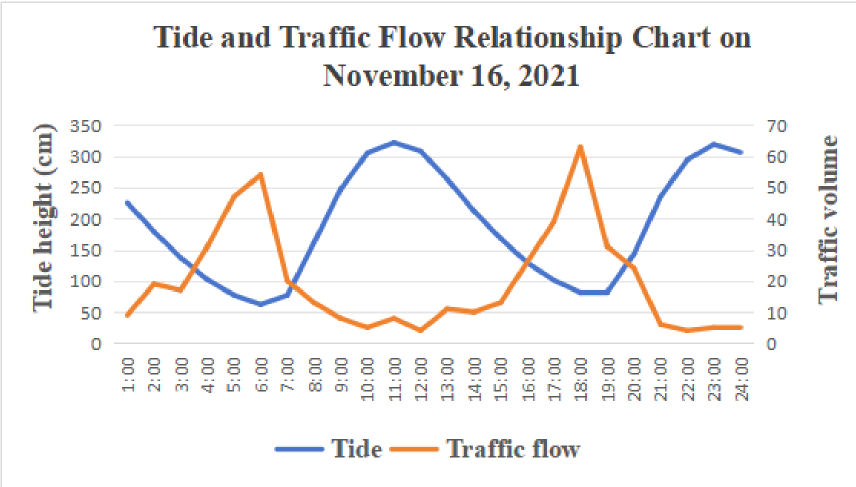

Figure 11. Tide and Traffic Flow Relationship Chart on November 16, 2021.

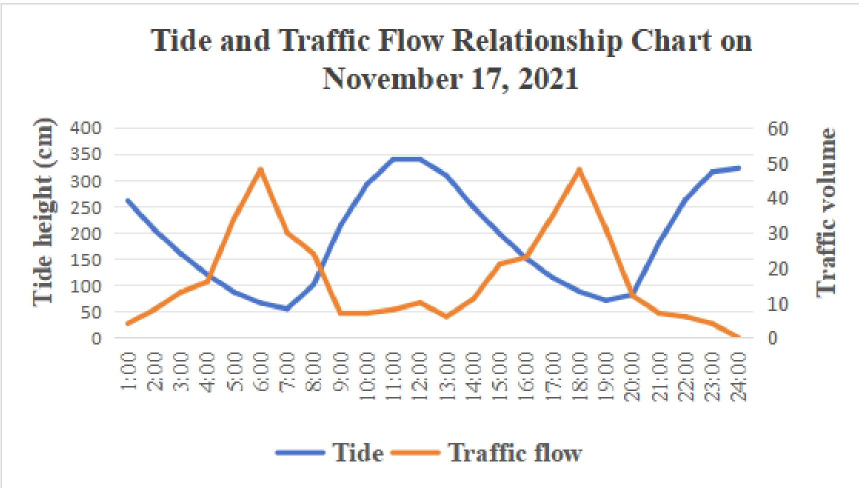

Figure 12. Tide and Traffic Flow Relationship Chart on November 17, 2021.

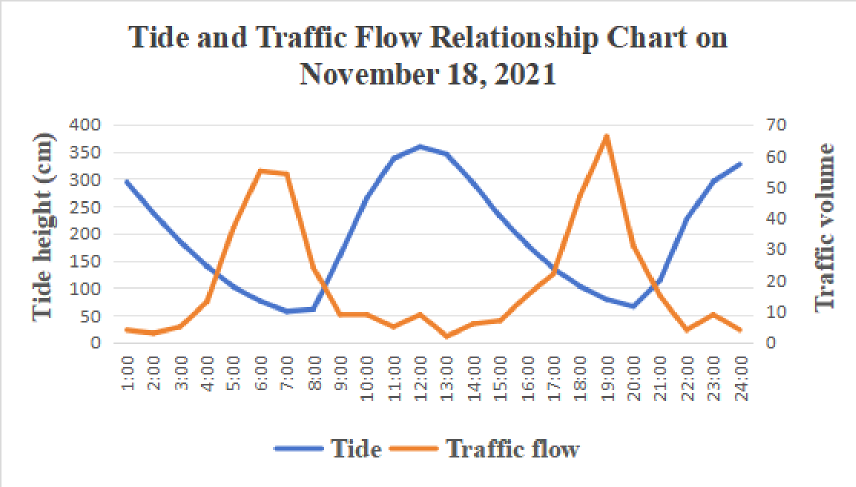

Figure 13. *Tide and Traffic Flow Relationship Chart on November 18, 2021.*

Through comparative analysis of vessel traffic flow and tidal conditions in the statistical data of Luojing Container Terminal, it was observed that vessel traffic begins to increase 3 hours before Wusong low tide and decreases until 1 hour after Wusong low tide. Specifically, the peak period of vessel traffic flow occurs on average between 2 hours before and half an hour after Wusong low tide. This peak period significantly impacts the berthing and unberthing operations of vessels in the waters of Luojing Container Terminal.

Figure 14. *Vessel Traffic Conditions in front of the Berths of Luojing Container Terminal During Peak Periods.*

The Baoshan South Channel does not have a traffic separation scheme, and downstream vessels generally navigate along the shoreline. As analyzed in Section 2.3, the majority of vessels passing through the berths of Luojing Container Terminal are outbound accounting for 90%. Among the outbound vessels, the vast majority are small cargo ships with a length of less than 75 meters accounting for 95%. Medium and small-sized vessels exiting from the Jiangsu section of the Yangtze River often choose to navigate through the Baoshan South Channel. Large outbound vessels departing from the Baoshan South Channel also select this route. Ferry vessels typically cross the Baoshan South Channel on the eastern side of the Baoshan South Anchorage [15]. The southern side of the Baoshan South Channel is lined with numerous berths, while the northern side is occupied by the Baoshan South Anchorage, where vessels frequently anchor to wait for berths or tides. During peak traffic periods, it is common to see multiple vessels navigating side by side, with overtaking maneuvers occurring frequently, resulting in a wider use of the channel, as shown in Figure 14. During these times, the safety risks for container ships crossing the Baoshan South Channel to berth or depart from Luojing Container Terminal are significantly heightened.

4.2. Berthing and Unberthing Time Windows for 100,000-ton Container Ships at Luojing Container Terminal

According to the simulated maneuvering test results for the berthing and unberthing of 100,000-ton container ships during the construction of the Luojing Container Terminal, the terminal's parameters, including its length, width, and depth, meet the corresponding size and draft requirements of the vessels. Under various adverse wind, wave, and current conditions, when the wind force reaches Beaufort scale 7, the 100,000-ton container ships can safely conduct berthing and unberthing operations with the assistance of four tugs, each with a power output of 3000 KW. However, when the wind force increases to Beaufort scale 8 or above, more than four tugs of the same power are required for these operations, but the associated risks are significantly higher. Therefore, the operational limits for wind and wave conditions during berthing and unberthing at Luojing Container Terminal are established as maximum wind force of Beaufort scale 7 and wave height of 4 meters, ensuring the safety and efficiency of port operations while mitigating potential hazards.

Based on the hourly correlation analysis between vessel traffic flow and tide levels at Luojing Container Terminal, as well as the simulated maneuvering test results for the berthing and unberthing of 100,000-ton container ships, the berthing and unberthing Time windows for 100,000-ton container ships at Luojing Container Terminal can be determined: When the wind force is less than Beaufort scale 8 and the wave height is below 4 meters, operations can be conducted at any time except during the period from 2 hours before to half an hour after Wusong low tide.

5. Conclusion

The determination of the time windows for vessel berthing and unberthing requires comprehensive consideration of various factors, including meteorological and hydrological conditions (such as wind speed, wind direction, currents, tides, and other natural elements), vessel traffic flow, and ship scheduling. Through reasonable planning and communication, this ensures that berthing and unberthing operations are conducted safely and efficiently. Once the feasibility of vessel berthing and unberthing under different meteorological and hydrological conditions is determined, studying the vessel traffic flow at the berths is significantly important for defining the time windows:

1) Understanding the traffic flow conditions at the berths enables ports to utilize resources more effectively. If traffic flow is heavy during certain periods, the timing of vessel berthing and unberthing can be adjusted to avoid congestion, thereby improving the overall throughput of the port.
2) It helps identify potential safety risks. By reasonably arranging the timing of vessel berthing and unberthing, the risk of collisions between vessels can be reduced, ensuring the safety of port operations.
3) Accurate prediction of the timing of berthing and unberthing helps minimize unnecessary delays, improve the operational efficiency of vessels, and reduce associated costs.

Abbreviations

VTS	Vessel Traffic Service
AIS	Automatic Identification System
GIS	Geographic Information System
DWT	Deadweight Tons
No.	Number
KW	Kilowatt

Conflicts of Interest

The authors declare no conflicts of interest.

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