Safety Assessment of Multi-Ships Entering and Berthing with Full Consideration of Real Navigation Environment in Complex Waters

Fuquan Fan, Ronghua Guo, Deling Wang*, Hejun Geng, Xiaobin Jiang

Merchant Marine College, Shanghai Maritime University, Shanghai, China

Email address:
fanfq@shmtu.edu.cn (Fuquan Fan), rhguo@shmtu.edu.cn (Ronghua Guo), dlwang@shmtu.edu.cn (Deling Wang),
genghj@shmtu.edu.cn (Hejun Geng), xbjiang@shmtu.edu.cn (Xiaobin Jiang)
*Corresponding author

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Abstract: NB port has proposed to build a new NBGB terminal for production needs. The navigational environment of NB port is complex, and the ships between adjacent terminals have obvious influence on each other when entering and berthing. In order to verify the feasibility of the proposed terminal's design vessel type entering and berthing, to fully reflect the influence of human factors on the vessel entering and berthing, and to be closer to the real situation of the proposed terminal's later operation, this paper simulates the ships entering and berthing maneuvering at NBGB terminal by using a large ship maneuvering simulator. Based on the real data of port navigation environment, port regulations, traffic density and so on. The simulation test simulates the real scenario of ships entering and berthing maneuvering and simulates the actual situation of the proposed terminal to the maximum extent, and at the same time, considering the mutual influence of ships maneuvering at adjacent berths, the simulation test of multi-ships berthing is carried out simultaneously. It can be demonstrated through simulation tests that the ships entering and berthing operations at adjacent berths during the same window period have little influence on the ships operations at NBGB terminal. Through the analysis of the test results, the rationalization suggestions for the orderly entry and exit of ships in complex waters are proposed, which can provide technical support for the assessment of navigational safety risks and the formulation of traffic organization plans for the entry and exit of ships in the project waters and enhance the safety and security measures and port management level.

Keywords: Complex Waters, Ship Handling, Simulation, Risk Assessment, Safety

1. Introduction

With the development of the global economy, maritime transportation has become increasingly busy, and the throughput of ports around the world has increased dramatically. In order to meet the needs of economic development, the ports continue to invest in large-scale engineering construction, making the navigational environment of port waters become complex, navigational safety issues continue to increase. In addition, the number and types of ships entering and leaving the port have increased, and the tonnage of ships has become larger, which makes it more difficult for ships maneuvering in the port waters, the possibility and damage of marine traffic accidents have increased, and the deteriorating navigation environment has eventually led to the frequent occurrence of marine traffic accidents in port waters, which seriously endangers the safety of ships and human lives, and also destroys the sustainable development of the port economy [1]. In order to change this situation, in addition to meeting the requirements of the “Design Code of General Layout for Sea Ports” [2] for port site selection, whether the design fairway and turnaround area and berth of the new port actually meet the design vessel type also requires conducting navigation safety simulation tests on a highly simulated ship handling simulator, evaluate and analyze the results to verify the feasibility of fairway design or
terminal modification project. At present, a number of professionals have conducted studies for specific terminal ship simulation maneuvering tests and proposed reasonable safety measures for entering and leaving the port. However, in most simulation tests, ships near the proposed terminal or routes all navigate follow the established routes, and the influences of ships maneuvering at adjacent berths are not considered, these influences are often the main reasons for maritime accidents.

In order to improve the consistency between the ships maneuvering studies and the actual situation, and to enhance the navigational safety of the proposed terminal, this paper fully considers the real situation of all aspects of the proposed terminal, including the hydro-meteorology of the terminal, the port management regulations, the traffic flow situation, the mutual influence of ships entering and leaving the port at the same time from the neighboring terminals, and the technical level and safety operation awareness of the operators, etc., the ships maneuvering simulation tests maximize the simulation of the actual navigation environment after the completion of the terminal. This study provides a practical and reliable test basis for the safe entering and leaving of ships at the proposed terminal and the formulation of management regulations by the competent authority for the waters under its jurisdiction, and puts forward reasonable suggestions.

2. Characteristics of Complex Waters and Ships Navigation

Usually, ice areas, island areas, polar areas, shallow water areas, narrow waterways and other waters are regarded as complex waters for ships navigation, which are mainly characterized by: (1) Geological conditions such as dangerous beaches and unstable sloping banks; (2) The busy flow of traffic formed by the rivers in a crisscross pattern and their mutual interference; (3) Complex Hydro-meteorological conditions; (4) The presence of bridges and piers on the surface, shallows and reefs underwater and so on. [3].

According to the navigation practice, it is known that the ships navigation characteristics in complex waters of the port are often manifested in the following aspects:

1) In terms of hydro-meteorology, wind, rain, fog and other adverse weather conditions as well as currents and waves will have an impact on the ships navigation, and the ports set different navigational time periods to ensure the safety of ships navigation according to their respective tidal characteristics. Different types and tonnage of ships have different navigational time periods according to the tides and current conditions in different port areas [4].

2) In terms of ships traffic flow, the situation is complicated by high traffic density, many types of vessels, and vessels crossing the main channel from time to time.

3) In terms of channel conditions, some waters have curved channels, frequent turns, large changes in water depth and currents, and more navigational hazards especially change course correctly under the influence of wind currents to keep the ship on the established route, make ship maneuvering more difficult [5].

4) The maneuvering operations of ships in adjacent berths affect each other due to same time window, which results in low efficiency of ships entering and leaving operations.

For the characteristics of complex waters and ships navigation, it is necessary to use a high simulation ship maneuvering simulator to simulate the design ship in the virtual design channel for navigation and berthing test before the construction of the new terminal to ensure the safe operation of the new terminal and improve the economic efficiency of the port, which is a more effective method than the actual ship verification. Real-time ship navigation safety simulation using a ship handling simulator can not only enhance ship navigation safety, predict navigation risk, reduce engineering test cost, and reduce unnecessary economic loss, but also help optimize channel engineering design, improve the economic efficiency and competitiveness of the port, discover the potential of port berths, and utilize the actual berthing capacity of the port fully [6]. This paper takes the ships entering and berthing maneuvering simulation test of NBGB terminal as an example to introduce how to properly use the large ship maneuvering simulator to assess the safety risks of the new terminal's entering and berthing operations, and put forward rationalized suggestions for port management.

3. Simulation Test Notes

The ultimate goal of the ship maneuvering simulation test is to prevent the occurrence of accidents at sea. There are three main factors in the occurrence of marine accidents: ship design, environment and traffic regulations [7]. How to conduct the ship maneuvering simulation test in complex waters to maximize the true reflection of the actual navigation environment of the waters and reduce the safety risks of ships operation in the waters, the test needs to pay attention to the following issues:

1) The simulated environment should be as close as possible to the actual navigational environment. The realism of simulations does not only depend on the accuracy of the mathematical models which describe the manoeuvring behaviour of ships, but also to a great extent, on how the Hydro-meteorological conditions and their effects on ships are modeled [8]. If the ship maneuvering simulator wants to get a good application effect in the work of ship operation risk identification, the staff is required to collect the test information related to the ship maneuvering test waters in advance, such as clarifying the Hydro-meteorological conditions around the test waters and the problems of electronic chart preparation. And on this basis, the collected information is automatically input into the navigation simulator to provide the preparation
conditions for the subsequent construction of the simulation environment [9].

(2) The ship traffic environment given in the simulation process should be as close as possible to the actual ship traffic in the investigated waters. Each port authority will set different navigation regulations for the waters under its jurisdiction according to the actual situation, and the staff should set the target ships according to the corresponding regulations and the actual navigation density of the waters to truly reflect the influence of the passing ships on the test ships entering and leaving the port.

(3) According to the actual situation of the proposed terminal, including berthing vessel type and port tug configuration, establish the model database of the required vessel, input detailed information of the actual vessel, create the database model, test the error between the simulation data and the actual vessel data through debugging data, and get a more accurate vessel model [10].

(4) The ship maneuvering simulation test of the proposed terminal should reflect the impact of other ships operation of the nearby built or planned terminals on ships operation at this terminal. As most ports choosing the same time window for ships entry and exit, ships can enter and exit in order according to the relevant regulations of the competent authorities, but during the operations, the different technical levels of operators or different perceptions of safety operations lead to mutual influence of ships at neighboring terminals during entering and exiting operations at the same time. Most current ship maneuvering simulations set ships at other berths in the vicinity of the proposed terminal to a stationary state, which does not reflect this potential safety hazard. If the conditions permit, the neighboring berths should be simulated at the same time according to their own design, which can reflect the mutual influence of ships entry and exit between neighboring berths on the one hand, and reflect the influence of human factors on ships maneuvering more realistically on the other hand.

(5) In order to build the most realistic schemes, simulators should also account for the psychological surroundings that operators’ experience [11]. Combined with the actual ships entering and leaving operation requirements, the personnel involved in the ship maneuvering simulation test must give priority to the personnel with good professional quality, familiar with the relevant ship maneuvering characteristics, the navigational environment and regulations of the test waters, and have actual maneuvering qualifications.

(6) Since the simulation model is generally complex, the simulation test often needs repeated debugging to achieve a satisfactory degree, and it is impossible to succeed at once. For the unreasonable data problems in the test process, the simulation data content can be properly debugged to guarantee the authenticity and accuracy of the simulation environment.

4. NBGB Terminal Ship Maneuvering Simulation Test

The simulation test method mainly includes: forming digital nautical charts of the engineering area that meet the requirements of the simulation test; establishing a simulated ship model that is basically consistent with the designed ship type; designing the simulation test plan according to the wind, current and other external effects and the safety elements of ship maneuvering; implementing the simulation test according to the designed simulation test conditions and recording the simulation-related data; analyzing the simulation test data and its application [12].

4.1. Navigation Simulator Introduction

This ship simulation maneuvering test uses the school's large ship maneuvering simulator. The simulator adopts the design ideas of advanced interactive simulation and high-level architecture, and interconnects the computers of the system. The simulator is fully functional and can completely simulate the operating environment of the ship's bridge, and can be used for advanced maneuvering and pilotage training including in restricted waters, and can provide technical support for research work such as engineering demonstration and maritime analysis in various ways with high simulation accuracy. The performance index of the simulator fully meets the relevant internationally recognized performance standards. Under the guidance of experienced captains, simulated ship maneuvering are conducted and the test results are analyzed to form test reports, which provides scientific basis for the safe entry and exit operations.

Figure 1. Experimental use of the navigation simulator.

4.2. Selection and Modeling of Simulated Ship Types

The actual location of NBGB terminal is close to the shipyard terminal on the west side, NO. 1 chemical terminal and NO. 2 chemical terminal on the east side, and the berthing time window of these three terminals within one hour of the first setting of the local high tide is basically the same as that of the new terminal, in order to verify the mutual influence of the four terminal vessels in the process of entering and berthing during this time window, the following design vessel types were selected for the adjacent berths in this simulation test according to the actual situation of the port:
Mathematical model of ship motion with three degrees of freedom under wind and wave current disturbance based on MMG model [13]:

\[
(m + m_x)u - (m + m_y)v r = F_{XH} + F_{XP} + F_{XR} \\
(m + m_y)v - (m + m_x)u r = F_{YH} + F_{YP} + F_{YR} \\
(I_{zz} + J_{zz}) r = M_{H} + M_{P} + M_{R}
\]  

(1)

In the formula, \( F_X, F_Y, M \) are the ship longitudinal force, transverse force and bow moment; \( u, v \) and \( r \) are the longitudinal velocity, transverse velocity and bow-rocking angular velocity; \( m \) is the hull mass; \( m_x, m_y \) are the additional masses of the ship in the longitudinal and lateral directions; \( I_{zz} \) and \( J_{zz} \) are the hull bow rocking moment of inertia and additional moment of inertia; the subscripts \( H, P, \) and \( R \) indicate viscous fluids, paddles, and rudders.

In this paper, we take the ship type selected for NBGB terminal simulation test as an example, and carry out the gyration test and Z-shaped test based on MMG model, the turning circle diagram of full speed right full rudder gyration test and the "Z-shaped" test diagram are shown in Figure 2 and Figure 3.

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### Table 1. Information of test vessels type.

<table>
<thead>
<tr>
<th>Berth</th>
<th>Ship’s type</th>
<th>DWT</th>
<th>LOA</th>
<th>Breadth</th>
<th>Depth</th>
<th>Draft</th>
</tr>
</thead>
<tbody>
<tr>
<td>NBGB terminal</td>
<td>Bulk carrier</td>
<td>70000t</td>
<td>223m</td>
<td>32.3m</td>
<td>17.9m</td>
<td>12.8m</td>
</tr>
<tr>
<td>Shipyard dock</td>
<td>Barge</td>
<td>10000t</td>
<td>118.8m</td>
<td>28m</td>
<td>7.2m</td>
<td>5.2m</td>
</tr>
<tr>
<td>NO. 1 Chemical terminal</td>
<td>Tanker</td>
<td>50000t</td>
<td>185m</td>
<td>32m</td>
<td>19.1m</td>
<td>13.3m</td>
</tr>
<tr>
<td>NO. 2 Chemical terminal</td>
<td>Tanker</td>
<td>50000t</td>
<td>185m</td>
<td>32m</td>
<td>19.1m</td>
<td>13.3m</td>
</tr>
</tbody>
</table>

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![Figure 2. Turning circle diagram of design ship type full speed right full rudder gyration test.](image)

![Figure 3. "Z-shaped" test diagram of the designed ship.](image)
4.3. Simulation Maneuvering Test Program Design

4.3.1. Berth Introduction

NBGB terminal is a 70,000-ton bulk carrier berth with a length of 315m, the terminal and trestle bridge are arranged in a "7" shape, with the elevation of the mud surface at the front of the terminal ranging from -9m to -11m (85 National Elevation), and the front line is about 320m away from the seawall, with NO. 1 chemical terminal and NO. 2 chemical terminal on the east side and the shipyard terminal on the west side. The layout is shown in Figure 4:

![Figure 4. Perimeter of NBGB terminal.](image)

4.3.2. Navigation

Navigation methods and the navigable environment of the nearby waters: According to the relevant provisions of the “Specification Requirements for Vessel Traffic Organization in NB Port Waters” [14], the simulation test vessels of NBGB Terminal, NO. 1 Chemical Terminal and NO. 2 Chemical Terminal imported from the north side of HM Island, while multiple import and export vessels are added to the north side of HM Island, each vessel navigated strictly in formation with the distance maintained at 0.5 nautical miles, Eastbound (export) vessels are set up between HM Island and ZZ Mountain, no vessels navigated between ZZ Mountain and YG Mountain, and the towing barges of shipyard terminal navigated from QL Anchorage.

Meteorological and current conditions of the navigating water: According to the maximum value of the average current speed and the wind direction which has a great influence on the ship berthing, the wind direction SSW (offshore wind) is selected, with Beaufort wind level 6; Before arriving at HM Island, the current is flood tide, flow direction 281°, flow velocity 1.2 knots; After arriving at Goose Reef, the current is ebb tide, flow direction 088°, flow velocity 1.5 knots.

4.3.3. Berthing

NBGB terminal, NO. 1 chemical terminal and NO. 2 chemical terminal berthing method: two tugs, parallel berthing.
Shipyard dock: main tug and harbor assistance tug, parallel berthing.
Meteorological and current conditions: According to the maximum value of the average current speed and the wind direction which has a great influence on the ship berthing, the wind direction SSW (offshore wind) is selected, with Beaufort wind level 6; The current is ebb tide, flow direction 088°, flow velocity 1.5 knots.

4.4. Simulation Test Process

4.4.1. Simulation Test Operation Mode and Simulation Test Scenario

This test was conducted by four experienced captains who each operated a test vessel in the nautical simulator and docked at the shipyard terminal, NBGB terminal, NO. 1 chemical terminal and NO. 2 chemical terminal at the same time.
The test includes both entering and berthing parts, after 10
tests to verify the interaction between the shipyard terminal, NBGB terminal, NO. 1 chemical terminal and NO. 2 chemical terminal vessels in the process of entering and berthing during the first hour of local high tide, the qualifications and scenarios of the test participants are shown in Table 2 and Figure 5.

Table 2. Qualifications of the participants in the test.

<table>
<thead>
<tr>
<th>terminal</th>
<th>Captain’s Qualifications</th>
<th>Main service vessels</th>
<th>Test vessel type</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shipyard Terminal</td>
<td>15 Years</td>
<td>General cargo vessels, Container vessels</td>
<td>10,000-ton Barge</td>
<td>Several participating test captains have multiple qualifications to enter and exit NB Port waters.</td>
</tr>
<tr>
<td>NBGB Terminal</td>
<td>10 Years</td>
<td>Bulk carriers</td>
<td>70,000-ton Bulk carrier</td>
<td></td>
</tr>
<tr>
<td>NO. 1 Chemical terminal</td>
<td>7 Years</td>
<td>Container vessels</td>
<td>50,000-ton Tanker</td>
<td></td>
</tr>
<tr>
<td>NO. 2 Chemical Terminal</td>
<td>21 Years</td>
<td>Tankers, Container vessels</td>
<td>50,000-ton Tanker</td>
<td></td>
</tr>
</tbody>
</table>

Since the ships of NBGB terminal, NO. 1 chemical terminal and NO. 2 chemical terminal are all imported from the north side of HM Island and need to navigate strictly in formation, considering the possible mutual influence during berthing, the order of the test ships entering the port is NBGB terminal-NO. 1 chemical terminal NO. 2 chemical terminal in this arrangement. The towing barge at QL Anchorage directly entered shipyard terminal after anchor aweigh, and the initial scenario is set as shown in Figure 6.

Figure 5. Test scenario diagram.

Figure 6. Initial scenario setting of the test.
4.4.2. Navigation

During the navigation process, each test vessel strictly complied with "Requirements for Vessel Traffic Organization in NB Harbor Waters" and navigated with caution, especially when crossing the traffic flow, grasped the crossing time, communicated and coordinated with other target vessels in time, and maintained a sufficient safe distance from other ships to pass through, the whole process was safe and stable. As shown in Figure 7 and Figure 8.

Figure 7. Vessels intersection situation near HM Island.

Figure 8. Test vessel crossing traffic flow.
4.4.3. Berthing
When berthing, parallel berthing mode is adopted, and the assistance function of the tugs is fully utilized to control the angle and normal velocity of the ship during berthing. The entire process is safe and stable, as shown in Figures 9, 10, 11, and 12.

Figure 9. Intersection with small boats before berthing.

Figure 10. The situation of the test vessels before berthing.
Figure 11. The situation of the test vessels berthed.

Figure 12. Trajectory of test vessels and target vessels.
4.5. Test Conclusions and Recommendations

4.5.1. Conclusions of Test
(1) Vessels of Shipyard Terminal, NO. 1 Chemical Terminal and NO. 2 Chemical Terminal entering and berthing operations within one hour after Local High Tide have little influence on the berthing operations of vessels at NBGB Terminal during the same period.

(2) As the barge berthed shipyard terminal has no power, it is completely dependent on the assistance of tugs when berthing, which is difficult to operate. NBGB terminal vessels need to pay close attention to the distance from the towing barge during berthing operations, and need to control the vessel's position and speed before arriving at the berth to prevent collision with the barge or the terminal [15].

(3) The implementation of "Requirements for Vessel Traffic Organization in NB Harbor Waters" has optimized the traffic pattern of the waters, and all vessels enter and exit safely and orderly, which largely reduces the potential risks of vessels entering, leaving and berthing operations, especially the prohibition of vessel traffic between ZZ Mountain and YG Mountain, which eliminates the factor of interference by other passing vessels during berthing operations and provides a guarantee for safe berthing operations of vessels.

4.5.2. Recommendations of Test
(1) Based on the previous analysis, the vessels of the adjacent berths should avoid berthing at the same time as far as possible to ensure the safety of ships berthing.

(2) Vessels berthing at NBGB terminal can be arranged in front of vessels berthing at NO. 1 chemical terminal and NO. 2 chemical terminal during inbound formation, which is convenient for adjusting vessel position and berthing angle before berthing. And at the same time, it will not have much influence on vessel berthing operation at NO. 1 chemical terminal and NO. 2 chemical terminal.

5. Conclusion
Recently, simulators have been widely used to develop the skills of manually operating a ship. Their main value is the reliability and realism of the physical processes that are modeled in the system [16]. As the research and development technology of navigation simulators continues to innovate, they are widely used in navigation safety assessment, planning and construction of water-related projects and ship maneuvering scheme design, creating opportunities for the sustainable development of industry safety. When using the ship handling simulator, it is necessary to simulate various sea conditions and navigation environments, input relevant parameters, generate electronic charts, and display the motion graphics of the ships.

In this paper, the ships maneuvering simulation test of NBGB terminal is carried out with full consideration of relevant port regulations and the influence of human factors in actual operations, then the simulation study of ships navigation, berthing and the demonstration, evaluation of navigational safety impact of the proposed ports are carried out to help the navigators to be familiar with the navigational environment of water-related projects in advance, which reduces the risk of actual operation and reduces the economic losses at the same time. In addition, it can make engineering optimization selection according to the problems existing in the simulation test, and provide the basis and important reference data for the design and construction of related projects and the management decision of the shipping management department in the future.

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