A Systematic Simulation Methodology for LNG Ship Operations in Port Waters: A Case Study in Meizhou Bay

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Abstract: With the increment for LNG (liquefied natural gas) demand, LNG carriers are becoming larger in size. The operational safety of the carriers and the associated terminals is increasingly attracting attention. This is particularly true when a large LNG vessel approaches a terminal, requiring a detailed investigation of ship handling in port waters, especially in certain unusual cases. A full mission simulator provides an effective tool for research and training in operations of both port terminals and ships. This paper presents an experimental design methodology of the full mission simulation. The details as to how the simulation is achieved are described, and the simulation strategies applicable to LNG ships are specified. A typical case study is used to demonstrate and verify the proposed design methodology. The proposed methodology of the full mission simulation provides guidance for port safety research, risk evaluation and seafarer training.

Key Words: Liquefied Nature Gas (LNG) Carrier, Full Mission Simulation, Simulation Strategy, Ship Handling, Port Safety.

1. Introduction

With the increasing demand for clean energy (*e.g.* liquefied natural gas (LNG)), many LNG terminals have come into operation in recent years all over the world (Lin *et al*., 2010). Large LNG carriers require high reliability and operational security in ports. For a new port that has no previous history of LNG operations, a complete risk assessment, a clear guidance for ship arrival and a comprehensive emergency plan should be developed. Simulation is the main research method for investigating these requirements, and the full mission simulator is the most powerful tool for these studies and for the training of the pilots and tug masters.

Generally, from the viewpoint of ship movement and control, there are two types of simulation methods for LNG ship handling in ports: autonomous and non-autonomous. The fast-time simulation is a typical autonomous simulation, which can simulate the ship arrival operation. It is relatively inexpensive, and a large number of repetitions of simulation runs can be carried out in a short period of time. However, there are a few disadvantages of this method: a lack of a full behavioural model of the navigators, a difficult verification and a limited set of scenarios. Because the LNG ship handling simulation involves a complex mathematical model of the behaviour of LNG ships, the non-autonomous simulation and the full mission simulation may better be employed.

The full mission simulation is a typical man-in-loop control system. In this type of research, a full mission simulator is very important because the fast-time simulation is impractical and the ship operates under the influence of a number of modelled parameters reflecting the environment in which it operates. These modelled parameters include the sea state, weather conditions, bathymetry and any other external influences that may affect the behaviour of the vessel (SIGTTO, 2010).

With the rapid development of information and modelling technology, the full mission simulator has become quite realistic; in particular, shipborne integrated navigation systems have been installed in some simulators. The precise mathematical model generates the ship motion, and the environmental data drives the integrated navigation system by simulating the sensor; the ship motion can be represented in 2D ECDIS (Electrical Chart Display and Information System), radar images and 3D virtual scenes. These visualizations give the navigator a vivid virtual world as if they are actually on board a ship.

For the safety of an LNG terminal, it is necessary to consider all elements that influence safety. Only the complex full mission simulation is capable of considering human (navigator) behavioural models, ship dynamics models, real traffic stream parameters and external conditions such as winds, wave, currents and visibility.

How to develop and carry out the simulation of LNG carriers operating in a port is a systematic process involving interdependent facilities and personnel. This research provides a general method for instigating how LNG ship operations are simulated in port areas. This paper is organized as follows. Section 2 reviews recent literature on full mission simulation and LNG ship handling. Section 3 demonstrates the general design framework for the experiment on LNG ship handling in port in the full mission simulation. Section 4 presents a typical case in Meizhou Bay, China. Section 5 concludes the paper and highlights the future research directions.

2. Literature Review

In the early 1960s, people tried to develop the first ship handling simulator in Sweden and the Netherland. At first, ship handling simulators were only used for scientific research. Their applications became increasingly important in maritime research and training in the 1990s (Board *et al*., 1992; Hensen, 1999).

With the implementation of the International Convention on Standards of Training, Certification and Watch-keeping for Seafarers (STCW1978/2010) (Mejia, 2010), the full mission simulator has been widely used for seafarer training and certification since the early 1990s (Salam, 2014).

There were further developments in ship handling simulators at the end of the 1990s. These included a more precise mathematical model, a more vivid scene and the addition of hydrodynamic effects, emergency response training and manned models (Muirhead, 2003). With the improvement of ship simulation techniques, ship handling simulators became more complicated and evolved into full mission simulators, with more applications developed. Full mission simulators have been the dominant tool for maritime simulation and application research, used for conducting operational training (*e.g.* emergency procedures and manoeuvring), analysing marine casualties, evaluating vessel designs for manoeuvrability, evaluating bridge equipment, evaluating navigational aids, and assessing the suitability of a particular vessel for a new port or transit situation (Board *et al*., 1992).

Most of these studies involve seafarer training (Salam, 2014). The STCW Manila amendments highlight the importance of structured ship-bridge simulation training in enhancing the competency of the masters and watch officers (Mejia, 2010). In recent years, there are many relevant studies in the maritime safety fields. Gucma & Gucma (2007) investigated the simulation methods used for the optimization of LNG terminals and navigational safety assessment in restricted sea areas. Regarding safe navigation and waterway design, Zhang *et al.*, (2003) simulated the process of ships moving from anchorage to quay using a ship handling simulator. The results from the simulator can be evaluated, and the design or modification of narrow channels can be validated. The simulator can be used to produce recommendations for improving navigational safety.

Barsan (2006) attempted to simulate the expansion of the Port of Constantza by the Constantza Port Master Plan. A simulation and several test case studies were undertaken, involving manoeuvring actions of large container ships, without tug assistance until approaching the berth. Gucma (2011) described the basic requirements for the process of designing LNG terminals, discussed the various possible applications of computer simulation models and presented a case for designing the LNG terminal in Świnoujście.

Despite the attractiveness of the above studies, LNG ship handling in ports through full mission simulation has not been systematically investigated. It is therefore crucial to carry out this study to fulfil the research gap, particularly given the fact that many new LNG port terminals are designed and built.

3. Methodology for LNG ship handling in port by full mission simulation

It is necessary to have an experimental system in full mission simulation and the methodology of carrying out LNG ship handling in port by full mission simulation. Fig. 1 shows the multistage process in the development of the full mission simulation. The approach shown in Fig. 1 consists of the following steps.

3.1. Formulation of the Research Objective

To successfully carry out the simulation, a detailed formulation must be proposed. Normally, the accuracy of the outcome of the simulation depends on how the research objective is formulated. The complex and volatile navigational environment should be taken into account. The relevant variables include

(1) The geographic features and waterway infrastructure (*e.g.* fairway, turn area and jetty) of the concerned area.

(2) The type of research ship (*e.g.* ship type, DWT).

(3) The hydro-meteorological conditions (*e.g.* winds, waves, currents and tides) under which operations in the examined area will be undertaken (*e.g.* manoeuvres and types and number of tugs in manoeuvres).

(4) The traffic stream of the concerned area.

Meanwhile, the unique features of LNG ships are also important in such simulation, especially their handling in ports, including

(1) Acceleration and stopping.

(2) Turning ability.

(3) Course-keeping stability.

(4) Turning ability with thrusters.

3.2. Modelling

It is important to develop quantitative models for the ships (ownships, target ships and tugs), the waterway, the related environment and the traffic flow of the concerned port before the simulation is developed. All of these models should be formulated accurately. The accuracy of the simulation outcome primarily depends on these models. Each of those computer-based models is described as follows.

3.2.1. Ship model design

A complete computer-based ship model pack consists of the following two types of information:

(1) A set of numerical constants of ship kinematic information.

(2) A structure (or framework) associated with the data.

Generally speaking, the numerical model includes all kinds of forces in the basic ship model, which can be expressed and calculated by the ship motion's mathematical model. The model of ship motion has 6 degrees of freedom (DoFs) (heaving, swaying, surging, pitching, yawing, and rolling). These DoFs best represent the real motion, but at the cost of computer processing power. Therefore, it is usually the case that the ship (*i.e.* ownship) has 6 DoFs, and the other models (*e.g.* target ship) have 3 or 4 DoFs (Lo *et al.*, 2014). The general equations of ship movement in 6 DoFs can be written in the form of six differential equations. To formulate the ship motion's mathematical model, the following Cartesian systems are used for the description of the ownship's motion (Fig. 2.a and Fig. 2.b):

$X_0Y_0Z_0$ earth-fixed reference frame with the O_0 origin:

1. The X_0-axis is directed towards the north and lies in the plane parallel to the undisturbed water surface;
2. The Y_0-axis is directed towards the east and lies in the plane parallel to the undisturbed water surface;
3. The Z_0-axis is directed downward at a right angle to the undisturbed water surface.

XYZ body-fixed frame with the O origin at the vessel's centre of gravity (CG):

1. The X-axis is directed from aft to fore, lies in the central lateral plane and is parallel to the water plane (longitudinal axis);
2. The Y-axis is directed starboard, is perpendicular to the central lateral plane and parallel to the water plane (transverse axis);
3. The Z-axis is directed from top to bottom at a right angle to the water plane (normal axis);

$X_1Y_1Z_1$ local frame with the O origin at the vessel's CG, is obtained by mapping the $X_0Y_0Z_0$ earth-fixed coordinate system onto the body-fixed coordinate system with their origins coinciding:

1. The X_1-axis is directed towards the north and lies in the plane parallel to the undisturbed water surface;
2. The Y_1-axis is directed towards the east and lies in the plane parallel to the undisturbed water surface;
3. The Z_1-axis is directed downward at a right angle to the undisturbed water surface.

In the above Cartesian systems, the general ship motion can be formulated from the following aspects.

(1) Ship Motion Equations

In the body-fixed reference frame, the equations of the vessel's spatial (6 DoFs) motion will have the following form (Xue *et al.*, 2011).

$$\begin{cases} m(\dot{u}_0 - v_0 r + \omega_0 q) = X \\ m(\dot{v}_0 + u_0 r - \omega_0 p) = Y \\ m(\dot{\omega}_0 - u_0 q + v_0 p) = Z \\ I_{x_c}\dot{p} + \left(I_{z_c} - I_{y_c}\right)qr = K \\ I_{y_c}\dot{q} + \left(I_{x_c} - I_{z_c}\right)rp = M \\ I_{z_c}\dot{r} + \left(I_{y_c} - I_{x_c}\right)pq = N \end{cases} \tag{1}$$

To determine the vessel's position, its centre of gravity coordinates in the earth frame are x_0, y_0 and z_0.

To determine the vessel's hull orientation, the ship's roll angle ϕ, pitch angle θ and heading angles ψ are used.

Forces and moments are recorded in the body-fixed frame.

By integrating the motion equations, the components $u, v, \omega, p, q,$ and r of the velocity and rate-of-turn vectors in the body-fixed frame are obtained.

The moments of inertias are expressed by $I_{x_c}, I_{y_c},$ and I_{z_c}.

Kinematic equations are used to determine the derivatives of the gravity centre coordinates and vessel angles: $\dot{x}_0, \dot{y}_0, \dot{z}_0, \dot{\phi}, \dot{\theta}, \dot{\psi}$.

By integrating the kinematic equations, the gravity centre coordinates and vessel angles at the following moment of time are obtained.

The summarized forces in the equations (1) are presented in the following form (Marine & Pro, 2011).

$$\begin{cases} X = X_I + X_H + X_P + X_R + X_T + X_C + X_A + X_W + X_{EXT} \\ Y = Y_I + Y_H + Y_P + Y_R + Y_T + Y_C + Y_A + Y_W + Y_{EXT} \\ Z = Z_I + Z_H + Z_W + Z_{EXT} \\ K = K_I + K_H + K_P + K_R + K_T + K_C + K_A + K_W + K_{EXT} \\ M = M_I + M_H + M_P + M_W + M_{EXT} \\ N = N_I + N_H + N_P + N_R + N_T + N_C + N_A + N_W + N_{EXT} \end{cases} \tag{2}$$

where:

$X_I;\ Y_I;\ Z_I;\ K_I;\ M_I;\ N_I$ -- inertial forces and moments;

$X_H; Y_H;\ Z_H;\ K_H;\ M_H;\ N_H$ -- hydrodynamic forces and moments;

$X_A; Y_A;\ K_A;\ N_A$ -- aerodynamic forces and moments;

$X_C; Y_C;\ K_C;\ N_C$ -- current forces and moments;

$X_R; Y_R;\ K_R;\ N_R$ -- rudder forces and moments;

$X_T; Y_T;\ K_T;\ N_T$ -- thruster forces and moments;

$X_P; Y_P;\ K_P;\ M_P;\ N_P$ -- propeller forces and moments;

$X_W; Y_W;\ Z_W;\ K_W;\ M_W;\ N_W$ -- wave forces and moments;

$X_{EXT}; Y_{EXT};\ Z_{EXT};\ K_{EXT};\ M_{EXT};\ N_{EXT}$ -- external forces and moments, which include the forces of interaction with other vessels, anchor forces, mooring lines, *etc*.

(2) Inertial Forces and Moments (associated with “ideal fluid” effects)

The additional hull forces in equation (1) are calculated with regard to the hull's shape. In the problem of modelling the vessel's spatial motion by the simulator, the cross members of the additional liquid forces matrix can be disregarded due to their relative small magnitude. Accordingly, the forces and moments associated with “ideal fluid” effects have the following form.

$$\begin{cases} X_I = X_{\dot{u}}\dot{u} - Y_{\dot{v}}vr + Z_{\dot{\omega}}\omega q \\ Y_I = Y_{\dot{v}}\dot{v} - Z_{\dot{\omega}}\omega p + X_{\dot{u}}ur \\ Z_I = Z_{\dot{\omega}}\dot{\omega} - X_{\dot{u}}uq + Y_{\dot{v}}vp \\ K_I = K_{\dot{p}}\dot{p} + \left(N_{\dot{r}} - M_{\dot{q}}\right)qr + (Z_{\dot{\omega}} - Y_{\dot{v}})v\omega \\ M_I = M_{\dot{q}}\dot{q} + \left(K_{\dot{p}} - N_{\dot{r}}\right)rp + (X_{\dot{u}} - Z_{\dot{\omega}})\omega u \\ N_I = N_{\dot{r}}\dot{r} + \left(M_{\dot{q}} - K_{\dot{p}}\right)pq + (Y_{\dot{v}} - Y_{\dot{u}})uv \end{cases} \tag{3}$$

where:

$X_I;\ Y_I;\ Z_I;\ K_I;\ M_I;\ N_I$ -- inertial forces and moments;

$u;\ v;\ \omega;\ p;\ q;\ r$ -- the velocity and rate-of-turn vectors in the body-fixed frame

(3) External Forces in the Motion Equations

The external forces $F_{EXT} = [X_{EXT}, Y_{EXT}, Z_{EXT}]^T$ and moments $M_{EXT} = [K_{EXT}, M_{EXT}, N_{EXT}]^T$ (*e.g.* forces from interactions with other vessels) are calculated as follows:

$$F_{EXT} = \frac{\sum P_{EXT}}{\Delta t};\ M_{EXT} = \frac{\sum L_{EXT}}{\Delta t}$$

where Δt is a step in the vessel's motion model integration,

$\sum P_{EXT} = \sum_i \int_t^{t+\Delta t} F_{EXT\,i}(t)dt$ is the sum of external moments acting on the vessel over the integration step, and

$\sum L_{EXT} = \sum_i \int_t^{t+\Delta t} M_{EXT\,i}(t)dt$ is the sum of external angular moments acting on the vessel over the integration step.

This method of considering the external forces allows momentarily acting and rapidly changing external forces to be taken into account.

As a complete ship model package, the numerical model calculates the ship's motion in real time. To represent a ship in a 3D scene, the 3D model of the ship is also important. The 3D ship model can be created by 3D max or Creator software, which only creates a skeleton pattern and representation on screen; however, the skeleton parameters of these 3D models should be accurate so as to create a visual image of the navigator. The 3D ship model is therefore expressed in the OpenFlight format, which is in the form of the *de facto* standard real-time 3D database file.

LNG ships are of either Moss-type or membrane-type. Typical LNG carriers are classified as an oversized Q-Flex type or a Q-Max type. The Q-Flex vessels have a cargo capacity ranging from 210,000 m^3 to 217,000 m^3, and the Q-Max ships can carry LNGs between 263,000 m^3 to 266,000 m^3.

Membrane-typed systems continue to dominate the new-build orders as the preferred containment option. Within the existing fleet, the share of vessels with alternative Moss-typed systems decreased from 31% in 2012 to 27% in 2013. Table 1 lists the main parameters of LNG carriers.

For tug models, modelling is provided for vector force tugs and for a complete interactive towing simulation between ownships. In the vector force tug model, each tug is treated as a vector force that acts at a specified location on the ownship and in a specified direction relative to the ownship. These forces are manipulated with respect to the rate of change, maximum force ahead, maximum force astern and "tug like" characteristics.

3.2.2. Port and Terminal Geographical Model

Creating a port model involves virtual reality technology, 3D geographical information systems, remote sensing and multi-dimensional visualization (Zhang *et al.*, 2011). Simulation is time-consuming if the concerned area is a new port; it will take much time to create the port model. Typical criteria and data include

(1) Detailed bathymetry, no more than 5m grid, ASCII format.

(2) Detailed imagery, orthophoto mosaic, 40cm resolution.

(3) Detailed terrain model (DTM), no more than 5m resolution.

(4) Light detection and ranging (LIDAR) data.

(5) Electronic nautical charts (ENCs) over the area of interest.

(6) Pilots/navigators willing to participate in the evaluation.

(7) Simulator interface.

The port modelling process consists of several steps. For different suppliers of the simulation, there may be different software used in the modelling process although the method and process are the same or similar. The port modelling process is shown in Fig. 3 where the main steps include the following:

(1) DTM integration (bathymetry and terrain).

(2) 3D building extraction from LIDAR data.

(3) ENC feature selection and conversion to mode format.

(4) Integrate all data types of the DTM, 3D buildings, ENC features, orthophotos, and digital photos in the final model.

(5) Develop a software interface with the port model for the simulation.

(6) Evaluation and correction by the navigator and the local pilots.

3.2.3. Environment and Parameter Models

The comprehensive environment in the full mission simulation should include the elements of winds, waves, currents, visibility, tides and the atmosphere. Most of the environmental data can be acquired in several ways for a specific port, and it is inputted into the simulator directly.

For an existing terminal or waterway, a field survey can be conducted to obtain the needed data. Hydraulic scaled models can also be used for existing terminals. These models are better used for determining the flow in terminals or ports that have not yet been built. These models are usually used to predict the gross characteristics of the environment (mainly for currents and waves). Computational fluid dynamics (CFD) may be the best way to obtain environmental data. It is less expensive than the physical models, and results in a wealth of predictions of the flow velocity, temperature, density, and chemical concentrations in any region where flows occur.

3.2.4. Model Validation

The accuracy of the models used in simulation is important. If the related models do not reflect the reality, the outcome of the simulation may be misleading. Unfortunately, there are no industry-wide standards for validation of simulators, simulations or standard ship models. Often, when the models are imported into a simulator, the simulator operator will test the preliminary models and determine which of them can run correctly. Then, navigators and pilots who are familiar with those models (including real ships, real ports and real environments) are invited to participate in the model validation. Generally, the following elements will require validation:

(1) Image portrayal including the content, quality, field, distance and depth of view, and movement of the visual scene.

(2) The predicted ship trajectories based on hydrodynamic and aerodynamic modelling.

(3) Ownship (ship model) characteristics, including acceleration, stopping ability, turning ability and course-keeping stability.

(4) The operational scenarios.

Impartial validation panels need careful selection of people from multiple disciplines, including, for example:

(1) A simulation instructor or assessor.

(2) A representative from the licensing authority.

(3) A subject-matter expert.

(4) A pilot or master to test the ship-model behaviour.

3.3. Simulation Strategy (Organization)

Simulation in a project is systematic and needs a careful and well-thought-out plan. The facilities and the personnel form the base of the simulation in terms of what type of simulator will be chosen and who will participate in the activity. In the plan, another important procedure is how to design the simulation in order to achieve the goal of the simulation.

3.3.1 Simulation Facilities

A full mission simulator is the most powerful facility for simulation. Due to the rapid development of information technology and modelling technology, there are many kinds of comprehensive full mission simulators. Typical full mission simulators include the Kongsberg Polaris, Force SimFlex, and the Transas NTPro 5000, *etc*. The following standards should be obeyed when choosing a suitable simulator out of the many available brands:

(1) At least one bridge with a 270° visual projection and shipborne equipment (in agreement with the DNV class A code).

(2) At least task navigation bridges with 120° visual projection or mock up with more than 3 large LCD screens and shipborne equipment including more than one Voith-Schneider or Z-Drive tug console (in agreement with the DNV class B code) (Veritas, 2011).

(3) Multiple desktop PC simulators with one monitor for visual projection and one monitoring screen for showing the movements of more than two tugs.

(4) An instructor station that can monitor the operation of the whole system and configure simulation runs.

(5) Secondary simulator development software kits to create and import the port model and ship models.

(6) A project that can synchronously play back the simulation log for debriefing and analysing the simulation results.

3.3.2. Qualified Personnel

The advantage of the full mission simulation is involving the typical man-in-the-loop function. The participants in the simulation are also important for the simulation's outcome. Qualified navigators include pilots, shipmasters and other ship officers; tug masters are preferred if available. The navigator must integrate the diverse information acquired via all aspects of the ownship, the operating environment, and vessel traffic, as well as navigational conventions and other factors. The navigator should have extensive knowledge of the operating vessels, local conditions, and tug assistance. In any emergency case during the simulation, the navigator should make a decision immediately and try to predict what to do next.

Apart from the navigator, the instructor should instruct the navigator operating the facilities at first and address the facility emergencies during the entire simulation process. To improve the performance of the terminal and the port, the harbour authorities should understand some of the navigator's operations on the spot. The jetty site supervisor should also be involved in the process for better simulation.

3.3.3. Design of Experimental System (Simulation Run Design)

The experimental design of the simulation is important. The main principle of the design is objective-oriented and based on reality. First, the instructor should have a good understanding of the objectives of the simulation activity and the goals for navigator training, taking into account the waterway's characteristics. Then, the external environment, and traffic stream and other associated issues are taken into account. For example, simulation runs under winds of the E direction are meaningless if a port exhibits prevailing south and north monsoons based on the meteorological statistics.

To achieve the goal of the simulation, a range of arrival and departure simulation runs should be designed. A good simulation design can take into account the potential risk of the LNG terminal and establish the operational limits of winds, currents, tides and visibility if the pilots, tug masters and shipmasters carry out the simulation runs effectively.

Moreover, the experimental design should provide the navigators and tug masters with the opportunity to practise handling LNG carriers under weather and tidal conditions that are close to the limits of operability. These scenarios may be difficult to handle in reality, such as departure during a typhoon while avoiding enormous destruction of port facilities. In fact, simulation runs of abnormal situations can truly give the navigator an opportunity to practise dealing with emergency situations and ensure that all manoeuvres are carried out safely while in full control of the LNG vessel at all times. These emergency situations include (but are not limited to) a loss of steering capability, a loss of propulsion, black-out, weather changes from favourable to unfavourable conditions, telemetry failure, vital systems, automation, tug breakdown and emergency berth evacuation (Training, 1996).

In general, it is challenging to design simulation runs. The simulation instructor, navigator and local pilot should participate in the simulation design activity. For LNG ship handling in port, simulation of the entire arrival and departure process is necessary, but special simulation runs are designed for the key sections/segments of the waterway and certain abnormal conditions. To address this problem, the entire ship arrival and departure process can be divided into the following three segments.

(1) Up-line segment: this segment extends from the open sea or anchorage to the artificial channel of the port of destination. LNG carriers speed up to their normal speed onward from the anchorage in this segment. The navigator should quickly determine the appropriate crab angle in the operation. There may be no strict planning or recommended route; small vessels and fishing boats may cross the bow, with a prevailing risk of a collision between an LNG tanker and another vessel. Because many factors that influence safety are random, Monte Carlo methods may provide a useful alternative way to address these related issues (Gucma, 2013) although this aspect is not covered in this work.

(2) Coastal waterway segment: this segment includes the entire artificial channel for port entry extending to the edge of basin water. There may be some narrow sections where there are large angle turning, gustiness and rapid current changes due to various underwater terrains. Determining the course, speed and crab angle at each key point and decreasing speed at the end of the channel is vitally important. The main risk of LNG handling is grounding in shallow waters or on a slope of the fairway channel. Normally, the artificial channels for LNG carriers are one-way channels, and they cannot meet vessels coming from an opposite direction. Therefore, apart from the normal operation simulation runs, it is also necessary to design critical simulation runs in this segment.

(3) Basin segment: this segment is located at the end of the channel and includes the basin water. The speed of the LNG carriers in this segment is very slow, and assisting tugs should be safely fastened prior to entering the basin water. The vessel's operations include entering the port, approaching the terminal, turning and mooring. Determining how to control the speed when approaching the jetty and giving the appropriate command to the assisting tugs are critical. The main risk in this segment is the collision of the LNG carriers with a marine port structure or the assisting tugs together with possible grounding. In some special cases of emergency operation in this segment, the LNG carriers may have to be manoeuvred in a situation of strong winds if a typhoon is forecasted, and need to move to an appropriate position for cargo handling.

3.4. Implementation of the Simulation Runs

Each participant in the simulation should have a clear mission; the mission allocation and job description of each participant are shown in Table 2.

First, a kick-off meeting is important and obligatory prior to the simulation. Every member involved in the simulation should take part in the meeting, which is face-to-face or via video conference. During the kick-off meeting, the following issues should be discussed and agreed upon.

(1) Information of the ships under investigation, environmental conditions, berths and areas to be tested is produced.

(2) All meteorological and environmental data is made available by the client, as well as data describing the layout of the terminal area.

(3) A simulation program and assessment method are agreed upon.

During the simulation, the LNG carrier will be controlled from a full-mission bridge, which will be equipped with all of the usual instrumentation available on a vessel bridge. Free-sailing interactive tugs will be included in the simulation.

A pilot or shipmaster will control the vessels from the full-mission bridge, and tug masters will control the tugs from the other bridges under the pilot's orders. Any additional tugs will be controlled from the vector tug console under the pilot orders.

For the free-sailing interactive tugs, all instrumentation normally found on Azimuth Stern Drive (ASD) tugs will be made available on the bridge. The tugs will be controlled with the typical handles used on ASD tugs. Additional controls will be made available for the bow winch and readouts for actual towing line length and tension.

In a typical simulation session, 6 simulation runs can be executed, depending on the length of arrival/departure and the type of vessel. Based on the local weather, the simulation runs will be produced under different combinations of winds and currents.

After each run, the results will be recorded with the advanced debriefing tools. Thereafter, the participants will be able to benchmark their performance so as to make improvements in their operations.

As part of the delivery, each participant will receive the necessary information about the objectives, training plan and comprehensive summary on ship handling.

The instructors involved in the simulation programs are given the time for familiarizing themselves with the client’s requirements prior to the first use of the program in order to effectively conduct the simulation and assessment.

3.5. Analysis and Application of the Simulation Results

After completion of the simulation, a report covering the completed work can be submitted electronically, and the study results can be compiled.

A typical report will include the following:

(1) Summary.

(2) Description of the jetty, port and navigational environmental conditions.

(3) List of simulation runs carried out.

(4) Documentation of simulator runs by track plots and time series of logged parameters.

(5) Manoeuvring considerations including an assessment of the safety level.

(6) Description of the simulated ships including the standard manoeuvres.

(7) Results, conclusions, recommendations and documentation of operational limits for the defined cases based on the defined criteria.

The training courses will be developed in full compliance with the authority's guidelines for the Quality Management of Maritime Training and Education and the STCW 95 (Cross, 2011). Furthermore, simulation facilities should be certified by an internationally recognized organization that complies with the international rules for simulators providing advanced training (Veritas, 2011).

The results of the study are an important reference for port authorities to formulate their port guidance, operating instructions for the pilot, and blueprints for the port or terminal design. Recommendations can be drawn from the simulation, and a review meeting is held to evaluate the simulation content for possible improvement and draw conclusions.

4. A Typical Case: LNG ship handling in the Meizhou Bay terminal

4.1. Case Study Description

China’s second LNG terminal was built in Putian in the Fujian province. In

November 2013 at the request of China National Offshore Oil Corporation (CNOOC) Fujian LNG Co., Ltd (CNOOC Fujian), the researchers of this work conducted a detailed simulation study and evaluation to determine the feasibility of safely navigating a 210,000 m^3 capacity Q-Flex LNG carrier from the pilot boarding area (PBA) in the vicinity of the entrance of the main channel of Meizhou Bay (see Fig. 4 near the anchorage) to the Fujian LNG (FJLNG) terminal at Xiuyu Port.

The approach to the Xiuyu LNG terminal has its own remarkable characteristics in terms of navigation. The total pilotage length is approximately 14 nm with narrow channels, strong currents (approximately 4 kts in some cases) and a large volume of traffic. Meizhou Bay has 44,000 vessel movements per year, but still has no Vessel Traffic Service (VTS), and not all vessels are equipped with Very High Frequency (VHF).

The detailed model of the terminal is shown in Fig. 4 where the bearing of the ship is 127°/307° parallel to the depth contours and consistent with the direction of the tidal current. The distance between the bow of the LNG carrier and the Longhu Reef in Fig. 5 is slightly larger than 200m. The berth is arranged as a “T” shape with 2 - 20m of natural water depth at the edge and 2 - 24m of natural water depth in the dock pool. The central platform of the berth is connected to the receiving station by a 345.5m long trestle bridge. The turning area of the LNG berth and the dock for the service ship are arranged in front of the berth (see Fig. 5) (Lin, 2008).

Because of limited experience in handling the Q-Flex LNG carrier, the pilots and the tug masters participated in the simulation study and training. The primary objectives of this simulation are given as follows.

(1) Assess the safety aspects of navigating and docking a 210,000 m^3 capacity membrane-typed LNG carrier from the PBA to the terminal.

(2) Define the tidal current windows for entering the port and docking at the terminal.

(3) Define the wind direction and velocity limits for entering the port and mooring at the terminal.

(4) Recommend any improvement on navigational aids that would enhance operational safety when the vessel enters the port.

(5) Assess the appropriate speed of the vessel entering the port.

(6) Identify other factors that would influence safe operations of the vessel.

4.2. Simulation Model

4.2.1. Ship models

During this phase of study and evaluation of the manoeuvring of the Q-Flex carrier, the ownship (Q-Flex) has 6 DoFs in the hydrodynamic models. In the simulation, the non-linear, coupled differential equations that describe the motions of the ownship (described in Section 3.2.1), the hydrodynamic forces represented in these differential equations and the external forces (some of which are hydrodynamic in origin time) yield the 6-DoF position of the ownship.

The hydrodynamic models used in many simulators are provided by the manufacturers; typically, the manufacturers provide a range of ownship model databases and a further development software kit to the customer or the researcher. In this study, Visual Ship Yard II provided by Transas (UK) Ltd was used to create a new ship model. Based on all of the manoeuvring data provided by the CNOOC Fujian, Q-Flex models in both a fully loaded condition and a ballasted condition were created; the principal parameters and skeleton are presented in Table 3 and Fig. 6, respectively. A validation test was performed by the pilot from the Putian pilot station, and the parameters and tracks of the test are shown in Fig. 7.

The assisting tugs in this simulation are the same as those from the CNOOC Fujian. They are of the vector type with the adequate bollard pull ratings. They are typical tugs in terms of propulsion and speed, operating under conditions of currents and waves. The detailed information of the tug models is shown in Table 4. Two simulated 5,000 horsepower Z-Drive tugs and two simulated 4,000 horsepower Z-Drive tugs were used in this study.

4.2.2. Port and Terminal Model

A simulator geographic database of Meizhou Bay was created according to the described methodology in Section 3.2.2. The database includes an out-of-windows view and a bird's eye view (see Fig. 8), including the nautical charts and radar images used in the simulator. The geographic database range of this study extends from the anchorage near buoy No.8 in the Meizhou Bay main channel to the FJLNG terminal. The LOD (level of detail) of the database includes the landmark and navigational aids along the entryway of the LNG carriers, especially near the terminal.

4.2.3. Environmental Data

The port area is influenced by a subtropical and ocean monsoon climate with rains. The elements greatly influencing the LNG handling are the winds, waves, currents and tides, the details of which are described as follows (Lin, 2008).

(1) Winds

According to the statistics of the Xiuyu observatory from 1985 to 2001, the direction of the prevailing wind in the area is NE with an average frequency of 28.9%, and the directions of the sub-prevailing winds are ENE and NNE with average frequencies of 12.1% and 10.1%, respectively. The direction of the strongest winds is SSW with a maximum speed of 22 m/s, and the direction of sub-strong winds is NNE and NE with a maximum speed of 18 m/s.

It is obvious that the frequency of the wind direction in the area changes seasonally. Based on the data from the Xiuyu Meteorological Bureau of Putian, the direction of NNE～ENE winds prevails from September to May next year, whereas there are mainly SW～S winds from June to August. The most frequent or strongest winds were taken into account during the simulation design.

(2) Currents

There were five tidal current observations carried out in June 1984, August 1990, January 25-26, 1997 (spring tides), January 30-31, 1997 (neap tides), and March 2003. After the terminal was put into use, the latest observation was from 11 a.m. on August 21, 2009 to 1 p.m. August 22, 2009. In general, the tide current in the bay is mainly a reversing current as a result of topographic control. The fluctuation trend complies with the flow direction in a deep groove. The current near the shoal scatters slightly.

The current velocity in spring tides is greater than that in neap tides. The current velocity at the surface is greater than that at the bottom.

From the measured flow velocity data, the maximum flow velocity area is from Linchijiao to Dasheng Island, and its maximum flow velocity is 1.78 m/s. The flow velocity from Huanggan Island to Jianyu is also large, and the largest flood tide velocity reaches 1.12 m/s meanwhile the largest ebb tide velocity reaches 1.01 m/s. Both the largest flood tide velocity and the largest ebb tide velocity are close to 1.25 m/s near the entrance of Jianyu. Douwei, located in the Dazhu deep groove, has an advantageous high tide flow, while its flood tide velocity reaches 2.4 m/s and its ebb tide velocity is close to 1.75 m/s. Fengwei-Dongwu and Xiaocuo, located in the Xiuyu deep groove, have their measured flow velocities 2.00 m/s and 1.85 m/s respectively.

(3) Waves

Meizhou Bay is long and narrow, 35 km from north to south and 15 km from the E direction to the W direction. There are many islands in the bay. The width of the bay's mouth facing the Taiwan Strait is approximately 10 km, near which Meizhou Island, Dazhu Island and other islands form a natural barrier. Based on Meizhou Bay's terrain, the predominant waves are a superposition of waves formed in gentle hilly regions with weak winds around Koumen in the northern area of Dazhu Island and the Qinglanshan Peninsula in the bay. The mouth of the bay is from the southern area of Dazhu Island and the Qinglanshan Peninsula to the waters around Jianyu. This area is mainly affected by external waves.

Three wave observations in Xiuyu port were conducted from 1978 to 1980 at 25°13'N, 118°59'E. The direction of the prevailing waves in the port area is NE with a frequency of 26%; the direction of the sub-prevailing waves is ENE with a frequency of 17.1%. The direction of the strongest waves is NE, and the direction of the sub-strong waves is ENE. The measured maximum wave height is 1.4m with the NE direction. 90.47% of the waves are with their heights equal to or smaller than 0.4m in $H_{1/10}$ (1 in 10). 99.69% of the waves are with their heights equal to or smaller than 0.9m in $H_{1/10}$. Wave heights equal to or larger than 1m in $H_{1/10}$ occurred only 4 times with the maximum of 1.4m.

(4) Tides

The tides in Meizhou Bay are regular semi-diurnal tides, where the high and low tides in and out of the bay appear almost simultaneously. A tidal wave is a standing wave. The rapid rising or falling of the tides occurs near the middle tide level, whereas the turn of tidal currents occur near the high or low tide levels.

Because LNG carriers need not take advantage of the tides, the high tide is not the main influential factor, and LNG carriers are more concerned with the speed and direction of the tidal current.

4.3. Simulation Design and Implementation

The length of the Meizhou Bay channel is 31.6 km. It was constructed to meet the standard of navigating 100,000 DWT vessels at a time. The effective width of the fairway is 300m, in which the width of section A-B (shown in Fig. 4 is 500m and the width of section F-G is 400m. The entire fairway is 18.3m in depth (points A-G in Fig.

4).

A series of simulation runs were designed and conducted under various conditions of winds, waves and tides, different tug configurations, different pilots and various approaching and departure scenarios, requiring pilots to manoeuvre the vessel when approaching or leaving the berth.

The environmental conditions were generally chosen to establish the limits for each vessel for both arrival and departure. In some cases, this was achieved by increasing the environmental forces and selecting the next scenario after considering the results of the previous run.

To achieve the objective of the study, these simulation runs can be divided into two broad categories: operation in normal circumstances and operation in abnormal circumstances. The goal of the first category of simulation runs is to verify the adaptability between the terminal and the Q-Flex carrier. Emergency situations are evaluated in the second category of simulation runs.

4.3.1 Adaptability research on waterways and terminal facilities under normal conditions

The FJLNG pilots have limited experience in handling the Q-Flex in Meizhou Bay. The first stage of the simulation study aims at investigating the ability of the Q-Flex carriers to enter the port safely, the adaptability of the navigational layout and aids, channel widths, channel depths, basin dimensions, berth location and depths.

The normal simulation runs in this study were designed as shown in Table 5. In the initial run, a moderate wind speed was used to allow the pilots to assess the ship's handling performance without large wind forces. An average high tidal velocity was used. Four tugs were used to reflect practical operations (two tugs each had the power of 5,000 HP while the other two each had the power of 4,000 HP). Two FJLNG pilots and three Putian port tug masters participated in the simulation runs for two days. All eight simulation runs were operated successfully, and the Q-Flex was safely manoeuvred into basin (tides) and berthed with the portside bow on the outside.

According to the statistics, calculations and simulator outputs, the following 3 types of parameters can be evaluated quantitatively:

(1) The width of the fairway

According to the regulations of the *Design Code of General Layout for Sea Port* (Gu, 2013), a fairway width W consists of a width of track A and an additional width b in each side of the track. When the fairway is longer, the natural conditions are relatively poor and the vessel positioning is difficult, it can be appropriately widened. In the segments in which natural conditions are favourable, the width of the fairway, W can be appropriately obtained based on the following (Gu, 2013).

One-way fairway: $W=A+2c$

Two-way track: $W=2A+b+2c$

where: the width of track (m), $A = n \times (L \times \sin\gamma + B)$,

n is the number of multiple drifting ships,

γ is crab angle,

b is additional width between ships,

c is additional width between the ship and the edge of the fairway, L is ship length (m), and

B is ship width (m).

The waterway for this project was designed as one-way. After several simulation tests with the ship, the width of track A can be obtained. Then, the necessary width of the fairway can be calculated on the basis of the test results (see Table 6).

(2) The depth of the fairway

To assess the adaptability of the depth of the fairway, two echo-sounding sensors in the Q-Flex carrier model were added. From these sensors, the dynamic UKC (under keel clearance) can be measured and calculated in real time.

The UKC is the minimum clearance available between the deepest point on the vessel and the bottom of the waterway and is calculated as follows.

UKC = (charted depth of the water + height of the tide) – (deep draft)

When calculating the depth of the water, the following factors were taken into account (Delefortrie *et al.*, 2007):

a. Vessel's trim and list characteristics.

b. Depth of the transit area.

c. Tide and current conditions.

d. Weather impact on the water depth.

From the above factors, the low-tide condition simulation runs can be designed to obtain the dynamic UKC data, and the curve in Fig. 9 is the dynamic UKC of the Q-Flex carrier when entering the port in conditions of NE winds at 25 kts, 1.2m waves and ebb tides. From the statistics and data calculations, the minimum UKC in the curve is 1.47m, which meets the safety requirements of the Q-Flex (in most port regulations, the UKC should be no less than 10% of the ship's draft).

(3) The dimensions of the basin

When the ship is berthing, the influence on the ship's manoeuvrability caused by currents and winds, the size of the turning area at the wharf apron and the available water depth, *etc*., should be considered. When the ship is leaving the berth, the influence on the ship's manoeuvrability in ballast caused by the increased wind area and the available water areas in the terminal from upstream to downstream should all be considered.

According to the general practices of large ships, it is necessary to berth or to leave berth at a time of no currents or slow currents, taking into account the ship's large displacement, large size and course stability as well as the poor rudder control over the ship's course.

According to the *Design Code of General Layout for Sea Port* (Gu, 2013), the size of turning water for the port, which is heavily influenced by currents, is at least 1.5L to 2.0L transverse to the current direction and 2.5L to 3.0L along the current direction. In the analysis of the scale of the turning water, several simulation runs of berthing and leaving berth were carried out under different operating conditions to determine the size of water required to stop the ship or make a turn.

When the Q-Flex LNG carrier is berthing or leaving berth, it must be assisted by tugs (Hensen, 2003). In this study, the vessel should be assisted by at least three tugs when berthing. In the simulation process, the requirements for tugs were given as follows:

- at least 18,000 HP ((5,000 HP × 2) + (4,000 HP × 2)) of tugs when the wind force is less than Beaufort Scale 6;

- at least 20,000 HP (5,000 HP × 4) of tugs when the wind force is greater than Beaufort Scale 7.

In the simulation, the required size of turning water for the Q-Flex LNG carrier safely berthing is shown in Table 5.

4.3.2 Emergency maneuvering

It is necessary to take the worse conditions and emergency circumstances into account in every simulation, which can give the navigators and tug masters an opportunity to practise operations that they may not often experience in reality. The channel of Meizhou Bay is approximately 15.4 nm long, has no VTS cover and has an intensive traffic flow. There are over 50 large berths in Meizhou Bay, including those capable of hosting oil tankers of 300,000 DWT, general cargo ships of 100,000 DWT and containerships of 100,000 DWT. In such a complex waterway, LNG carriers may be at risk unexpected under severe conditions. Therefore, the following simulation scenarios were developed for training the pilots and the tug masters.

(1) Application of the Williamson Turn for Q-Flex Evacuation in Channels

When Q-Flex carriers depart from anchorage and enter the channel, an abnormal situation may occur in the fairway ahead. For example, an emergency may happen in the terminal where the Q-Flex LNG carrier has to make a turn and evacuate when it enters the key section B-C in Fig. 4.

Because the heading of section B-C is 136°19′, when the LNG carrier turns from point B to section B-C, the winds are on the beam if the wind direction is NE. The tide current reaches the maximum of almost 4 kts. The LNG carrier may have to turn starboard and reverse course because there is a 300,000 DWT oil jetty on her portside.

Because the available water area is limited, the Williamson turning operation is the best choice. Several simulation runs under such severe circumstances showed the following:

- When the winds are at Beaufort Scale 7 or lower and the wind direction is NE, the Q-Flex LNG carrier should turn to the north where the water is relatively open. Moreover, this turning operation is relatively easier (see Fig. 10, left) due to the wind deflection.
- When the wind direction is SW and influenced by the Linchi Reef, the Q-Flex LNG carrier can only turn around towards the north. When the turn is close to 90º, the Q-Flex LNG carrier will be influenced by the winds more strongly. In these conditions, assistance from tugs with large power is necessary. The simulation runs indicate that at least two 4,000 HP tugs were used to assist the ship turning at bow (see the right side of Fig. 10).

(2) Response to equipment failure

Assuming the same bad conditions (the maximum current velocity of 3.5 kts in ebb tides, and winds at Beaufort Scale 7) when the ship is passing by section B-C, if its steering gear breaks down and cannot control the course of the ship in a normal way, then tug assistance is necessary. The simulation run shows that two 4,000 HP tugs and one 5,000 HP tug are required. A description of the towing process is shown in Fig. 11 (the 5,000 HP tug operating aft to control the ship's speed and the direction of the stern, and the two 4,000 HP tugs operating along the ship's side near the bow to control the turning of the ship). By operating this way, the ship can avoid the Linchi Reef and pass through section B-C slowly.

Under the same conditions, if its main engine breaks down, the towing procedure is shown in Fig. 12 (one 5,000 HP tug towing aft to control the ship's speed and the direction of the stern, and the other two 4,000 HP tugs towing along the ship's side near the bow to control the turning of the ship and provide the power).

(3) Avoiding collision in an emergency in sections C-D and D-F

The Meizhou Bay channel is a very long one-way channel, and there is no VTS monitoring vessels' movements. Therefore, if an emergency occurs in the channel, the vessel could anchor alongside the channel, blocking the traffic. If the port authority gives a wrong schedule, the inbound vessel and outbound vessel may encounter one another.

In such a long one-way channel, it is necessary to establish an emergency area for such emergency situations. In the Meizhou Bay channel, an emergency area of 300m × 2500m is established along the side-line of the fairway in sections C-D and D-F (see Fig. 4) so that a ship can enter the emergency area to avoid collision with the assistance of tugs.

In the simulation run in the C-D section (in the left half of Fig. 13), the Q-Flex carrier entered the emergency area to avoid collision with a 100,000 DWT container ship. The transverse distance between the two ships ranged from 318m to 322m (about the length of the Q-Flex carrier), as shown in the left half of Fig. 13.

In the simulation run in the D-F section, the Q-Flex carrier entered the emergency area to avoid collision with a 100,000 DWT bulk carrier with the transverse distance between the two ships ranging from 317m to 339m (about the length of the Q-Flex carrier), as shown in the right half of Fig. 13.

(4) Evacuation from the terminal under emergency conditions

Emergency situations in ports are related to explosions, fires or gales in terminals, especially those storing oil, gas or chemical products. In these cases, the moored ships must leave the port as quickly as possible (Paulauskas *et al.*, 2012).

In the event of an emergency situation, there may be limited time to make a complete plan for unberthing. It is necessary to design simulation runs of unberthing under emergency and provide experience to the masters and the pilots. It is dangerous to berth or unberth with winds of Beaufort Scale 9 or higher. It is necessary to have enough tugs because the large size of the LNG carrier is clearly influenced by winds when berthing or unberthing at low speed. With on-shore winds, it is necessary to use at least six 5,000 HP tugs to assist the unberthing operation (see Fig. 14).

4.4. Discussions

In this simulation, apart from two local pilots and three tug masters participated in the exercise, officers from Maritime Safety Administration (MSA) and those involved from the CNOOC were also overseeing the simulation. There were eight simulation runs under normal conditions and eight simulation runs under emergency conditions. The simulations were successful, but some simulation runs were difficult when the operational conditions were extreme.

From the results obtained from the simulation, the followings are obtained.

4.4.1 Adaptability between the Q-Flex carrier and the terminal facilities

(1) Condition of the fairway

According to the simulation, the Q-Flex carrier was tested under conditions of the prevailing wind direction at Beaufort Scale 7 or lower with high or ebb tides. The track width and the required width of the fairway in different sections are obtained as shown in Table 6.

(2) Basin area of the terminal

The layout of the basin area is oval, where the major axis (parallel to the current direction) is 870m long and the minor axis (perpendicular to the current direction) is 630m long after optimization. The simulation data indicates that the minor axis is relatively small with winds of Beaufort Scale 7 and spring tides. In the simulation, the maximum size of the basin area was 812m × 698m under winds of Beaufort Scale 7, whereas it was 777m × 598m under winds of Beaufort Scale 6. Therefore, the designed basin area can satisfy the berthing and unberthing requirements of the Q-Flex carrier under winds of Beaufort Scale 6 or lower, but not under winds of Beaufort Scale 7 or higher.

(3) Tug configuration

According to the simulation data, the Q-Flex carrier needs at least 18,000 HP of tugs ((5,000 HP × 2) + (4,000 HP × 2)) when entering the port under normal conditions. When encountering a gale, more tug power is needed. The emergency test with winds of Beaufort Scale 9 showed that at least 5,000 HP × 6 of tugs would be required to assist the Q-Flex carrier with a full load when unberthing.

(4) Limitation of natural conditions

According to the simulation test and the *Liquefied Natural Gas Terminal Design Procedures*, the Q-Flex carrier should enter or leave the port only in the daytime and under conditions of no less than 2,000m of visibility, wave heights of 3.0m or lower and winds of Beaufort Scale 6 or lower. When the wind force is Beaufort Scale 7 and higher, the ships should not be allowed to enter or leave the port.

4.4.2 Suggestions for Q-Flex carriers

(1) The pilot experienced significantly better rudder effectiveness at 8 kts compared to 6 kts.

(2) Flood tide arrivals should be avoided due to the lack of rudder effectiveness and the large crab angle required to keep the ship on track (i.e. steering at angels from 287^{o} to 311^{o}). Such large crab angles increase the effective beam width by a factor of three or more.

(3) Much large rudder efforts were required to maintain the ship’s heading when the winds and currents came from the same direction.

(4) Docking operations with the current tug capabilities should be avoided when winds with a speed of 20 kts or higher are expected. The current tugs are effective with an adequate margin of safety for winds with a speed of less than 20 kts.

(5) Dockings portside to the jetty should be undertaken at the beginning of the flood tide.

(6) Dockings starboard side to the jetty are preferred when the ship arrives during an ebb tide.

(7) Inbound transits during the ebb tide were successfully conducted with a high level of comfort and control.

(8) The following navigational aids could be better positioned:

- ✓ Relocate buoy “21” to the far western edge of the 8m deep area.
- ✓ Relocate buoy “24” to the far eastern edge of the 9m deep area.
- ✓ Relocate buoy “20” 0.3 nautical miles SSE of its present location to a position near the far eastern edge of the 9m deep area.

5. Summary

The full mission simulator is a vitally important platform for marine research and training. This paper presents an experimental methodology for LNG ship handling in ports using the full mission simulator and describes the implementation of the proposed procedure in simulation development. For the methodology of conducting a fruitful simulation, this paper provides the detailed experimental procedure systematically. Using the described procedures, one can organize a complete study for LNG ship handling in a port using the simulator, which can provide preliminary adaptability research for the design of an LNG terminal as well as training of local pilots and other navigators.

To demonstrate the methodology, a detailed simulation case study in the Meizhou Bay terminal in China was conducted. Two types of manoeuvring experiments were designed for the Q-Flex carrier: adaptability handling and emergency handling. By analysing the statistics and simulation data, several conclusions and suggestions were obtained for LNG ship handling, providing the local pilots and tug masters with empirical operational guidance.

The high cost of the full mission simulation is controversial, and it may be a disadvantage to this method. However, its fruitful outcomes make it worthwhile, and the cost will decrease with the development of information and modelling techniques.

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References

Barsan, E. (2006). Optimization of port manoeuvring techniques in the constantza-south agigea port. *Journal of Maritime Studies, 20*(2), 65-78.

Board, M., Simulation, C. A. S., Webster, W. C., Sciences, D. E. P., Systems, C. E. T. & Council, N. R. (1992). *Shiphandling Simulation: Application to Waterway Design*: National Academies Press.

Cross, S. J. (2011). *Quality MET through quality simulator applications.* Paper presented at the International conference IMLA.

Delefortrie, G., Vantorre, M., Verzhbitskaya, E. & Seynaeve, K. (2007). Evaluation of safety of navigation in muddy areas through real-time maneuvering simulation. *Journal of Waterway, Port, Coastal, and Ocean Engineering, 133*(2), 125-135.

Gu, M. (2013). Design code of general layout for sea port (JTS165-2013): China Communications Press.

Gucma, L. (2013). *LNG terminals design and operation: Navigational safety aspects*: Marine Traffic Engineering.

Gucma, M. & Gucma, M. (2007). *Simulation method of navigational risk assessment in optimization of LNG terminal parameters.* Paper presented at the Proceedings ESREL.

Gucma, S. (2011). Simulation methods in LNG terminal design. *Scientific Journals Maritime University of Szczecin, Zeszyty Naukowe Akademia Morska w Szczecinie*.

Hensen, H. (1999). *Ship Bridge Simulators: A Project Handbook*: Nautical Institute.

Hensen, H. (2003). *Tug use in port: a practical guide*: Nautical Institute.

Lin, W., Zhang, N. & Gu, A. (2010). LNG (liquefied natural gas): A necessary part in China's future energy infrastructure. *Energy, 35*(11), 4383-4391.

Lin, Y. R. W. (2008). *Feasibility Study Report of Fujian LNG Project*. Retrieved from GuangZhou,China.

Lo, D. C., Su, D. T. & Lin, J. T. (2014). A numerical simulation investigation of the hydrodynamic motions of a ship advancing in waves. *International Journal of Maritime Engineering, 156*, A353-A361.

Marine, T. & Pro, N.T. (2011). 5000 Ship Mathematical Model. *Sankt Petersburg*.

Mejia, M. Q. (2010). The STCW Conference in Manila. *WMU Journal of Maritime Affairs, 9*(2), 231-234.

Muirhead, P. (2003). *Broadband Technology and marine Simulation: Why not simulator training anywhere, anytime?* Paper presented at the International Conference on Marine Simulation and Ship Maneuverability (MARSIM 2003) conference Proceedings, Japan.

Paulauskas, V., Lukauskas, V., Plačiene, B. & Barzdžiukas, R. (2012). Ships leaving a port under emergency conditions. *Transport, 27*(4), 345-350.

Salam, A. K. M. D. W. (2014). The importance of using ship bridge simulation training to enhance the competency of masters and watch-officers: a case study of the iraqi dredging fleet. World Maritime University Dissertations.

SIGTTO. (2010). The Use of Computer Simulation in LNG Shipping and Terminal

Applications. Retrieved from http://www.sigtto.org/media/1874/SIGTTO - Simulation Information Paper.pdf

Training, N. R. C. C. o. S. B. S. (1996). *Simulated Voyages: Using Simulation Technology to Train and License Mariners*: National Academy Press.

Veritas, D. N. (2011). Standard for Certification No. 2.14 Maritime Simulator Systems. *Det Norske Veritas (DNV) Standards for Certification*.

Xue, Y. Z., Clelland, D., Lee, B. S., & Han, D. F. (2011). Automatic simulation of ship navigation. Ocean Engineering, 38(17-18), 2290-2305.

ZHANG, X.F., HONG, B.G. & JIN, Y.C. (2003). Evaluation Ship navigation security with ship handling simulator [J]. *Navigation of China, 3*, 006.

Zhang, X., Dong, W., Liu, J. & Chi, T. (2011). A Three-dimensional geographical information system design for polar region scientific research. *Journal of Coastal Research*, 1760-1763.

Figures

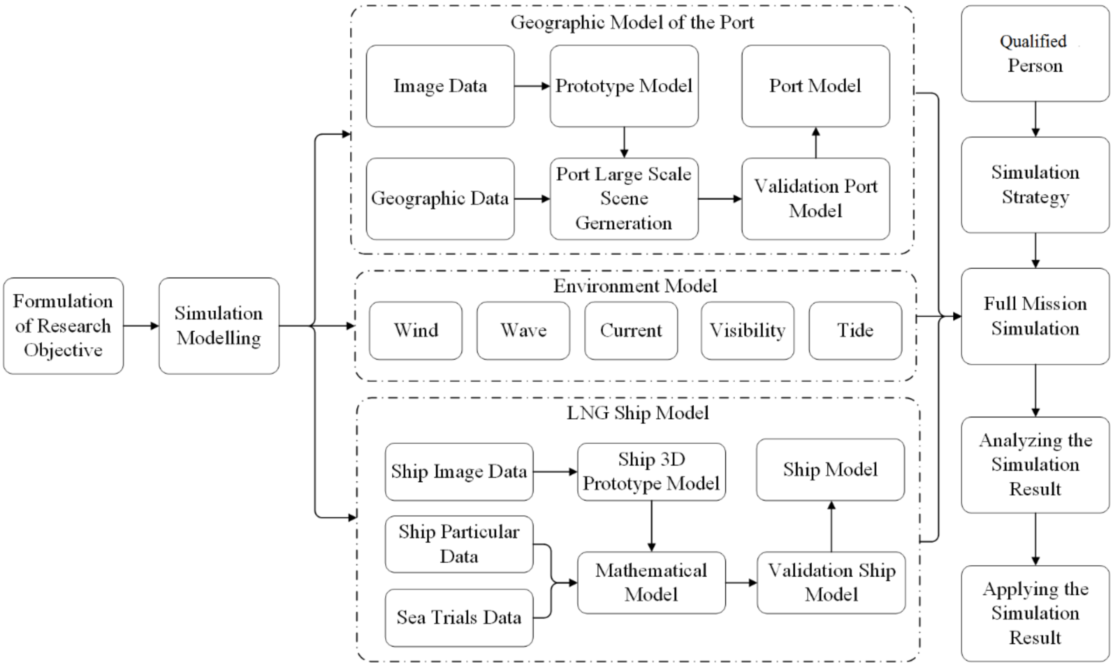
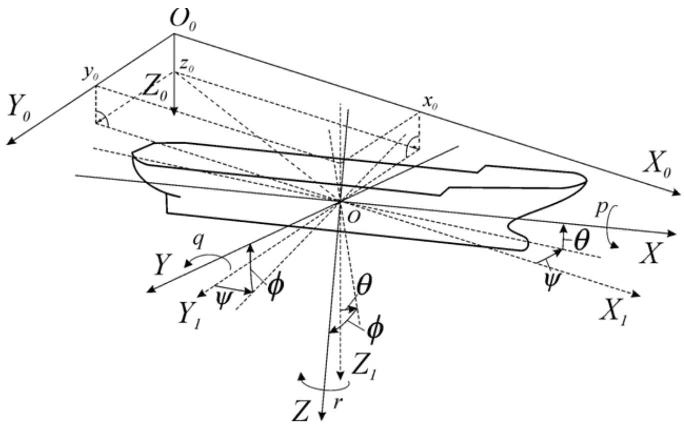


Fig. 1. Process of Full Mission Simulation



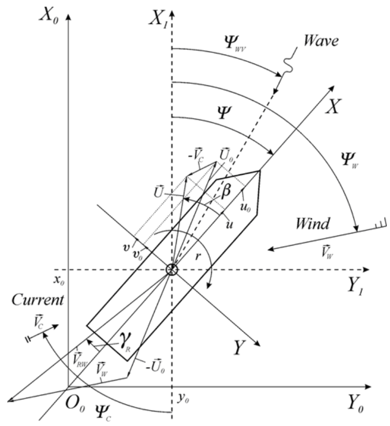


Fig. 2.a Coordinate Systems

Fig. 2.b Coordinate Systems (Horizontal)

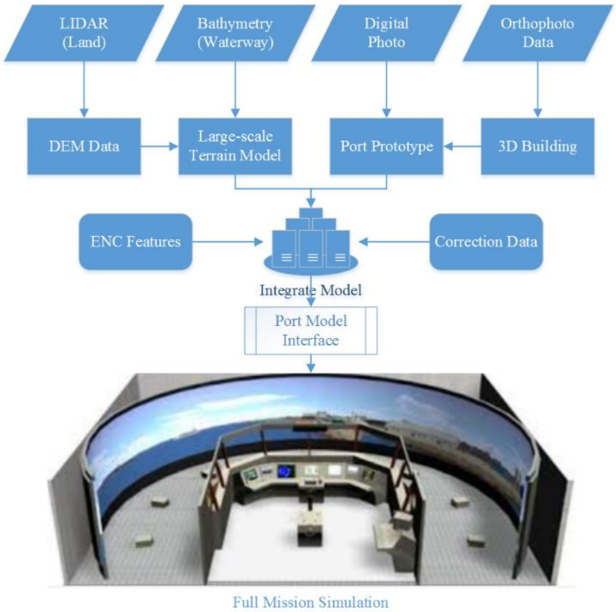


Fig. 3 the Process of Port Modelling

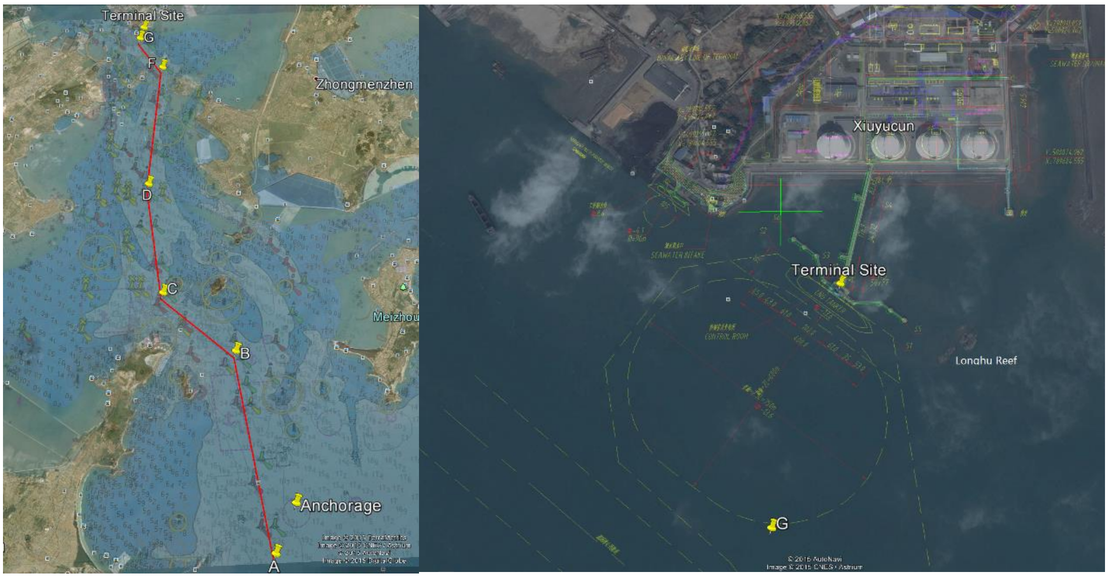


Fig. 4 the Site and Layout of the Terminal

Fig. 5 Aerial View of the Terminal

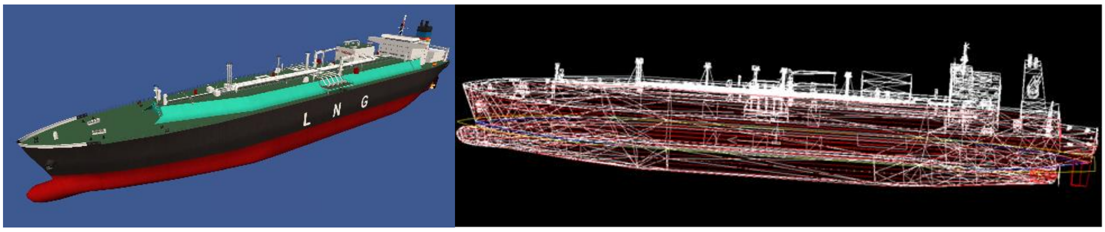


Fig. 6 3D Visual and Skeleton of the Q-Flex LNG carrier

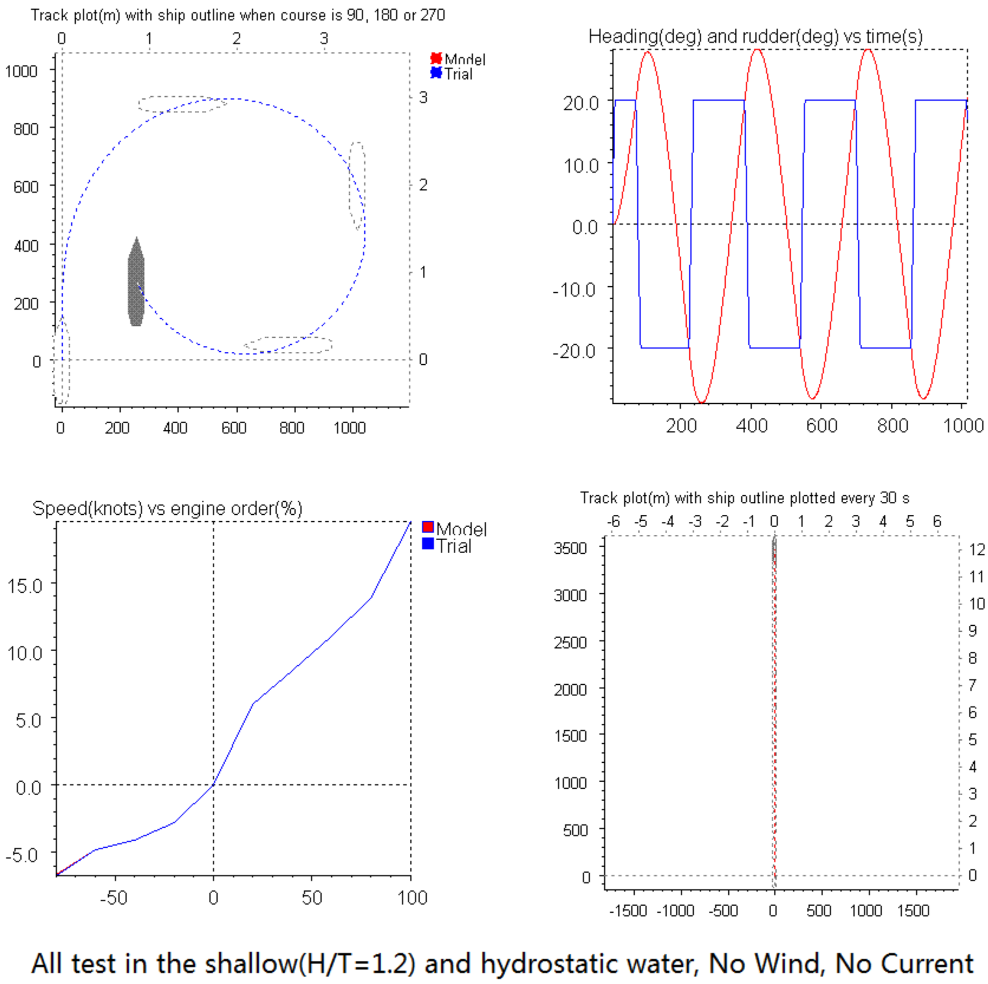


Fig. 7 Test Tracks for the Q-Flex Carrier

Fig. 8 Nautical Chart and 3D Model of the Fujian Terminal

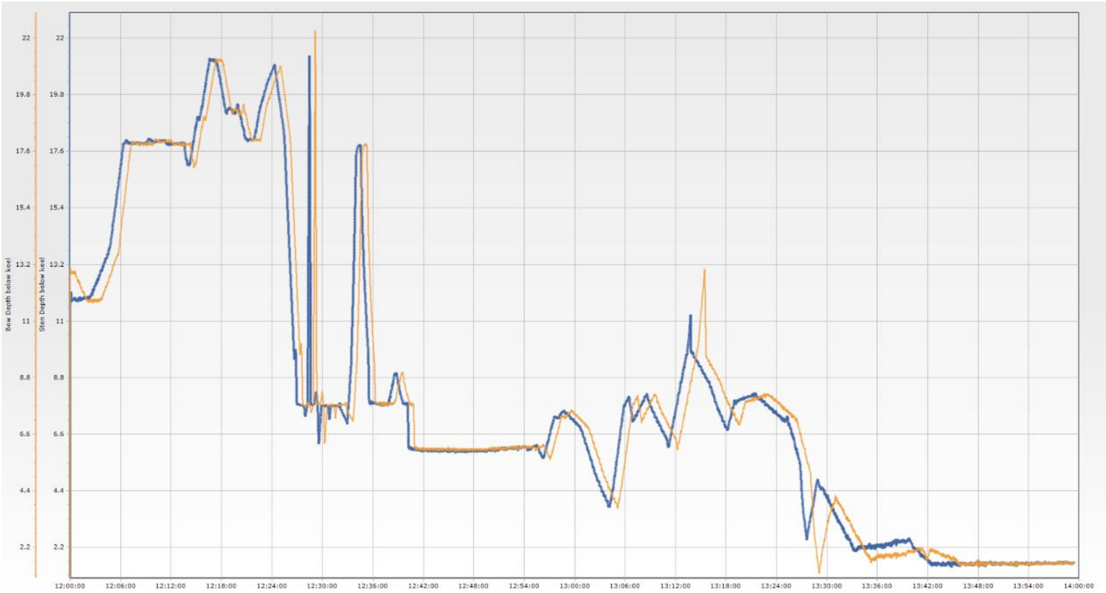


Fig. 9 Dynamic UKC of the Q-Flex Entering Port

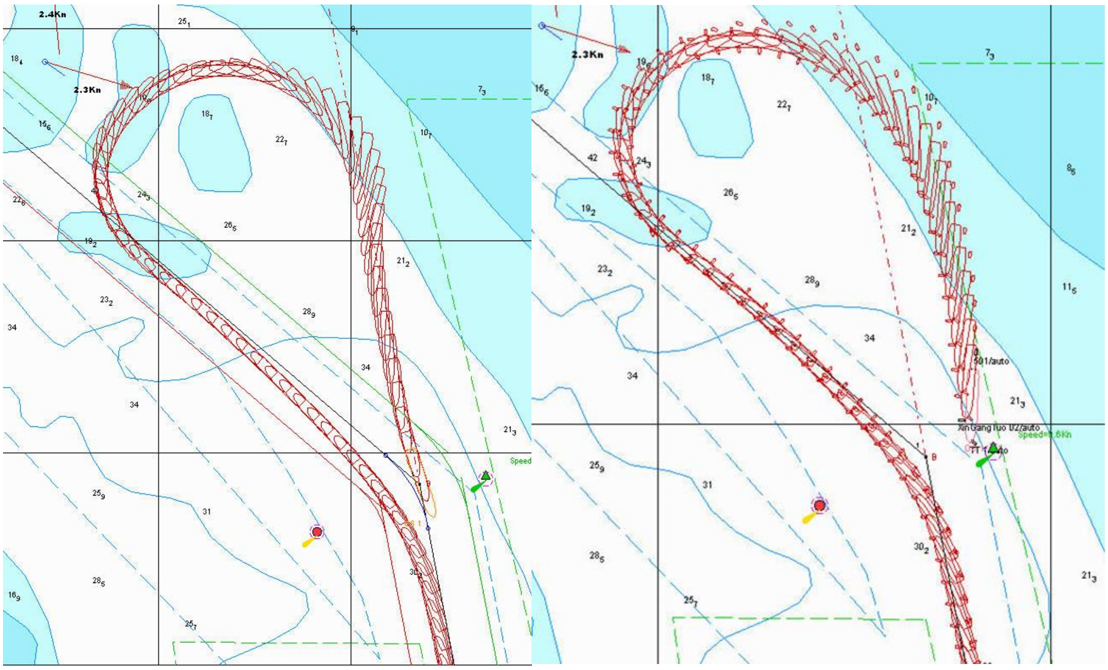


Fig. 10 Track of a Williamson Turn in the Channel

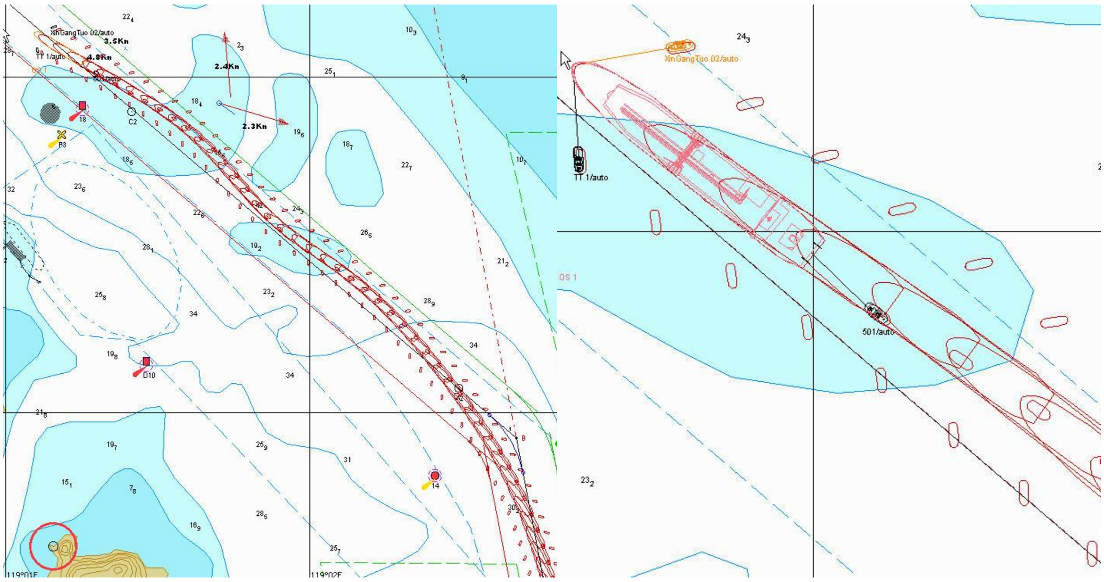


Fig. 11 Track of a Steering Gear Failure Emergency

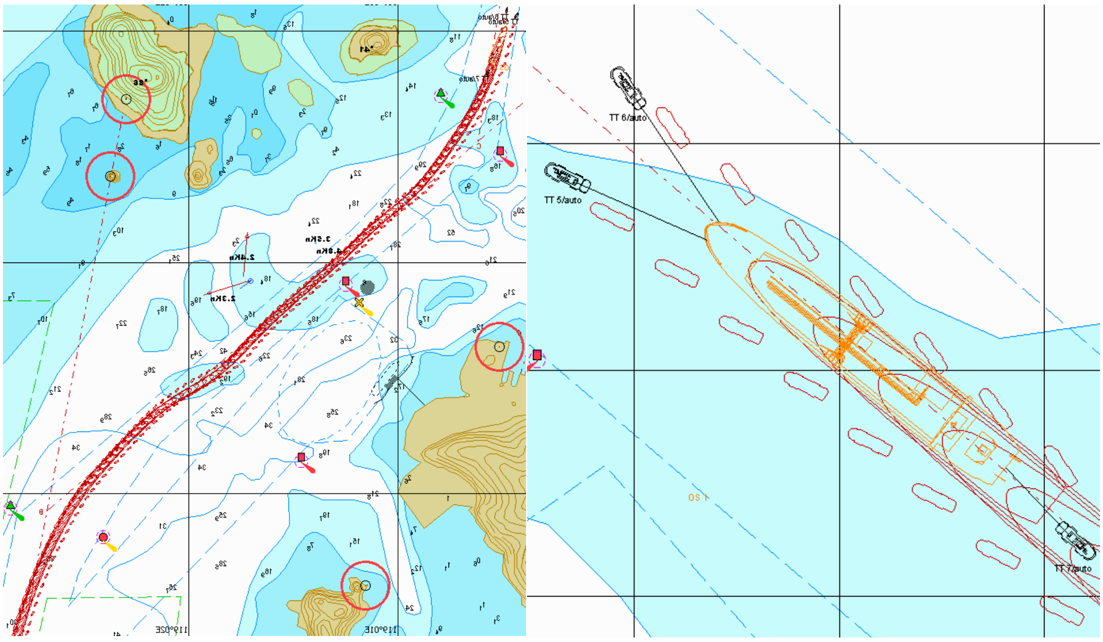


Fig. 12 Track of a Main Engine Failure Emergency

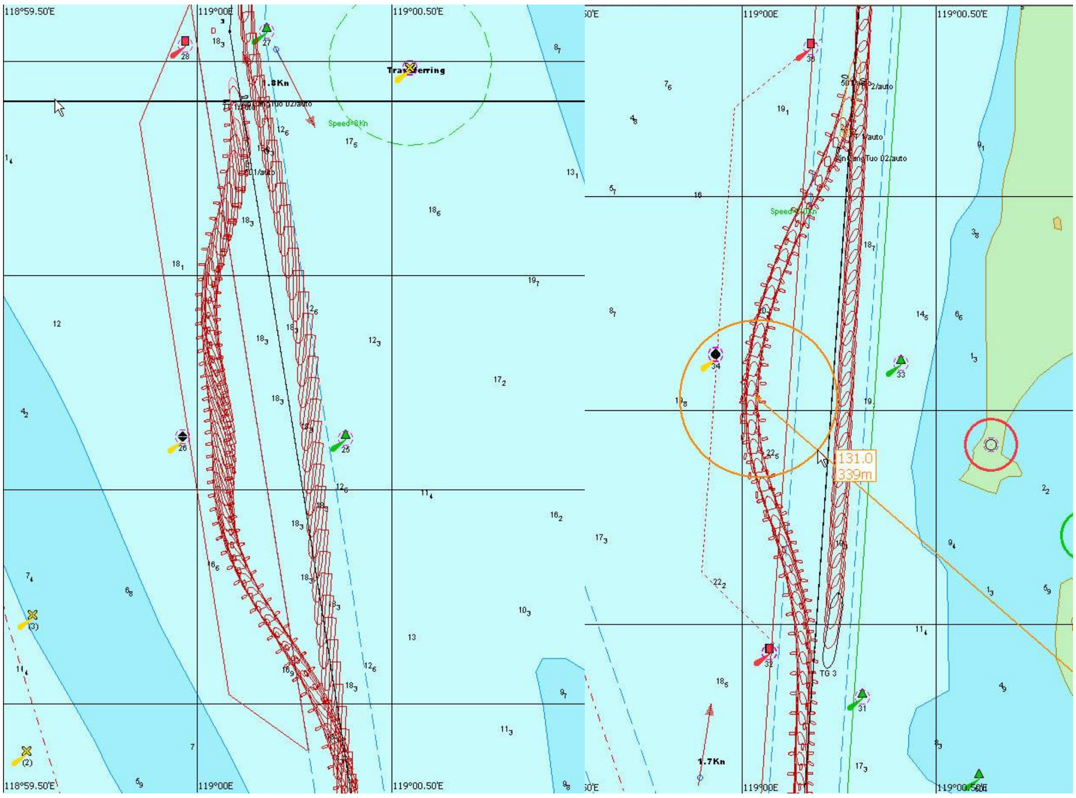


Fig. 13 Collision Avoidance with a 100,000 DWT Container in Sections C-D and D-F
(Ebb tides with a wind direction of SW and a velocity of 17 m/s)

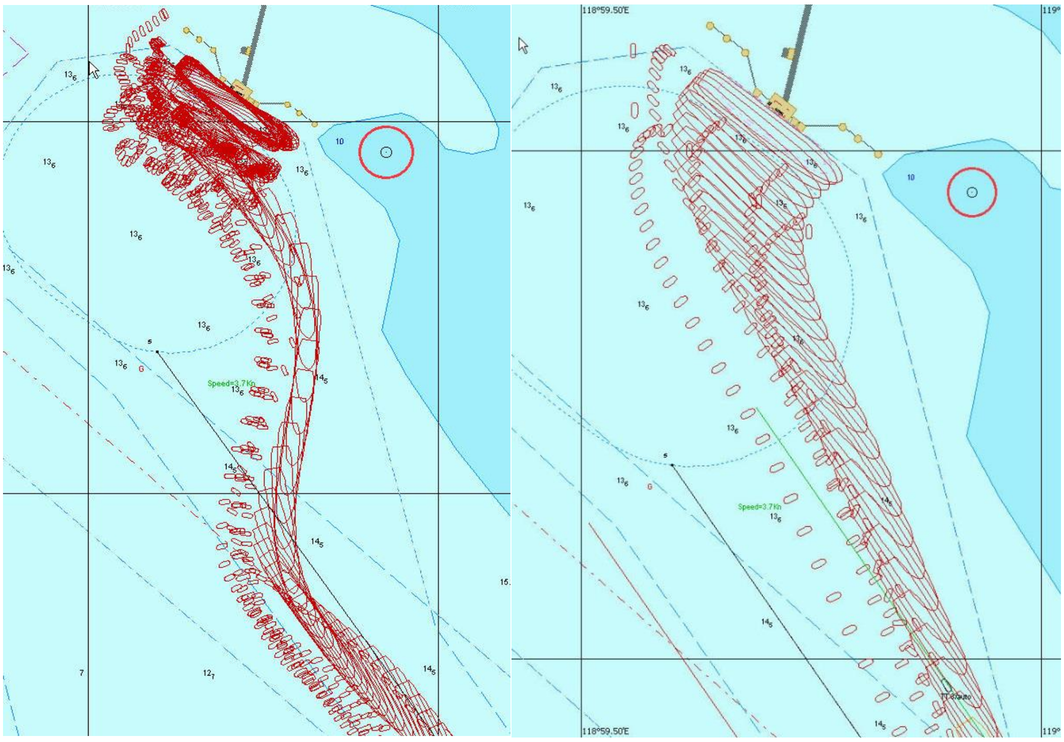


Fig. 14 Unberth in a Gale Emergency
(The beginning of a flood tide with a wind direction of SW and a velocity of 24 m/s, assisted by 6×5,000 HP of tugs)

Tables

Table 1 Parameters of Typical LNG carriers

Ship Name	Type of Tanks	Tank Capacity $\times10^3$[m^3]	Gross Tonnage $\times10^3$[t]	Length Overall Loa [m]	Beam B [m]	Draft T [m]
Surya Aki	Spherical	19	20.5	151	28.0	7.6
LNG Lerici	Membrane	36	40	216	33.0	9.5
Polar Alaska	Membrane	87	66	239	40.0	11.0
Northwest Seaeagle	Spherical	125	80	272	47.0	10.5
Inigo Tapias Golar	Membrane	132	90	270	42.0	11.0
Maran Gas Asclepius	Membrane	145	97.5	285	43.5	12.5
Muscat LNG	Spherical	145	118	289	49.0	11.9
Q-Flex	Membrane	216	136	315	50.0	12.0
Q-Max	Membrane	266	162	340	53.8	12.0

Table 2 Personnel Allocation in Simulations

Participant	Job Content Prescription	Remark
Simulation Instructor	In charge of executing the simulation program and undertaking the assessment	Director
Navigator	Handling the LNG carrier and giving the orders to the tugs in accordance with the designed simulation runs	Actor
Port Supervisor	Observer who verifies the simulation in accordance with the port's operational practices	
Port Authority	Observer who should understand the entire simulation program to guide the port	
Simulation Maintainer	Standby for the breakdown or failure of the simulator	

Table 3 Principle Parameters of the Q-Flex LNG carrier

Parameters		Q-Flex
Length overall (Loa) (m)		315
Length Between Perpendiculars (LBP) (m)		303.0
Breadth Moulded (m)		50.0
Draught (m)	Ballast	9.7
	Full	12.0
Displacement (m^3)	Ballast	108988.0
	Full	143400
Number of Rudders		2.0
Rudder Type		SEMI-SUSPENDED
Rudder area (m^2)		55.885
Number of Propellers		2.0
Propeller type		Fixed-Pitch
Propeller diameter (m)		7.7

Engine Type	Slow speed diesel engine
Engine internal power (kW)	2×16,650

Table 4 Details of the Tug Models

Tug Name	Bollard Pull (T)	Dimensions L×W×D (m)	Propulsion Shaft Power	Fire Fighting Capability (m^3/H)
HANHAI SHIYOU 501	60	37.7×10.4×4.8	"Z" DRIVE 1838kW(2500 HP)×2	2400
HANHAI SHIYOU 502	60	37.7×10.4×4.8	"Z" DRIVE 1838kW(2500 HP)×2	2400
XINGANG TUO 01	50	36×9.6×4.4	"Z" DRIVE 1471kW(2000 HP)×2	NA
XINGANG TUO 02	50	36×9.6×4.4	"Z" DRIVE 1471kW(2000 HP)×2	475
FUXIN TUO 01	50	35.5×9.8×4.3	"Z" DRIVE 1471kW(2000 HP)×2	360
FULIAN 801	40	32.8×9.5×4.3	"Z" DRIVE	360

Table 5 Simulation Runs for the Q-Flex under Normal Conditions

Run	Arr./ Dep.	Wind [kts]	Wave [m]	Tide [kts]	Operation	Tug	Turning Area Major Axis [m]	Turning Area Minor Axis [m]	Rating
N01	Arr.	20-25 NE	0.8-1.2 Outside	1.5-2.5 Flood	Bow Outside Portside Berth	2×5000 HP 2×4000 HP	583	499	5
N02	Arr.	20-25 SW	0.8-1.2 Outside	1.5-2.5 Flood	Bow Outside Portside Berth	2×5000 HP 2×4000 HP	622	508	4
N03	Dep.	20-25 NE	0.8-1.2 Outside	1.5-2.5 Flood	Bow Outside Portside Berth	2×5000 HP 2×4000 HP	669	541	5
N04	Dep.	20-25 SW	0.8-1.2 Outside	1.5-2.5 Flood	Bow Outside Portside Berth	2×5000 HP 2×4000 HP	607	522	5
N05	Arr.	20-25 NE	0.8-1.2 Outside	1.0-2.0 Ebb	Bow Outside Portside Berth	2×5000 HP 2×4000 HP	712	598	4
N06	Arr.	20-25 SW	0.8-1.2 Outside	1.0-2.0 Ebb	Bow Outside Portside Berth	2×5000 HP 2×4000 HP	756	582	3
N07	Dep.	20-25 NE	0.8-1.2 Outside	1.0-2.0 Ebb	Bow Outside Portside Berth	2×5000 HP 2×4000 HP	684	539	4
N08	Dep.	20-25 SW	0.8-1.2 Outside	1.0-2.0 Ebb	Bow Outside Portside Berth	2×5000 HP 2×4000 HP	744	548	3

Notes: The rating is the degree of safety of the approach, seaway, basin and berthing evaluated by the operator; the value is 1 to 5; the degree of safety is low if the value is low.

Table 6 Width of the Channel of the Q-Flex LNG carrier

Run	Arr. Speed	Arr. Drift Angle [°]	Track Width A-B [m]	Channel Width A-B [m]	Track Width B-F [m]	Channel Width B-F [m]	Track Width F-G [m]	Channel Width F-G [m]
N01	7.65	6.8	69	219	63	213	68	168
N02	7.82	7.7	65	215	62	212	69	169
N03	7.12	6.5	68	218	65	215	72	172
N04	6.93	6.3	82	232	79	229	85	185
N05	7.11	7.9	77	227	74	224	79	179
N06	7.32	8.7	84	234	83	233	93	193
N07	8.12	7.9	68	218	70	220	75	175
N08	7.94	9.3	70	220	72	222	81	181

Table 7 Width of the Channel in the Different Sections

	A-B	B-C	C-D	D-F
Width of Track [m]	88	147	96	148
Required Width of Channel [m]	238	297	246	298