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Conditions for the location of a universal LNG tanker berth designed for the port of Świnoujście

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Abstract
This article describes the methodology to design a universal berth for LNG discharge from tankers with a wide cargo capacity range of 500 m^3 to 220,000 m^3. Based on a waterway optimization simulation, the methodology has been used to determine parameters of the designed universal cargo handling berth located in the port of Świnoujście.

Introduction

The LNG facility in the Świnoujście port contains a universal terminal for handling LNG tankers, feeder ships, and LNG bunker ships ranging in capacity from 500 m^3 to 220,000 m^3.

- LNG bunker tankers with a capacity of 500 m^3 to 7500 m^3 are loaded only with LNG, and are intended for small customers and ships powered by that fuel;
- Feeders and LNG tankers with capacities in the range of 7500 m^3 – 220,000 m^3 are used for LNG discharge or loading.

Such assumptions and limitations of the loading systems of these vessels have created the basis for the creation of a universal LNG terminal in the outer port of Świnoujście. The terminal will be composed of two berths:

- No. 1 will be used for handling LNG tankers and feeders (vessels with cargo capacities from approximately 7500 m^3 to 220,000 m^3);
- No. 2 will be used to load LNG bunker ships (cargo capacities from approximately 500 m^3 to 7500 m^3).

The following limits are used to determine the minimum and maximum parameters of vessels expected to operate at these berths:

- The maximum vessel permitted to approach berth No. 1 is, according to investor guidelines, a Q-flex LNG tanker with a cargo capacity of up to 220,000 m^3.
- The maximum length of the smallest vessel allowed to approach berth No. 1 is limited by the fendering and mooring systems.
- The maximum length and draft of a vessel approaching the loading berth No. 2 is limited by:
  - The minimum distance of this berth from the shore.
  - The minimum safe maneuvering area for these vessels, situated between this berth and the shore.
  - The minimum depth of the safe maneuvering area situated between this berth and the shore.

The above limits and dimensions of existing LNG tankers and those being built (Analiza, 2008; 2017) specify the parameters of maximum and minimum gas tankers coming along berths Nos 1 and 2.

Given the above limitations, the ranges of overall length (LOA) of gas tankers approaching each berth and their maximum draft have been defined as:

- Un/loading berth No. 1
  - LOA = (110÷320) m,
  - T_{max} = 12.5 m;
- Loading berth No. 2
  - LOA = (50÷110) m,
  - T_{max} = 6.0 m.

The overall lengths of incoming gas tankers have been used to parameterize the fendering and mooring systems, while the maximum draft is used to determine the minimum depth of safe maneuvering areas and navigable areas.

Navigable areas of maximum vessels approaching the universal LNG terminal were determined using a simulation optimization method, which is also used to calculate safe maneuvering areas of Q-Flex gas tankers approaching berth No. 1, as well as the existing LNG discharge berth and the maximum of LNG bunker ships coming alongside berth No. 2.

Conditions for the safe operation of a designed universal LNG terminal in Świnoujście's outer port

Conditions for the safe operation of a designed LNG terminal in the outer port are determined by:

a) risks arising from LNG un/loading technology and the proximity of the existing discharge berth, which affects the location of a universal LNG terminal with loading and discharge functions in the outer port;
b) safety of maneuvering LNG tankers toward the universal terminal and the existing discharge berth, which is determined by the parameters of the navigable areas available to these ships;
c) safety of mooring and cargo transfer from/to LNG tankers along the universal terminal, which depends on the fendering and mooring system parameters;
d) acceptable hydrometeorological conditions for maneuvering and mooring LNG tankers.

Ad a) The construction of a universal LNG berth in the outer port of Świnoujście is limited by risks caused by the proximity of the existing LNG discharge berth.

The main hazards arising from the LNG cargo transfer operations affecting the location of the universal terminal and the mooring ships are as follows:

- leakage that, due to a technical failure or operator's error, may occur in the piping system including LNG transfer valves, on the ship or shore sides;
- damage to the transfer pipeline due to a failure to maintain a ship's position at berth, e.g., due to breakage of a ship's mooring lines;
- maneuvering of another ship near the tanker on which gas transfer is carried out.

Analyses of potential risks related to ship un/loading technology and ship maneuvering have led to the identification of risk zones in the outer port of Świnoujście. A border zone has been designated where the thermal radiation intensity shall not exceed 5 kW/m^2 (SANDIA, 2004; Budowa, 2018) because thermal radiation with such an intensity has no destructive impact on devices or stored cargo. In this area, rescue personnel wearing personal protective clothing may be present. The boundaries of the 5 kW/m^2 impact zone were used as the minimum distance for gas tanker mooring, which is measured from the manifold of one tanker to the side of another. The radius of thermal radiation intensity of up to 5 kW/m^2 will be approximately 550 m (Figure 1).

Ad b) Navigable areas within the outer port of Świnoujście were determined based on safe maneuvering areas of gas tankers and LNG bunker vessels, which, in turn, were defined by a ship movement simulation. A relevant analysis covered berthing maneuvers of Q-Flex tankers approaching the universal terminal (berth No. 1) and existing LNG discharge berth and maneuvering of an LNG bunker ship coming along berth No. 2.

Ad c) The universal LNG terminal is composed of two berths located on opposite sides of the technological platform:

- Dolphin berth No. 1, which is intended for handling gas tankers with LOA values ranging from 110 m to 315 m.
- Berth No. 2 with a low mooring and technological deck intended to handle LNG bunker ships with LOA values ranging from 50 m to 110 m.

The fendering system of the dolphin berth (berth No. 1) must meet the following requirements:

- The smallest LNG tankers to be handled (loaded and under ballast) must contact a minimum of two fenders with the flat parts of their sides.
- The maximum LNG tankers (LOA > 270 m) intended for operation should contact at least four fenders with the flat parts of their sides.
- Medium-size LNG tankers (180 m < LOA < 270 m) should have the flat parts of their hull interact with a minimum of three fenders.

The length of the flat part of the hull of LNG tankers (*lp*) relative to their overall length (LOA) depends on the ship's loading condition and ranges:

Figure 1. Preliminary location of the universal LNG transfer terminal and the existing LNG discharge berth

$$lp = (0.45 \div 0.55) \text{ LOA} \quad (1)$$

The flat surface of the side of an LNG tanker is offset relative to the manifold by approximately 0.25 *lp* toward the stern. Taking into account the above limits, we have determined the following line of five fenders distributed at intervals of 25 m, 15 m, 15 m / 30 m, and 25 m, suspended on four mooring-fender islands and one fender island (Figure 2).

The mooring system of berth No. 1 consists of the following mooring devices:

- Quick-release double mooring hooks with increased swivel angle.
- A capstan mounted at each mooring hook for heaving up mooring lines passed from the ship.
- A remote hook release system with a local release option.
- Mooring load determination and on-board monitoring systems.

The detailed choice of holding forces, swivel angles, and number of mooring hooks has been determined according to OCIMF guidelines (OCIMF, 2013) using a dynamic mooring load simulation program.

The design of mooring hook positions and calculation of their working loads is carried out by a graphic-analytical method, with the following assumptions:

- A distance between the extreme mooring devices should not exceed one-and-a-half lengths of the maximum ship length (1.5 LOA).
- The minimum number of mooring lines is four forward, four aft (double lines for LOA > 180 m) and three forward, three aft (double lines for LOA ≤ 180 m).
- Calculations are performed for the highest wind speeds occurring in the area concerned, perpendicular to the mooring line (pushing wind) and parallel to the mooring line (in the outer port of Świnoujście $V_w = 25$ m/s).
- The working load of the mooring hooks for the maximum tanker length has been determined to be an LOA of 315 m.

The bunker ship berth No. 2 should be constructed on the opposite side of the LNG tanker transfer platform. This berth must be equipped with a set of fenders mounted on a low mooring-technological deck. The intended height of the bridge and fenders should allow the handling of as many small-scale LNG vessels as possible, i.e., it should range from 1.2 m to 5 m above the water level.

The mooring diagram of LNG tankers with LOA values of 315 m and 110 m at berth No. 1 and bunker ships with LOA values of 110 m and 50 m at berth No. 2 of the universal terminal are shown in Figure 2.

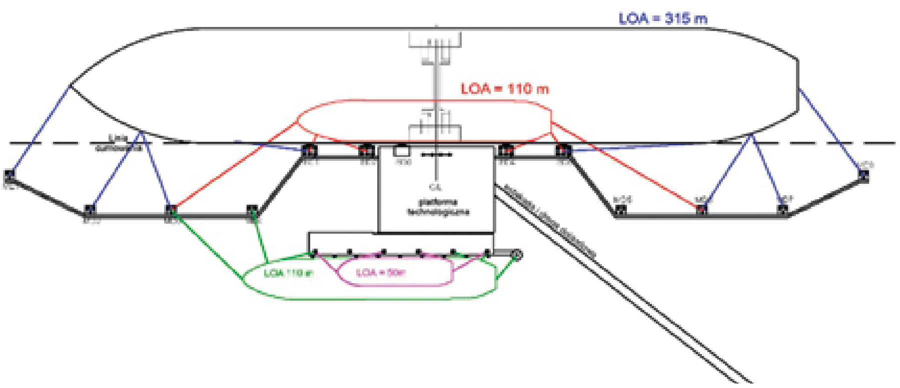

Figure 2. The mooring diagram of LNG tankers with LOA = 315 m and LOA = 110 m at berth No. 1, and for LNG bunker ships with LOA = 110 m and LOA = 50 m at berth No. 2

The kinetic energy absorbed by the fenders is determined by a computer simulation which modeled the most severe hydrodynamic conditions in which a vessel can maneuver.

Ad d) Allowable hydrometeorological conditions for LNG tankers and bunker ships arriving at the universal terminal:

- Allowable wind speed $V_w = 12.5$ m/s;
- Allowable current speed at buoys 15-16 is $V_p = 0.5$ knots;
- Minimum visibility $c = 1.0$ Nm.

The dimensions of navigable areas available for gas tankers and bunker ships approaching the berths of the universal LNG terminal were determined using computer simulations. Computer simulations generally involve actions aimed at creating simulation models and tests performed on these models. Computer simulations are used during the detailing stage of designing sea waterway systems (PIANC, 2014; Gucma et al., 2017). These methods make it possible to accurately specify safe maneuvering areas used or intended to be used by "maximum ships" in each section of the waterway during acceptable operation conditions for these ships at a preset confidence level $\mathbf{d}_{\mathbf{ijk}(1-\alpha)}$. Using basic navigation conditions, it is possible to determine the navigable waterway area $\mathbf{D}_{\mathbf{i}(\mathbf{t})}$ as a set of safe maneuvering areas in each (i) waterway section.

$$\mathbf{d}_{\mathbf{ijk}(1-\alpha)} \subset \mathbf{D}_{\mathbf{i}(\mathbf{t})} \tag{2}$$

where

$\mathbf{D}_{\mathbf{i}(\mathbf{t})}$ – navigable area in the i-th section of the waterway (the condition of safe depth at instant t is satisfied);

$\mathbf{d}_{\mathbf{ijk}(1-\alpha)}$ – the safe maneuvering area of the k-th ship performing a maneuver in the i-th section of the waterway in the j-th navigational conditions determined at a confidence level $1-\alpha$.

The simulation test procedure during marine traffic engineering is as follows (Gucma, Gucma & Zalewski, 2008):

- Problem formulation, including the indication of design objectives, simulation methods, and types of simulators to be used.
- Construction or choice of vessel movement models on a selected simulator and their verification.
- Design of the experimental system and performance of the experiment.
- Development and statistical analysis of the test results.

Computer simulation methods that determine a ship's safe maneuvering area width use the results obtained during the preliminary design stage.

The formulation of a research problem for a simulation experiment during waterway design involves these actions:

- Determination of a research objective.
- Determination of the level of confidence or acceptable risk for safe maneuvering area.
- Choice of a simulation method.
- Choice of the type of ship handling simulator.

Simulation tests were designed to determine the parameters of the universal LNG terminal (with berths Nos 1 and 2) and safe maneuvering areas of maximum vessels approaching berths No. 1 and No. 2 in the outer port of Świnoujście. The confidence level used for the determination of safe maneuvering areas was $(1-\alpha) = 0.95$.

The tests used of real-time simulation (RTS) and non-autonomous models of ships, where ship movement is controlled by a human (pilot or captain). Simulations were performed on a multi-bridge ship handling Polaris simulator from Kongsberg Maritime AS with a 3D projection. This full-mission bridge simulator (FMBS) is located at the Marine Traffic Engineering Centre, Maritime University of Szczecin.

Two simulation ship movement models were built and verified for testing the maneuvers of port entry and berthing. The models represent a Q-Flex tanker and an LNG bunker ship with a 6000 m^3 cargo capacity (Table 1).

Table 1. Basic parameters of modelled ships

Name	Q-Flex type LNG tanker 216,000 m^3	LNG bunker ship 6000 m^3
1. Length overall – LOA	320	104
2. Length between perpendiculars – L_{PP} [m]	308	98.00
3. Breadth – B	51.0	16.6
4. Draft – T	12.5	6.0
5. Front windage area – A_{AF} [m^2]	1790	350
6. Lateral windage area – A_{AL} [m^2]	6800	900
7. Nominal power ME – BHP [kW]	35 800	3 600
8. Nominal rpm ME/propellers – rpm [min^{-1}]	87	146
9. Propeller	convent.	cpp
10. Propeller diameter – D [m]	9.00	4.1
11. Prop. pitch ratio – P/D [m]	0.852	0.689
12. Rudder	conventional 35	conventional 45 (Becker)
13. Bow thruster (power)	–	400 kW

Experimental simulations of entry, turning, and berthing to berth No. 1 by a Q-flex tanker were conducted using the least-favorable wind directions N and W for these maneuvers and a speed (V_w) of 12.5 m/s. Four tugs assisting in the maneuvers had azimuth propellers and a bollard pull of 2×55 tons and 2×45 tons.

The simulation experiment of entry, turning, and berthing to the berth No. 2 by an LNG bunker ship with a 6000 m^3 capacity was performed under the least-favorable wind directions N and E, at a speed (V_w) of 12.5 m/s. The maneuvering ship was assisted by one pushing tug with a bollard pull of 15 tons.

The width of the safe maneuvering area at the j-th point of the port basin for a specific series of simulated maneuvers (test series) was determined from the following relationship (Gucma et al., 2015):

$$d_{(1-\alpha)} = \left(\bar{y}_{lj} + cm_{lj}\right) + \left(\bar{y}_{pj} + cm_{pj}\right) \tag{3}$$

where

$d_{(1-\alpha)}$ – width of the safe maneuvering area at the *i-th* point of the waterway at the confidence level $1-\alpha$;

$\bar{y}_{lj}$ – arithmetic mean of the maximum distances of a ship's point to the left of the j-th point of waterway center line;

$\bar{y}_{pj}$ – arithmetic mean of the maximum distances of a ship's point to the right of the j-th point of waterway center line;

m_{lj}, m_{pj} – standard deviations of a test series for the maximum distances of the j-th point of the waterway;

c – coefficient dependent on the adopted level of confidence (e.g., $c = 1.96$ for the confidence coefficient $(1-\alpha) = 0.95$).

$$\bar{y}_{lj} = \frac{1}{n}\sum_{i=1}^{n} y_{lij} \tag{4}$$

$$\bar{y}_{pj} = \frac{1}{n}\sum_{i=1}^{n} y_{pij} \tag{5}$$

were

y_{lij} – maximum distance to the left from the j-th point of the waterway center line in the i-th simulation test of the ship;

y_{pij} – maximum distance to the right from the j-th point of the waterway center line in the i-th simulation test of the ship;

$$m_{lj} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(y_{lij} - \bar{y}_{lj}\right)} \tag{6}$$

The relationship is similar to the right-hand part of the waterway.

The determination of maneuvering areas was based on the parallel-strip and polar methods.

For each simulation test series of berthing, the average kinetic energy absorbed by the fender-berth system, its standard deviation, and energy at the 95% confidence level are calculated. The berthing energy at the instant of a ship's first contact with the berth is calculated from the following relationship (Gucma et al., 2015):

$$E = \frac{1}{2}mu_o^2\left(1 - \frac{a^2}{k^2 + r^2}\right) - mu_o\omega_o\frac{k^2 \cdot a}{k^2 + r^2} + \frac{1}{2}m\omega_o^2\frac{k^2 \cdot r^2}{k^2 + r^2} \quad \text{[kNm]} \tag{7}$$

where:

m – virtual mass of the ship [t];

u_o – linear speed of the ship, normal to the berth line [m/s];

ω_o – ship's rate of turn [1/s];

r – distance between the ship's center of gravity and the point of contact with the berth [m];

a – distance between the ship's center of gravity and the point of contact with the berth projected on the line of berth [m];

k – distance between the ship's center of gravity and the point of contact with the berth projected on the diametrical line of the ship [m].

The following times required for each series of maneuvers were calculated:

- The average time to perform entry, turning, and berthing maneuvers of a Q-flex gas tanker, from the moment of passing the entrance groin to the first contact of the tanker's hull with the berth.
- The average time for the approach maneuver at berth No. 2 and mooring of an LNG bunker ship 6000 m^3 from the center to the turning basin to the moment of first contact with the berth.

The optimization of sea waterways system parameters is carried out when such systems are built or rebuilt (water area and navigational subsystems). The parameters of marine waterway system components are a function of the designed (i.e. assumed) safe ship operating conditions.

The costs of construction and operation of the waterway system and the corresponding costs of the navigation system depend on both the size and depth of the available navigable area.

The main objective of marine waterway parameter optimization is the minimization of construction and/or reconstruction costs of waterway elements and the subsequent operation and maintenance costs of waterway subsystems. Given these requirements, the objective of the optimization of waterway parameters can be written in this form (Gucma et al., 2017; Gucma, 2017).

$$Z = F\left(\mathbf{D_i}, h_{xy}\right) \rightarrow \min \tag{8}$$

For sea waterways with permanent depths (Q-Flex depth h = 14.5 m, bunker ship depth h = 7.3 m), the objective function can be written as follows:

$$Z = F\left(\mathbf{D_i}\right) \rightarrow \min \tag{9}$$

with the constraint:

$$\mathbf{d_{i(1-\alpha)}} \subset \mathbf{D_{i(t)}} \tag{10}$$

The optimal navigable area (depth contour 14.5 m) is determined using safe maneuvering areas of Q-Flex gas tankers approaching the designed universal LNG terminal (berth No. 1) and the existing LNG discharge berth with a least favorable wind direction (V_w) of 12.5 m/s (Figure 3).

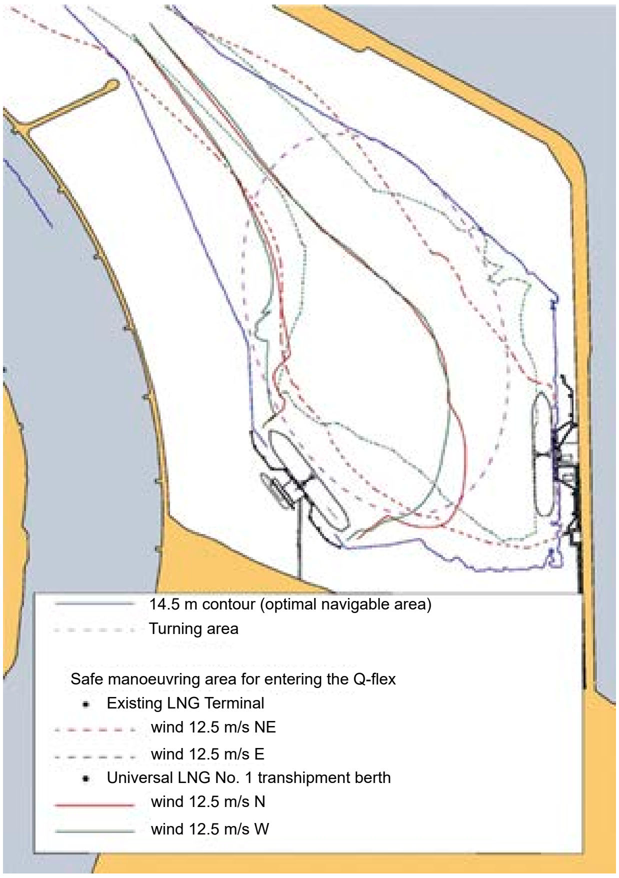

Figure 3. The available navigable area (depth contour 14.5 m) and safe maneuvering areas of Q-Flex gas tankers approaching the existing LNG discharge berth and to berth No. 1 of a designed universal transhipment berth

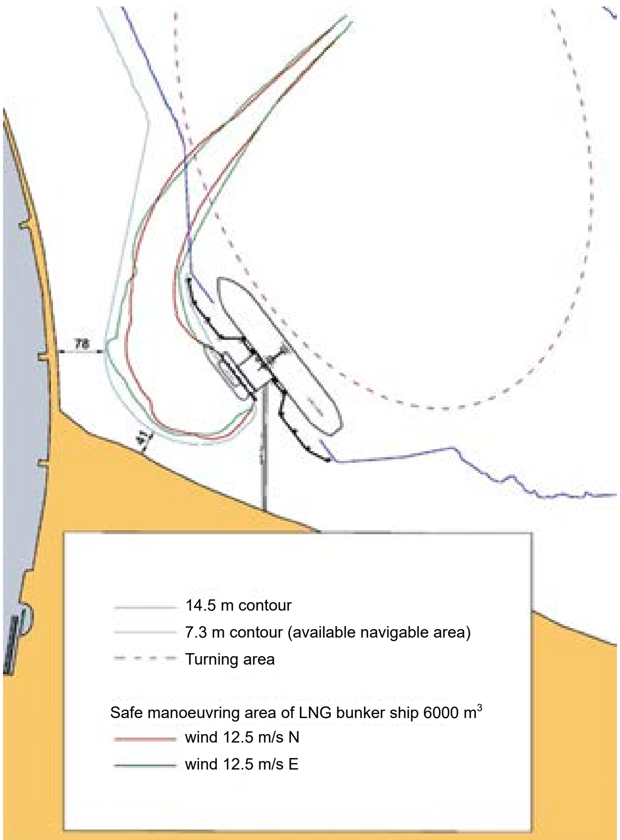

Figure 4. The available navigable area (depth contour of 7.3 m) and the safe maneuvering area of 6000 m^3 for an LNG bunker ship approaching berth No. 2 of the designed universal LNG terminal

The optimized navigable area (depth contour of 7.3 m) has been determined using the safe maneuvering areas of 6000 m^3 for an LNG bunker ship approaching berth No. 2 at the universal terminal with the least favorable wind direction $V_w = 12.5$ m/s (Figure 4).

The kinetic energy of first ship-berth contact absorbed by fenders, determined at a confidence level $(1–\alpha) = 0.95$ is, respectively:

- Q-flex LNG tanker: $E = 1100$ kNm;
- LNG Bunker 6000 m^3: $E = 100$ kNm

and the average maneuvering times:

- Q-flex LNG tanker, from the groin of the central breakwater abeam until the first contact with berth $t = 45$ min;
- LNG bunker 6000 m^3 from the turning basin center to the moment of first contact with the berth $t = 17$ min.

Conclusions

This article presents test results where simulations were used to optimize waterway parameters, which allowed the determination of:

- The optimal location in the outer port of Świnoujście of a universal terminal for LNG operations of small bunker ships, feeders and large LNG tankers, with a total range of cargo capacity from 500 m^3 to 220,000 m^3.
- Parameters of the universal LNG terminal consisting of two berths: No. 1 for the handling of LNG tankers with lengths from 110 m to 320 m and a draft $T \leq 12.5$ m, and No. 2 for loading LNG bunker ships with lengths of 50 m to 110 m and a draft $T \leq 6.0$ m.
- Optimal parameters of available navigable waters with a depth (h) of 14.5 m for LNG tankers handled at berth No. 1 and with a depth (h) of 7.3 m for LNG bunker ships handled at berth No. 2.

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