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Safety of manoeuvring, mooring and unloading of LNG carriers in the outer port of Świnoujście

Bezpieczeństwo manewrów cumowania i przeładunków zbiornikowców LNG w porcie zewnętrznym Świnoujście

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Key words: LNG terminal, safety of maneuvering, outer port of Świnoujście

Abstract

First LNG import terminal on the Baltic Sea will be located in Poland at the outer port of Świnoujście. Safe entrance to the port of LNG carrier (vessel of length abt. 300 m) to the terminal requires considering of technical and navigational aspects, as well as fulfilment of series of safety criteria related to manoeuvring, mooring and unloading of LNG C carrier (LNGC). Complex manoeuvring, mooring and unloading safety assessment of LNG in port, might be done as an assessment of particular types of manoeuvres and exploitation operations. Paper describes all those aspects and show procedure of LNG terminal design with navigational and operational problems consideration.

Słowa kluczowe: terminal LNG, bezpieczeństwo manewrowania, port zewnętrzny w Świnoujściu

Abstrakt

Pierwszy w rejonie Morza Bałtyckiego terminal odbiorczy LNG zostanie wybudowany w porcie zewnętrznym Świnoujście. Bezpieczne wejście statków LNG do portu (długość ok. 300 m) oraz terminalu, wymaga rozważenia wielu aspektów zarówno nawigacyjnych, technicznych, jak również wypełnienia kryteriów bezpieczeństwa dotyczących manewrowania, cumowania oraz rozładunku statków LNG (LNGC). Kompleksowe oszacowanie bezpieczeństwa statków LNG w porcie może być wykonane jako oszacowanie poszczególnych typów manewrów oraz operacji. W artykule opisano wszystkie te problemy oraz przedstawiono procedury projektowania terminalu LNG w aspekcie wspomnianych problemów nawigacyjnych i obsługi terminalu. Całościowe ujęcie tematu zostało przedstawione w [1].

Introduction

Safe entrance to the port of LNG carrier (vessel of length abt. 300 m) to the terminal requires considering of technical and navigational aspects, as well as fulfilment of series of safety criteria related to manoeuvring, mooring and unloading of LNG carrier (LNGC).

Complex manoeuvring, mooring and unloading safety assessment of LNG C in port, might be done as a assessment of particular types of manoeuvres and exploitation operations.

As specific navigational problems, port manoeuvres and operation of LNGC in port following can be characterized:

– Baltic Sea passage navigational safety,
– port approach manoeuvres,
– entering to the port manoeuvres,
– turning of LNGC inside port area,
– under keel clearance during entrance to port,
– mooring manoeuvres to the unloading terminal (mooring and unmooring),
– stay of vessel at terminal,
– unloading operations.

Safety of each of these operations and manoeuvres is assessed with different criteria. Fulfilment of these criteria relies on navigational and operational conditions, like type of vessel and area. These conditions might be different for particular types of operations.

Baltic Sea passage

Two alternative localisations on polish coast have been considered (western in Świnoujście and eastern in Gdańsk). To chose final localisation several aspects have been considers. One of them was probability of navigational accident during passage to terminal. To solve this problem specially designed model of navigational safety have been applied.

In authors opinion the most appropriate approach to assess the safety of complex marine traffic engineering systems is stochastic simulation models [2, 3]. The model presented in figure 1 could be used for almost all navigational accidents assessment like collisions, groundings, collision with fixed object [3], indirect accidents such as anchor accidents or accidents caused by ship generated waves. The model could comprise several modules responsible for different navigational accidents.

This methodology has been used already by several authors before with different effect [4, 5]. In presented studies the model was used to assess the safety of different variants of LNG terminal localisation.

The presented models of collisions, fire and groundings have adapted to the stochastic model of safety determination. The models were adjusted to LNG carriers according to available statistical data. Several experiments were performed with total real time duration of 6634 years for grounding and 3195 years for collision. The long time of experiments is necessary to achieve of statistical stable results. The accidents are very rare events. The navigational conditions and ships traffic was not changed during the experiment. The ships traffic was estimated on level of 2005 year. The LNG traffic was estimated to 2 LNG carriers passages per week – one entrance and one departure from Baltic Sea (96 per year).

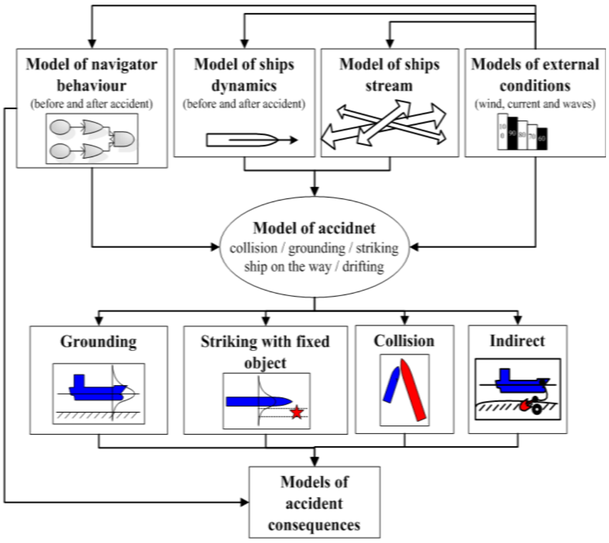

Fig. 1. Diagram of fully developed stochastic model of navigation safety assessment
Rys. 1. W pełni opracowany model stochastyczny szacowania bezpieczeństwa nawigacyjnego

The simulated places of LNG carriers collisions are presented in figure 2. The quantitative results are presented in table 1. The routes of highest collision probability are the S2, G1 and G4.

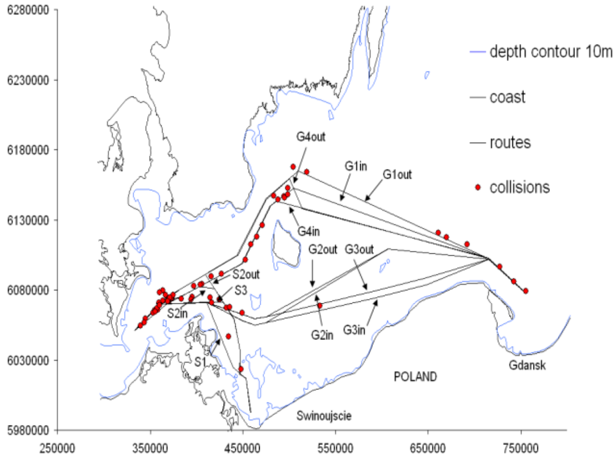

Fig. 2. Places of simulated collisions and fires on LNG board (cumulated simulation time)
Rys. 2. Obszary symulowanych kolizji oraz pożarów na statkach LNG (całkowity czas symulacji)

Table 1. Safety factors on given ships routes with consideration of grounding, fire and collision accidents
Tabela 1. Współczynniki bezpieczeństwa na danych trasach statków z uwzględnieniem wejścia na mieliznę, pożaru oraz kolizji statków

LNG route	No. of groundings	P_{ag}(year)	No. of fires	P_{af}(year)	No. of collisions	P_{ac}(year)
S1	6	9.04E–04	2	6.26E–04	5	1.56E–03
S2	4	6.03E–04	2	6.26E–04	9	2.82E–03
S3	16	2.41E–03	3	9.39E–04	7	2.19E–03

Port approach maneuvers determination of approach waterway parameters

To find the navigation safety and determine waterway parameters during port approach of LNG carrier to Świnoujście fast time simulation (FTS) model have been applied. Model is based on similar to one presented in chapter 4 and 5 to but instead of navigator is controlled by mathematics model of navigator [6]. Fundamental advantages of fast time simulations are:

- a great number of ship passages in the examined waterway executed in a short period of time,
- many initial variants of research can be considered,
- low cost.

Model of ships control is presented in [7] and is based on following PID controller:

$$G(s)=\frac{u(s)}{e(s)}=\frac{e^{-sT_0}}{(1+sT_{nm})(1+sT_r)}\left(k_P+sk_D+\frac{k_I}{s}\right) \qquad (1)$$

where: T_0 – delay time, T_{nm} – time constant characterizing the inertia of human nervous and muscular systems, T_r – another time constant of inertia dependent on object control, k_P, k_D, k_I – the proportional, derivative and integral gains.

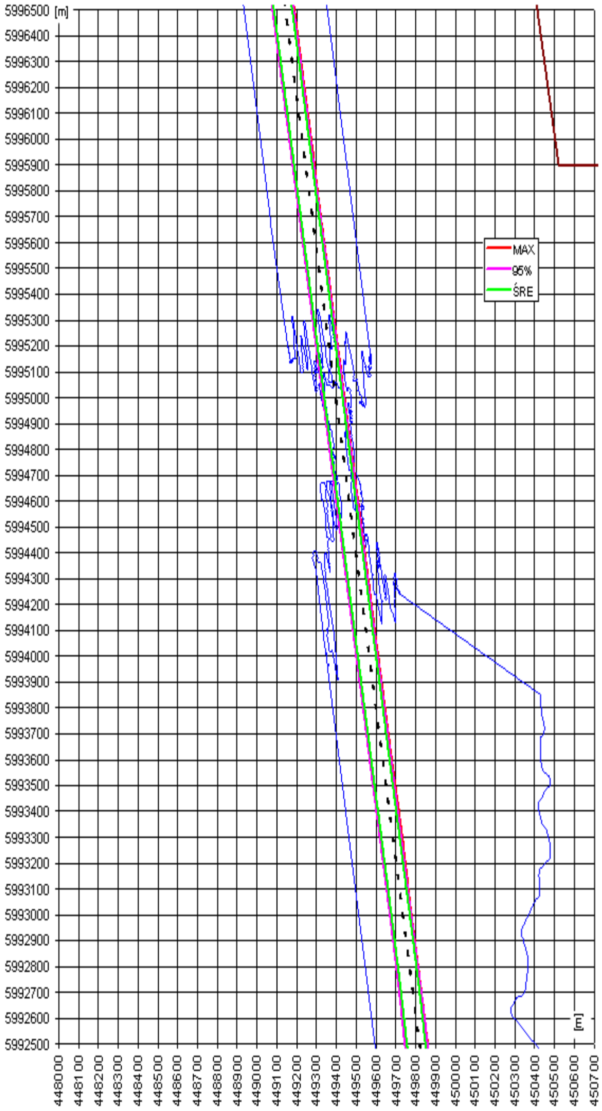

Fig. 3. Safety waterway obtained by FTS model of LNG 200 during entrance to Świnoujście port. Wind W 12,5 m/s (MAX – maximal waterway width, 95% – waterway width on 95% level)

Rys. 3. Bezpieczny tor wodny określony modelem FTS tankowca LNG o długości 200 m, podczas wejścia do portu Świnoujście. Wiatr W 12,5 m/s (MAX – maksymalna szerokość toru wodnego, 95% – schemat modelu symulacyjnego)

Example path of LNG carriers approaching to Świnoujście obtained by several passages of ships approaching to port is presented in figure 3. The safe width for typical examined LNG 200 m^3 on approach should be more than 180 m to fulfill the safety criteria and 0,9995 probability of no accident during passage.

Entering to port – determination of entrance breakwater layout

The real time simulation model have been applied to determine the safety of LNG maneuvering in port and on close approach. The model used in researches is based on modular methodology where all influences like hull hydrodynamic forces, propeller drag and steering equipment forces and given external influences are modelled as separate forces and at the end summed as perpendicular, parallel and rotational ones.

The model is operating in the loop where the input variables are calculated instantly (settings and disturbances) as the forces and moments acting on the hull and momentary accelerations are evaluated and speeds of movement surge, sway and yaw. The most important forces acting on the model are:

1) thrust of propellers,
2) side force of propellers,
3) sway and resistant force of propellers,
4) bow and stern thrusters forces,
5) current,
6) wind,
7) ice effects,
8) moment and force of bank effect,
9) shallow water forces,
10) mooring and anchor forces,
11) reaction of the fenders and friction between fender and ships hull,
12) tugs forces,
13) other depending of special characteristics of power and steering ships equipment.

The functional idea of the ship manoeuvring simulation model is presented in figure 4.

Interface of model is typical 2D chart interface (fig. 5). The interface covers information of ships state (position, course speed, yaw etc), quay and shore line location, navigational markings, soundings, external conditions, tug and line control and control elements of the model. The model is implemented in Object Pascal with use of Delphi™ environment and Visual C™ with use of C++ language.

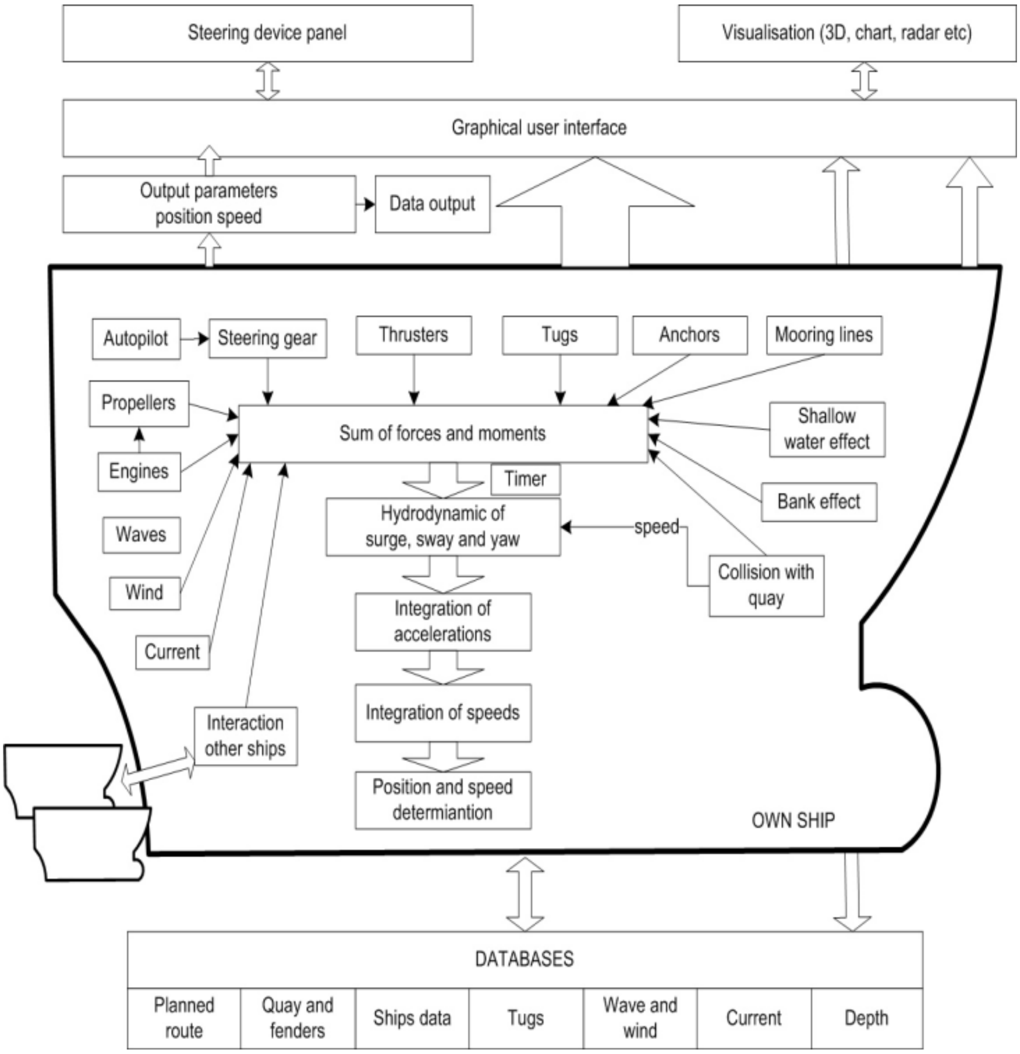

Fig. 4. The main diagram of simulation model
Rys. 4. Schemat główny modelu symulacyjnego

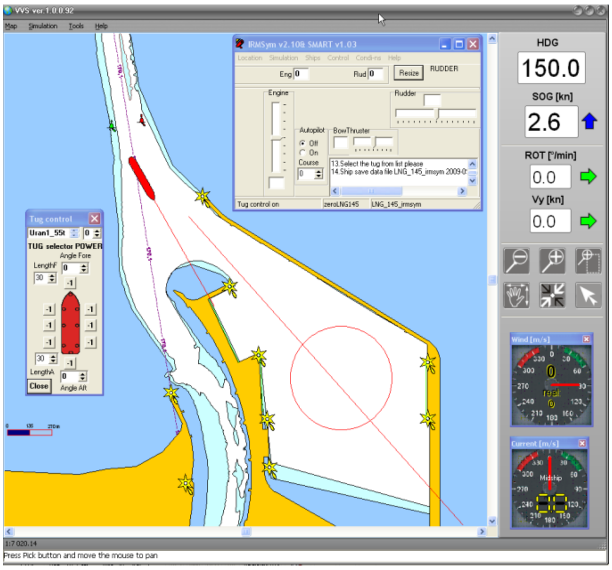

Fig. 5. Interface of simulation model
Rys. 5. Interfejs modelu symulacyjnego

Limiting to the usual 3DOFs (the horizontal planar motion), the ship movement over the ground (thus the so-called dynamic effect of the water current is introduced) is given by [8]:

$$\begin{cases} (m+m_{11})\dfrac{\mathrm{d}v_x^g}{\mathrm{d}t} = (m+c_m m_{22})\,v_x^g\omega_z + \\ \qquad + (m_{11}+c_m m_{22})\,v_y^c\omega_z + F_x \\ (m+m_{22})\dfrac{\mathrm{d}v_y^g}{\mathrm{d}t} = -(m+m_{11})\,v_x^g\omega_z + \\ \qquad + (m_{11}+m_{22})\,v_x^c\omega_z + F_y \\ (J_z+m_{66})\dfrac{\mathrm{d}\omega_z}{\mathrm{d}t} = -(m_{22}-m_{11})(v_x^g - v_x^c)(v_y^g - v_y^c) + \\ \qquad + M_z \end{cases} \tag{2}$$

$$\frac{\mathrm{d}x_0}{\mathrm{d}t} = v_{NS}^g\,, \quad \frac{\mathrm{d}y_0}{\mathrm{d}t} = v_{EW}^g\,, \quad \frac{\mathrm{d}\psi}{\mathrm{d}t} = \omega_z \tag{3}$$

$$\begin{bmatrix} v_{NS}^{g} \\ v_{EW}^{g} \end{bmatrix} = \begin{bmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{bmatrix} \cdot \begin{bmatrix} v_{x}^{g} \\ v_{y}^{g} \end{bmatrix} \tag{4}$$

where: $v_x{}^g$, $v_y{}^g$, ω_z – ship surge, sway and yaw velocity over the ground, x_0, y_0, ψ – position Cartesian coordinates and heading, m – ship mass, m_{11}, m_{22}, m_{66} – added masses, c_m – empirical factor, F_x, F_y, M_z – external excitations (resultant/total surge, sway force and yaw moment), generally consisting of the following items (denoted by additional subscripts) and being generally the functions of ship speed through the water ('v_w'):

$$\begin{cases} F_x = F_x\left(v_x^w, v_y^w, \omega_z\right) \\ F_y = F_y\left(v_x^w, v_y^w, \omega_z\right) \\ M_z = M_z\left(v_x^w, v_y^w, \omega_z\right) \end{cases} \tag{5}$$

$$v_x^w = v_x^g - v_x^c, \quad v_y^w = v_y^g - v_y^c \tag{6}$$

$$\begin{bmatrix} v_x^c \\ v_y^c \end{bmatrix} = \begin{bmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{bmatrix} \cdot \begin{bmatrix} \left|\vec{v}^{\,c}\right| \cos\gamma_c \\ \left|\vec{v}^{\,c}\right| \sin\gamma_c \end{bmatrix} \tag{7}$$

where: $\left|\vec{v}^{\,c}\right|$ and γ_c represent the velocity and geographical direction of the water current (a uniform current by default).

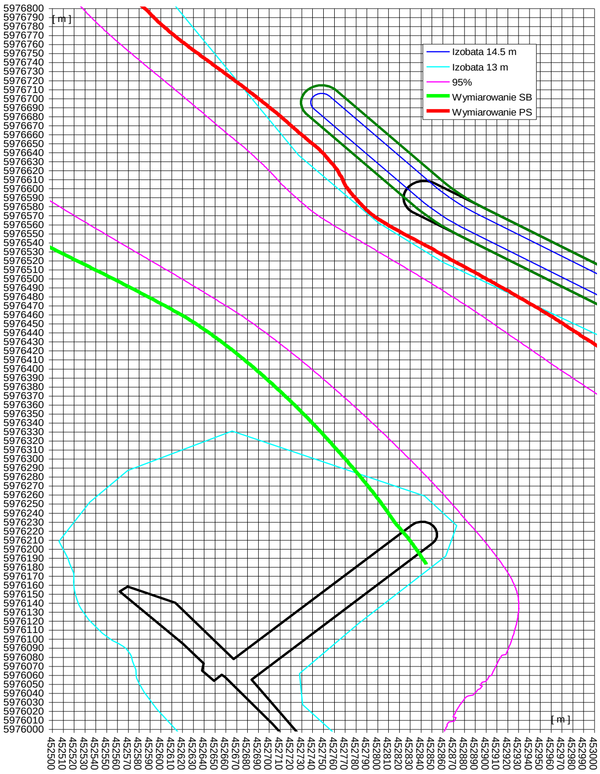

Fig. 6. Stages of development of final shape of entrance breakwaters
Rys. 6. Etap opracowania ostatecznego kształtu falochronu wejściowego

Example of results obtained by the model is presented in figure 6 where steps leading to obtain final shape of entrance breakwater are presented.

Safety of LNG turning manoeuvres in Świnoujście port

Main safety of navigation condition during manoeuvre of turning can be formulated as follows:

$$\left.\begin{array}{ll} p(x,y) \in D(t) & d_{ijk} \subset D(t) \\ h(x,y,t) \geq T(x,y,t) + \Delta(x,y,t) & \end{array}\right\} \tag{8}$$

where: $D(t)$ – accessible navigational area (meeting the condition of accessible depth at moment t), d_{ijk} – accessible manoeuvring area (traffic lane) of the i-th vessel, performing the j-th manoeuvre in k-th navigational conditions, $h(x, y, t)$ – the depth of the area at point with coordinates (x, y) at moment t, $T(x, y, t)$ – the draft of the vessel at area point with coordinates (x, y) at moment t, $\Delta(x, y, t)$ – underkeel clearance at area point with coordinates (x, y) at moment t.

Sets of points of the accessible navigational area $D(t)$, as also the safe manoeuvring area d_{ijk} can be identified with areas of definite linear parameters.

These criteria were applied to estimation of accessible area in outer port of Świnoujście. Simulation method were developed for this purpose. Simulations were carried out at simulators in Marine Traffic Engineering Centre over Kongsberg's Polaris full mission simulator. Researches were conducted on 3 types of mathematical LNGC's models:

- s/v Exmar Excalibur capacity = 138 000 cu.m., Loa = 277.0 m,
- s/v Umm Bab capacity = 145 000 cu.m., Loa = 285.4 m,
- m/v Al Gatarra (QFlex) capacity = 216 000 cu.m., Loa = 315.0 m.

Manoeuvres of turning were conducted at wind conditions of 12.5 m/s (different directions), with 4 tugs:

- tugs of pulling force 48 t (azipod drive),
- tugs of pulling force 30 t (conventional drive).

Full mission Simulator made by Kongsberg Polaris™ located at Marine Traffic Engineering Centre (MTEC) premises in Maritime University of Szczecin have been applied in this stage of researches. The MTEC simulator comprises (fig. 7):

- one full mission navigation bridge simulator with 270° visual projection and live marine ship equipment (DNV class A),

Fig. 7. Bridge A at MTEC (with 270° visual projection)
Rys. 7. Mostek symulatora CIRM (z 270° projekcją wizji)

- two part task navigation bridges with 120° visual projection and mix of real and screen-simulated ship-like equipment including one Voith-Schneider tug console (DNV class B),
- two desktop PC simulators with one monitor visual projection and one monitor screen-simulated ship-like equipment.

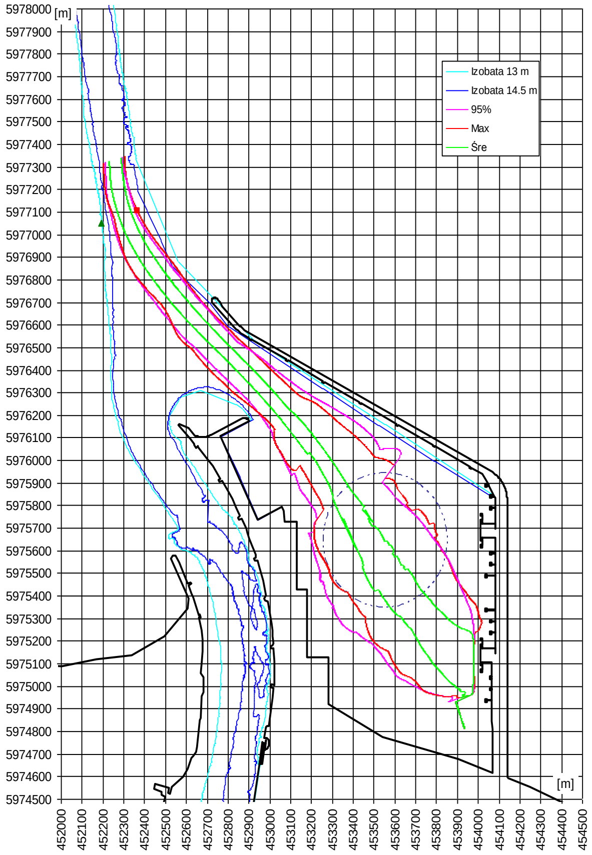

Fig. 8. Results from researches – turning area determination of LNGC 138 k cu.m. in Oputer Port of Świnoujście at wind N 12 m/s
Rys. 8. Wyniki badań – obszar obrotnicy dla LNG 138 k m^3 w porcie zewnętrznym w Świnoujściu, wiatr N 12 m/s

Example results from this researches of LNGC 138 k cu.m., at wind N 12 m/s are presented in figure 8. Diameter of turning place was set up to 600 m.

Underkeel clearance

The stochastic model of under keel clearance evaluation was presented in [2]. It is based on Monte Carlo methodology where overall ships underkeel clearance is described by following mathematical model (fig. 9):

$$\begin{aligned} UKC = \left(H_0 + \sum \delta_{Hoi}\right) - \left(T + \sum \delta_{Ti}\right) + \\ + \left(\Delta_{Swa} + \sum \delta_{Swi}\right) + \delta_N \end{aligned} \tag{9}$$

where: δ_{Hoi} – the uncertainties concerned with depth and its determination, δ_{Ti} – the uncertainties concerned with draught and its determination, δ_{Swi} – the uncertainties concerned with water level and its determination, δ_N – navigational and manoeuvring clearance.

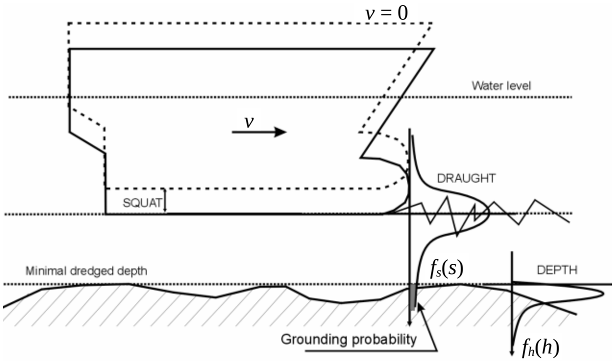

Fig. 9. Concept of stochastic UKC model
Rys. 9. Koncepcja stochastycznego modelu zapasu wody pod stępką

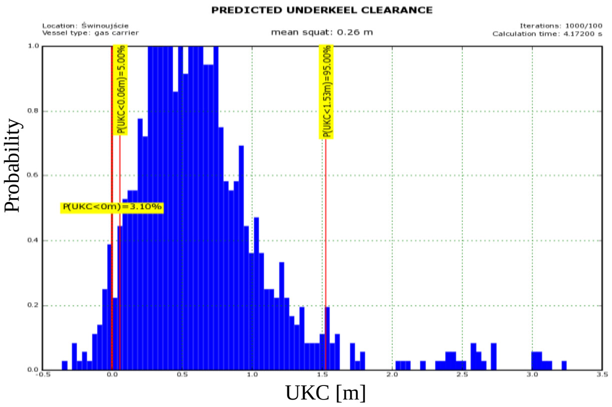

Fig. 10. Distribution of underkeel clearances for an LNG tanker approaching Świnoujście (speed: six knots, wave height: one metre)
Rys. 10. Rozkład zapasu wody pod stępką dla tankowca LNG wchodzącego do Świnoujścia (prędkość 6 w, wysokość fali – 1 m)

The result obtained by the model [9] as histogram of expected underkeel clearances of approaching LNG in given conditions are presented in figure 10. Figure 11 presents probability of accident in function of two main factors affecting UKC: ships speed and wave height.

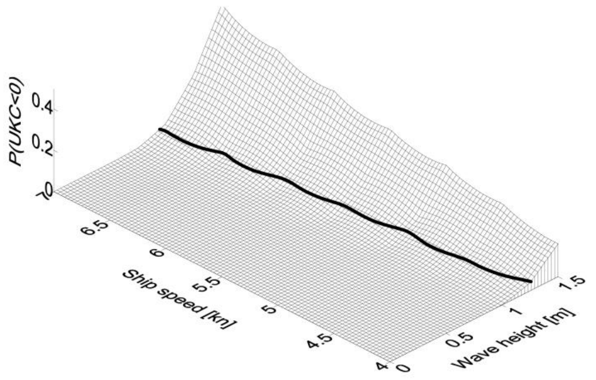

Fig. 11. Probability of an accident ($P(z<0)$) at various speeds of approaching ships and various wave height. The marked line indicates identical probabilities of expected losses p ($P = 0.043$)

Rys. 11. Prawdopodobieństwo wypadku ($P(z<0)$) dla różnych prędkości podchodzących statków oraz na różnych wysokościach fal. Wskazana linia oznacza takie samo prawdopodobieństwo spodziewanych strat p ($P = 0{,}043$)

Safety of manoeuvres of mooring LNGC in outer port of Świnoujście

Analysis of maundering tactics proved, that most crucial moment of manoeuvres is first contact of vessel's hull with structure. During this time kinetic energy is transformed into work of collision that affects on hull and fendering system. Energy induced in fendering system will affect potential damages, whilst second and following contacts wont induce that amount of energy as firs one. Keeping this assumption in mind it can be stated that safe mooring criteria is energy absorbed by fendering system Ea during first contact of vessel's hull and berth. It should be treated as a kinetic energy induced on berth.

Amount of absorbed by fendering-vessel system energy reflects reaction forces that decides over potential damage. Thus, criteria of navigation safety can be formulated as follow:

$$\left.\begin{aligned} E_a(t_i) &\le E_d^{nab} \\ E_a(t_i) &\le E_d^{stat} \end{aligned}\right\} \qquad (10)$$

where: $E_a(t_i)$ – maximum kinetic energy of vessels contact absorbed by fendering-vessel system [kNm], E_d^{nab} – permissible kinetic energy of vessels contact absorbed by fendering-vessel system [kNm], E_d^{stat} – permissible kinetic energy, of which induced work will not deflects vessels hull permanently [nNm]:

$$\delta \le \delta_d \qquad (11)$$

where: δ – singular maximum hull stress from fender reaction force [kN/m^2], δ_d – permissible singular hull stress from fender reaction force [kN/m^2].

Parameters of kinetic energy distribution of 216 kcu.m. LNGC contact with terminal in Świnoujście are presented in figure 12. These parameters were obtained from real time simulation researches.

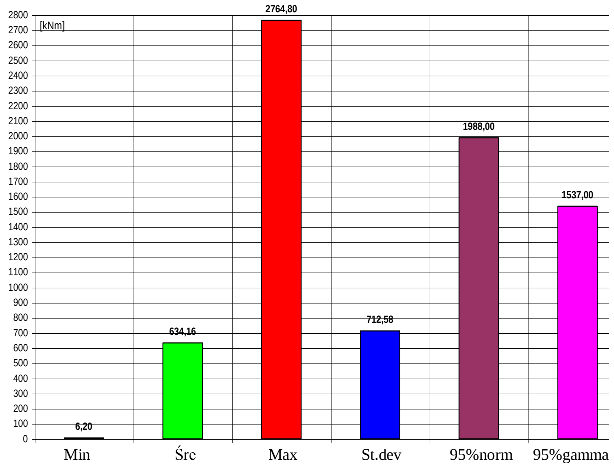

Fig. 12. Energy induced during mooring of LNGC 216 k cu.m. to terminal in Świnoujście

Rys. 12. Energia indukowana podczas cumowania statku LNGC 216 k m^3 w porcie Świnoujście

Fenders shall be selected for mooring energy induced by maximum vessel, which can be described by gamma distribution on confidence level. Area of contact between terminal and mooring vessel shall be taken into account for maximum allowable hull stress.

Safety of LNGC alongside terminal jetty

Gas carrier can safely stay alongside at unloading terminal under conditions: that hull's flat body (fig. 13) is in contact with fenders (with permissible forces as well as for hull and fender line); permissible tensions of all mooring lines is higher than longitude and traverse pull forces induced by maximal wind speed blows for given port. Thus, general conditions of safe stay alongside the unloading terminal can be as follows:

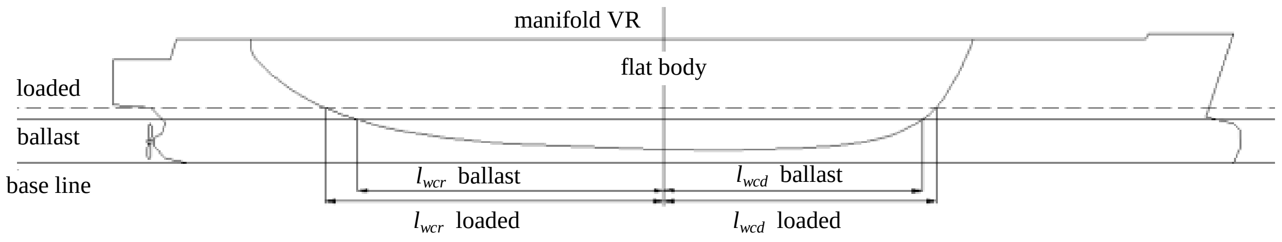

Fig. 13. Flat body section of LNGC
Rys. 13. Przekrój tankowca LNG

$$\left.\begin{array}{l} l \geq l_{wcd} \\ l \geq l_{wcr} \end{array}\right\} \tag{12}$$

where: l – distance from C/L (centre line) of manifold (i.e. vapour return manifold line) to last fenders – this distance is measured on terminal; l_{wcd}, l_{wcr} – length of flat body from C/L to bow and sterns directions, for ballast condition – this distance is specific to given vessel.

$$\begin{array}{l} \sum\limits_{i=1}^{n} P_{ib} \leq Q_b \\ \sum\limits_{i=1}^{n} P_{iw} \leq Q_c \end{array} \tag{13}$$

where: P_{ib}, P_{iw} – tension of i-th mooring line traverse and longitude respectively; Q_b, Q_c – maximum pull force form wind blows traverse and longitude respectively.

Additionally for location of fenders following shall be considered:

1) stability of vessel during mooring will be fulfilled for distance of fenders from manifold minimum 1/3 of maximum vessels length;
2) symmetrical fender distribution that will affect tensions on spring lines.

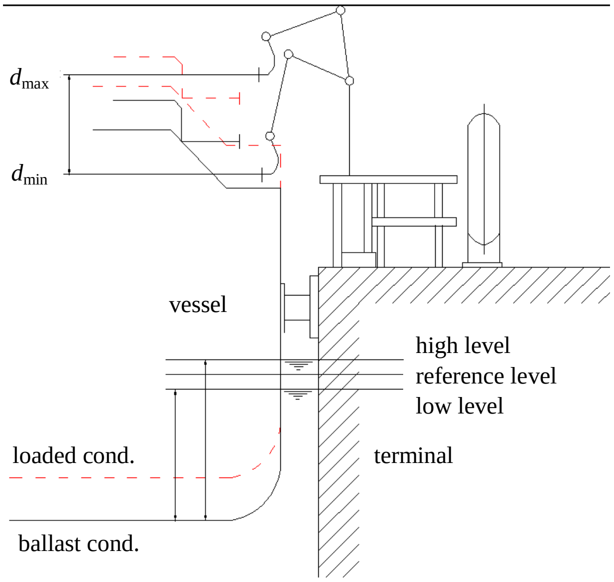

Fig. 14. Loading arms working range
Rys. 14. Zasięg pracy ramion ładunkowych

Safety of unloading operations

Interconnection of vessels and land systems is performed by connecting adequate pipes flanges of unloading arm to ships manifold. Formulating this basic safety condition of unloading can be written as (fig. 14).

$$\left.\begin{array}{l} d_{\max} \geq D - T_{\mathrm{bal}} + \Delta h_{\max} \\ d_{\min} \leq D - T_{\mathrm{lad}} + \Delta h_{\min} \end{array}\right\} \tag{14}$$

where: $d_{\max}$, $d_{\min}$ – working range of unloading arms, max and min respectively, measured from reference line; D – height of manifold from vessels base line; T_{lad}, T_{bal} – draft of LNGC loaded and in ballast condition; $\Delta h_{\max}$, $\Delta h_{\min}$ – difference in water level in accordance to reference line (maximum and minimum for given period).

Conclusions

Safety of manoeuvring, mooring, staying alongside and unloading of LNGC inside port requires fulfilment of several criteria concerned with:

- safety during Baltic Sea passage,
- port approach,
- manoeuvre of turning,
- berthing manoeuvre,
- mooring alongside unloading terminal,
- unloading of cargo.

Some of above aspects related to new design polish LNG terminal have been presented in limited extend. All LNG tankers going inbound port must comply with these criteria. For designing process of outer port in Świnoujście safety assessment has been conducted for typical LNG vessels within range of prospected operations inside the port. Vessels that will be delivering cargo to Poland are in ranges of capacities from 120 000 to 216 000 cubic meters. Final layout of LNG outer port in Świnoujście is presented in figure 15.

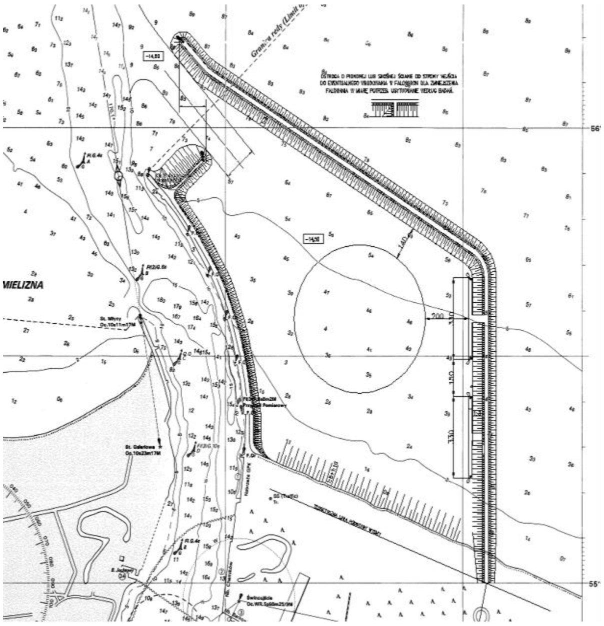

Fig. 15. Final layout of LNG terminal in Świnoujście
Rys. 15. Ostateczny plan terminalu LNG w Świnoujściu

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