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Determination of optimal waterway system parameters and operating conditions for LNG Tanker operation in the port of Świnoujście

Określenie optymalnych parametrów systemu dróg wodnych i warunków eksploatacji gazowców LNG w porcie Świnoujście

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Key words: marine traffic engineering, safety of navigation, LNG

Abstract
The article describes the method of the determination of optimal parameters of the approach channels leading to the outer port in Świnoujście assuring safe navigation of LNG tankers of Q-flex type. The method used was specially developed for optimized design of waterway systems. Conditions of safe vessel operations within the system were defined.

Słowa kluczowe: inżynieria ruchu morskiego, bezpieczeństwo nawigacji, LNG

Abstrakt
W artykule wyznaczono optymalne parametry systemu podejściowych dróg wodnych do portu zewnętrznego w Świnoujściu zapewniających bezpieczną nawigację gazowców LNG typu Q-flex. Zastosowano specjalnie opracowaną metodę optymalnego projektowania systemów dróg wodnych. Określono warunki bezpiecznej eksploatacji systemu.

Introduction

The outer port in Świnoujście is now under construction. It will be a site of an LNG terminal handling LNG tankers of Q-flex type with the following parameters:

- cargo capacity: $V_L = 215\,000\ m^3 \div 217\,000\ m^3$;
- length overall: $L_c = 315$ m;
- breadth: $B = 50$ m;
- draft: $T = 12.5$ m.

The shape and parameters of the outer port in Świnoujście and the LNG berth were developed on the basis of research done at the Institute of Marine Traffic Engineering, Maritime University of Szczecin [1].

The research employed a specially developed simulation method of waterway parameters optimization and assessment of navigational and economic risks [2]. The layout of outer port under construction in Świnoujście is presented in figure 1.

The outer port in Świnoujście is approached through a waterway crossing Pomorska Bay. In terms of underkeel clearance assessment, the waterway leading to Świnoujście can be divided into three parts:

- western approach channel to buoy N-1 (via SWIN-N) crossing the territorial sea of Germany east of Rugen Island; the natural minimum depth of the area crossed by the western approach channel is 15.1 m;
- northern part of the approach channel leading from buoy N-1 (43.175 km) to N-2 (35.6 km) and farther to 18.0 km of the fairway. Its minimum depth of 14.5 m with the channel width of

220 m is mainly a natural depth of the sea except for the section (27.8 ÷ 31.4 km) running north of buoy N-3 that is a dredged fairway;

– southern part of the approach channel crossing Pomorska Bay from 15.0 km of the fairway to the eastern head at the entrance to the port of Świnoujście (0.0 km); the dredged fairway has a minimum depth of 14.3 m and a width of 180 m.

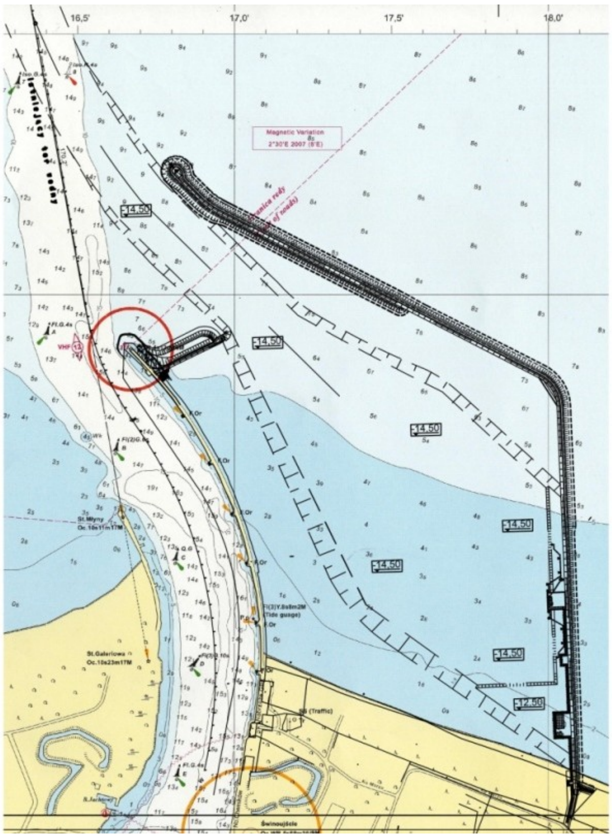

Fig. 1. Layout of the outer port under construction in Świnoujście
Rys. 1. Plan obecnie budowanego portu zewnętrznego w Świnoujściu

Figure 2 depicts a chart fragment of the approach channel leading to the port of Świnoujście and its anchorages.

The assurance of appropriately high level of safety of LNG tanker manoeuvring in waterways leading to the LNG terminal in Świnoujście is a basic problem that has to be solved while designing waterways and identifying the operating conditions. The problem comes down to the determination of safe manoeuvring area parameters of approach channels and their aids to navigation.

Parameters of a safe manoeuvring area can be defined using a probabilistic model. The ship can manoeuvre safely only within an area that at each point satisfies the condition of required depth. Such area is a navigable area that can be represented as an area **D** of a set of points satisfying the condition

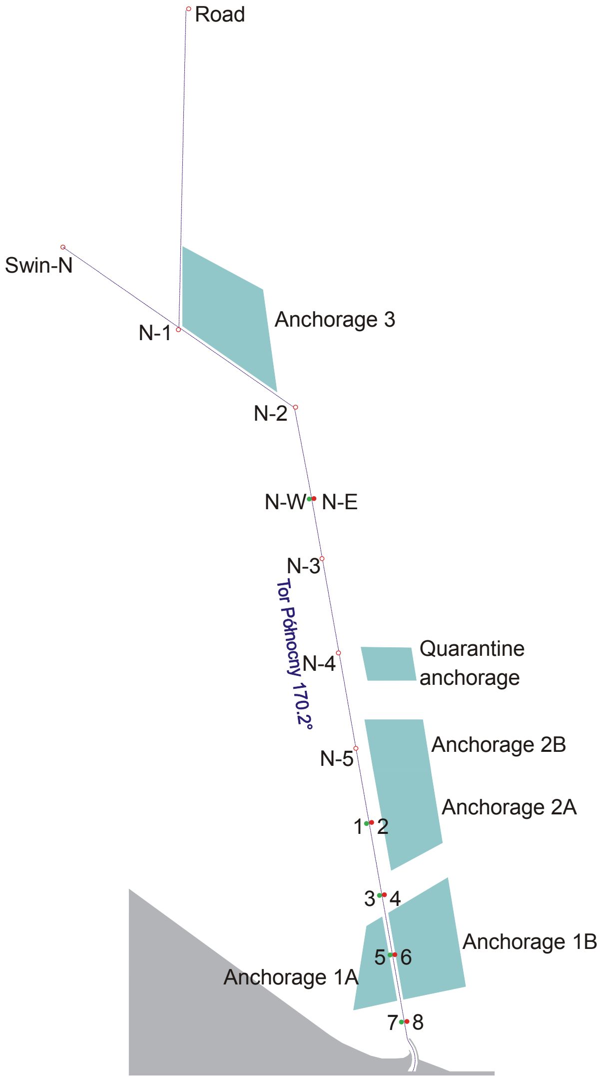

Fig. 2. Approach channel leading to Świnoujście and anchorages
Rys. 2. Tor podejściowy do Świnoujścia z zaznaczonymi kotwicowiskami

of required depth at an instant t. The ship performing a given manoeuvre within a navigable area during that manoeuvre occupies a certain area defined by its subsequent position in the area. The parameters of this area are random and depend on a number of various factors. The area, calculated at a certain level of confidence, is referred to as safe manoeuvring area $\mathbf{d}(1-\alpha)$ [3]. With this definition of the safe manoeuvring area the basic condition of navigational safety can be written as follows:

$$\begin{gathered} \mathbf{d}_{ijk}(1-\alpha) \subset \mathbf{D}(t) \\ \bigwedge_{p(x,y)\in \mathbf{D}(t)} h(x,y,t) \geq T(x,y,t) + \Delta(x,y,t) \end{gathered} \qquad (1)$$

where:

$\mathbf{D}(t)$ – navigable area (safe depth condition is satisfied at instant t);

$\mathbf{d}_{ijk}(1-\alpha)$ – safe manoeuvring area at confidence level $1-\alpha$.

The sets of points of a navigable area $\mathbf{D}(t)$, and those of safe manoeuvring area $\mathbf{d}_{ijk}(1-\alpha)$ can be identified as areas with specific linear parameters. In various types of waterways the basic linear parameter that is critical for the safety of a manoeuvre to be performed is their width. Therefore, the condition of performing a given manoeuvre safely can be transformed to this form:

$$D(t)_{ijk} \geq d_{ijk}(1-\alpha) \tag{2}$$

where:

$D(t)_{ijk}$ – width of navigable area available at instant t (navigable area available for i-th ship for j-th type of manoeuvre performed in k-th hydrometeorological conditions;

$d_{ijk}(1-\alpha)$ – width of safe manoeuvring area of i-th ship, for j-th type of manoeuvre performed in k-th hydrometeorological conditions at confidence level $(1-\alpha)$.

It follows from the above considerations that the assurance of safe navigation of LNG tankers in approach channels leading to LNG terminals is strictly connected with a choice of proper (safe) confidence level when parameters of the waterways and navigational systems are determined. The design or modernization of waterways at the stage of safe parameters determination is closely related to the design of position determination systems for the planned waterway. That is why this stage is often referred to as the **design of waterway system** [Gucma S. 2011].

Design of waterway systems can be divided into the following working stages:

1. Establishment of operating conditions of the waterway.
2. Preliminary determination of waterway parameters, consisting of:
   – division of the waterway into sections characterized by different types of manoeuvres performed within them and different hydrometeorological conditions;
   – determination of safe waterway depth at each section and preliminary determination of parameters of navigable areas.
3. Design of position determination system and optimization of navigable area parameters, consisting of:
   – defining requirements for position determination systems;
   – choice of the type of position determination systems for each waterway section for various groups of characteristic ships and various hydrometeorological conditions;
   – determination of navigational system parameters at each waterway section;
   – determination of safe manoeuvring areas for ships under consideration at an assumed confidence level;
   – determination of optimal parameters of navigable areas that are safe in given operating conditions.

Safe depths of the approach channels leading the outer port in Świnoujście

Certain manoeuvres, such as anchoring, approach to the port or turning, are burdened with a risk of ship's hull contact with the sea bottom. This undesired event may result in losses of various kinds, sometimes disastrous, e.g. damage to the ship and port infrastructure, loss of life, or pollution of the marine environment.

If a given manoeuvre in harbour waters is to be safe, the safe depth condition has to be satisfied. It can be written in this form:

$$h(x,y,t) \geq T(x,y,t) + \Delta(x,y,t) \tag{3}$$

The underkeel clearance is critical for safe manoeuvring. Safe underkeel clearance depends on many factors that can be expressed as this function:

$$\Delta(x,y,t) = \\ = f\big(A(x,y,t), S(x,y,t), H(x,y,t), M(x,y,t)\big) \tag{4}$$

where:

$A(x, y, t)$ – area parameters at point (x, y) at instant t;

$S(x, y, t)$ – ship parameters at area point (x, y) at instant t;

$H(x, y, t)$ – parameters of hydrometeorological conditions at area point (x, y) at instant t;

$M(x, y, t)$ – parameters of the performed manoeuvre at area point (x, y) at instant t.

Underkeel clearance (UKC) can be determined by one of two methods:

– method of static UKC, where the underkeel clearance is regarded as a maximum clearance over the whole period of waterway use (deterministic method);
– method of dynamic UKC, where the underkeel clearance is assumed for present navigational conditions prevailing in the given waterway (probabilistic method).

Taking into account operating conditions of LNG tankers that first and foremost have to enter the terminal on time with a maximum navigational safety, UKC determined at the design stage is different from that determined during LNG terminal operation. The static UKC method is applied during design, the dynamic UKC method applies during vessel operation.

The use of the static method leads to the assumption of the largest underkeel clearance that occurs in a given area throughout the period of port operation. Consequently, the LNG tanker has no restrictions to enter the port requlary. The static method assumes that:

$$\Delta(x, y, t) = \Delta = \text{const.} \tag{5}$$

In this connection, the maximum draft of an LNG tanker entering the port is calculated from this relation:

– in tidal areas:

$$T \le h_{\min}(t) - \Delta \tag{6}$$

– in non-tidal areas:

$$T \le h_{\min} - \Delta \tag{7}$$

where:

$h_{\min}(t)$ – minimum depth of port area at instant t,
$h_{\min}$ – minimum depth of port area during port operation.

Approach channels leading to the port of Świnoujście can be divided into sections that differ in operating and hydrometeorological conditions. For this reason, the sections have various magnitudes of UKC components, thus have a different minimum depth assuring safe manoeuvres of LNG tankers in port waters. For the determination of UKC, the waterway running to the outer port in Świnoujście has been divided into these sections:

Section 1. Anchorage No. 3;
Section 2. Northern part of approach channel, from N-1 (43.175 km) to 15.0 km of the fairway;
Section 3. Northern part of approach channel, from 15.0 km of the fairway to buoys 7–8;
Section 4. Outer port in Świnoujście, from buoys 7–8 to the discharge berth.

Safe depths of approach channels and the outer port in Świnoujście for a "maximum" LNG tanker to be accommodated (L_c = 315 m; B = 50 m; T = 12.5 m) are as follows [4]:

– anchorage No. 3: h = 15.8 m;
– quarantine anchorage: h = 14.5 m (emergency anchorage – restricted stay);
– approach channel from buoy N-1 to buoys 7–8: h = 14.5 m;
– outer port in Świnoujście, from buoys 7–8 to the discharge berth: h = 14.5 m.

It should be noted that at these depths the dynamic UKC determination method has to be implemented, as UKC affects the speed at which an LNG tanker can proceed along each section.

A restricted stay at Quarantine anchorage refers to a situation where ship's main engines cannot be shut down due to extremely bad weather conditions as then the ship may hit its own anchor.

Design of approach waterway system for the outer port in Świnoujście

Determination of navigational system parameters

Navigational systems are designed according to the following procedure [5]:

1. Navigational systems in a given waterway are designed separately for specific size groups of ships.
2. The system for the largest size ships should be designed first, because requirements for small vessels are in most cases satisfied by systems for large vessels [5].
3. Position determination systems are designed for three kinds of visibility:
   – daytime (good visibility);
   – night time (good visibility);
   – poor visibility.

   Operating guidelines for a given waterway can restrict the number of design conditions set forth for specific size groups of ships, e.g.:
   • navigation of specific group of ships takes place only at daytime;
   • in a given waterway navigation takes places only in good visibility.
4. Position determination systems for each kind of visibility have to be doubled, otherwise a failure of a single system creates a risk of a navigational disaster (threat of a few accidents at the same time).
5. Position determination systems designed for a selected waterway section have to meet these requirements:
   – availability;
   – reliability;
   – accuracy at a specific confidence level.

The availability of ship's position determination system depends on ownership status and prevailing hydrometeorological conditions:

– ownership status that allows the owner to restrict the access to the system or change its parameters without consultation with and consent of the system users. Position determination system designers should take into consideration the system exclusion or change of parameters;
– hydrometeorological conditions in which some position determination systems are not available; for instance, reduced visibility (S < 2 Nm) at

which terrestrial methods are not available or ice conditions that necessitate removal of floating aids to navigation;

– extreme hydrometeorological conditions in which the whole waterway system is not available for a specific ship; these are determined by operating conditions for ships on the waterway under consideration, e.g. maximum wind speed of 12.5 m/s for LNG tankers manoeuvring within the approach channel to Świnoujście.

The reliability of ship position determination is the ship's ability to define its position at an assumed accuracy. It is technical reliability is estimated on the basis of the failure rate of system elements. Defects of these elements reduce the assumed accuracy or make it impossible to determine a position. The probability of reliable system elements operation is calculated by using the failure rate function $\lambda(t)$ at instant t. This is a function of failure occurrence density on condition that there was no failure till that instant. If we consider only the stable operation of the system [6], the failure rate function $\lambda(t)$ does not depend on time and is constant $\lambda = \text{const.}$ and the probability of system element reliable operation is calculated from this relation:

$$P(t) = e^{-\lambda t} \quad (8)$$

The requirements of **position determination accuracy** of a system designed for a given waterway is described by this condition:

$$D(t)_{ijk} \geq d_{ijk}(1-\alpha) \quad (9)$$

The position determination system accuracy and assumed confidence level determine the width of a safe manoeuvring area.

It is assumed in the described design method that the width of safe manoeuvring area is a function of position determination systems accuracy, i.e. accuracy of the system parameters. Therefore:

$$d = f(d_n) \quad (10)$$

hence

$$d = f(N_i) \quad (11)$$

where:

d – width of safe manoeuvring area;
d_n – navigational component of safe manoeuvring area width;
N_i – parameters of position determination system.

Having considered the availability and reliability of position determination systems in the approach channel to the outer port in Świnoujście and:

– parameters of approach waterways;
– parameters of a maximum LNG tanker;
– present practices of piloting "maximum ships" (bulk carriers L_c = 270 m, T = 13.2 m);

it could specify the requirements for position determination systems for an LNG tanker within approach waterways, assuming that:

I. Basic position determination methods are:
   1. Satellite method using the Pilot Navigation System (PNS) based on a DGPS.
   2. Terrestrial (optical) method using stationary and floating aids to navigation.

II. Additional (emergency) position determination method:
   3. Radar method using stationary and floating aids to navigation.

The use of method 1 depends on the availability provided by the system owner. Method 2 depends on the availability related to visibility $S \geq 2$ Nm. The availability of methods 2 and 3 depends on the presence of floating aids to navigation that may periodically be removed.

The reliability of method 1 is determined by technical fault (software and hardware) of the system. The reliability of method 2 is affected by drifting of floating aids to navigation or light defect in the night. The reliability of method 3 is affected by drifting of floating aids to navigation only, as the technical failure of a radar is negligible because ships are equipped with two radars, operating on hot redundancy basis.

To define parameters of safe manoeuvring areas, it has to specify confidence levels for position determination for each of the navigational methods (systems) used. While specifying these levels, the following were taken into account:

– parameters and characteristics of each method (system) of position determination;
– LNG tanker operating conditions in the examined waterway;
– safety (navigational risk) of the manoeuvring LNG tanker [2].

The following design confidence levels were defined for planned tanker position determination methods to be used by an LNG tanker in approach channels leading to the outer port in Świnoujście:

– basic methods:
  • PNS $1 - \alpha = 0.997$;
  • terrestrial $1 - \alpha = 0.997$;
– additional method:
  • radar $1 - \alpha = 0.95$.

Determination of optimal parameters of navigable areas

Depending on the type of water area, various methods of calculation were used for the determination of approach waterway parameters:

- Approach channel from buoy N-1 to buoys 7–8:
  - probabilistic-deterministic method that determines widths of a safe manoeuvring area;
  - simulation method of ship movement in fast time (autonomous models).
- Entrance to the outer port from buoys 7-8 and port basin:
  - real time simulation of ship movement (non-autonomous models).

In the deterministic-probabilistic method, the manoeuvring component of area (swept path) width d_m is defined by the deterministic method, while the navigational component of the manoeuvring area has probabilistic character and is determined at the confidence level $d_n(1-\alpha)$. The width of safe manoeuvring area for a rectilinear waterway section is defined as follows:

$$d(1-\alpha) = d_m + 2d_n(1-\alpha) \qquad (12)$$

Safe widths of manoeuvring area in waterways for the selected navigational systems have to meet this condition:

$$\begin{aligned} D &\geq d(1-\alpha) + d_r^p + d_r^l = \\ &= d_m + 2d_n^k(1-\alpha) + d_r^p + d_r^l \end{aligned} \qquad (13)$$

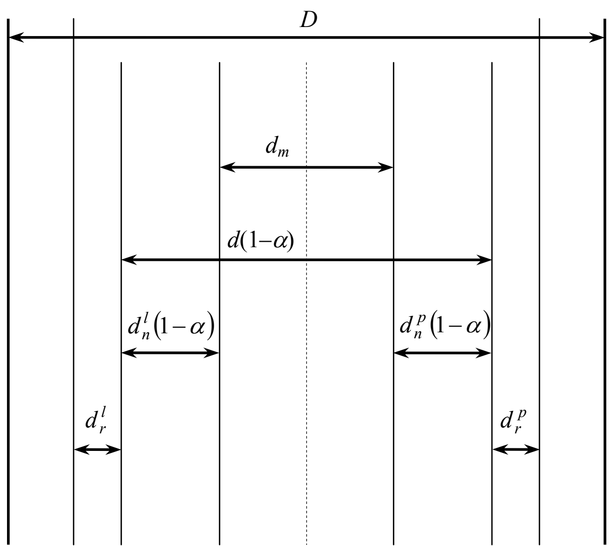

Fig. 3. Safe width of manoeuvring area at a specific confidence level (one-way fairway)

Rys. 3. Bezpieczna szerokość obszaru manewrowego na określonym poziomie ufności (jednokierunkowy tor wodny)

where:

D – waterway width at the bottom with safe depth (available fairway width);

$d_n^k(1-\alpha)$ – navigational component of safe manoeuvring area for k-th position determination system for the appropriate confidence level $(1-\alpha)$;

$d(1-\alpha)$ – safe width of manoeuvring area at the confidence level $(1-\alpha)$;

d_m – manoeuvring component of safe manoeuvring area width;

$d_n^p(1-\alpha)$, $d_n^l(1-\alpha)$ – navigational components (port and starboard) of safe width of manoeuvring area at the confidence level $(1-\alpha)$;

d_r^p, d_r^l – margin of manoeuvring area width.

The navigational component of manoeuvring area along a rectilinear fairway section for a given position determination system is directional error of ship's side position determined at a preset confidence level. The directional error is perpendicular to the fairway centre line and equals [5]:

$$\begin{aligned} d_n(1-\alpha) &= p_{yB}(1-\alpha) = \\ &= \pm\sqrt{p_y(1-\alpha)^2 + \left(\frac{m_{KR}(1-\alpha)\cdot L_D}{57.3^\circ}\right)^2} \quad [\mathrm{m}] \end{aligned} \qquad (14)$$

where:

$p_{yB}(1-\alpha)$ – directional error of ship's side position determined at a confidence level $(1-\alpha)$ [m];

$p_y(1-\alpha)$ – directional error of ship's (observer's) position at a confidence level $(1-\alpha)$ [m];

$m_{KR}(1-\alpha)$ – ship's course error at a confidence level $(1-\alpha)$ [°];

L_D – distance between ship's bow and bridge [m].

Widths of each fairway section safe for an outgoing LNG tanker (Q-flex) are shown in figure 4 for the present state of aids to navigation (V = 8 knots), figure 5 reflects designed aids to navigation (V = 8 knots) while figure 6 shows designed aids to navigation for V = 10 knots.

As a result of performed simulation tests (autonomous method) the safe manoeuvring area width was determined using the PNS. The width is 199.5 m for manoeuvre performance probability PBM = 0.9994 [1]. The results are comparable with the results of the deterministic-probabilistic method at the same confidence levels.

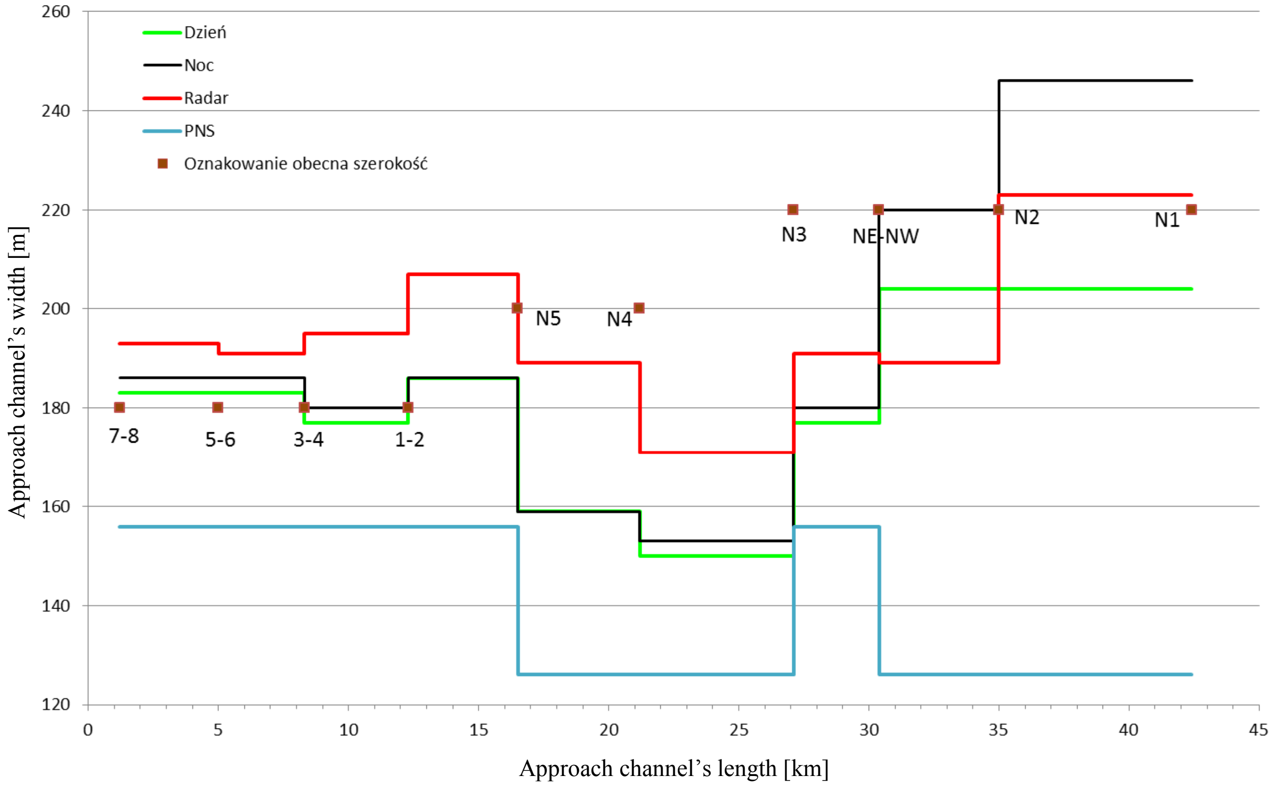

Fig. 4. Safe widths of approach channel for an outgoing LNG tanker (speed 8 knots) – present state of aids to navigation
Rys. 4. Bezpieczne szerokości podejściowego toru wodnego dla wychodzącego gazowca LNG (prędkość 8 w) – stan aktualny oznakowania

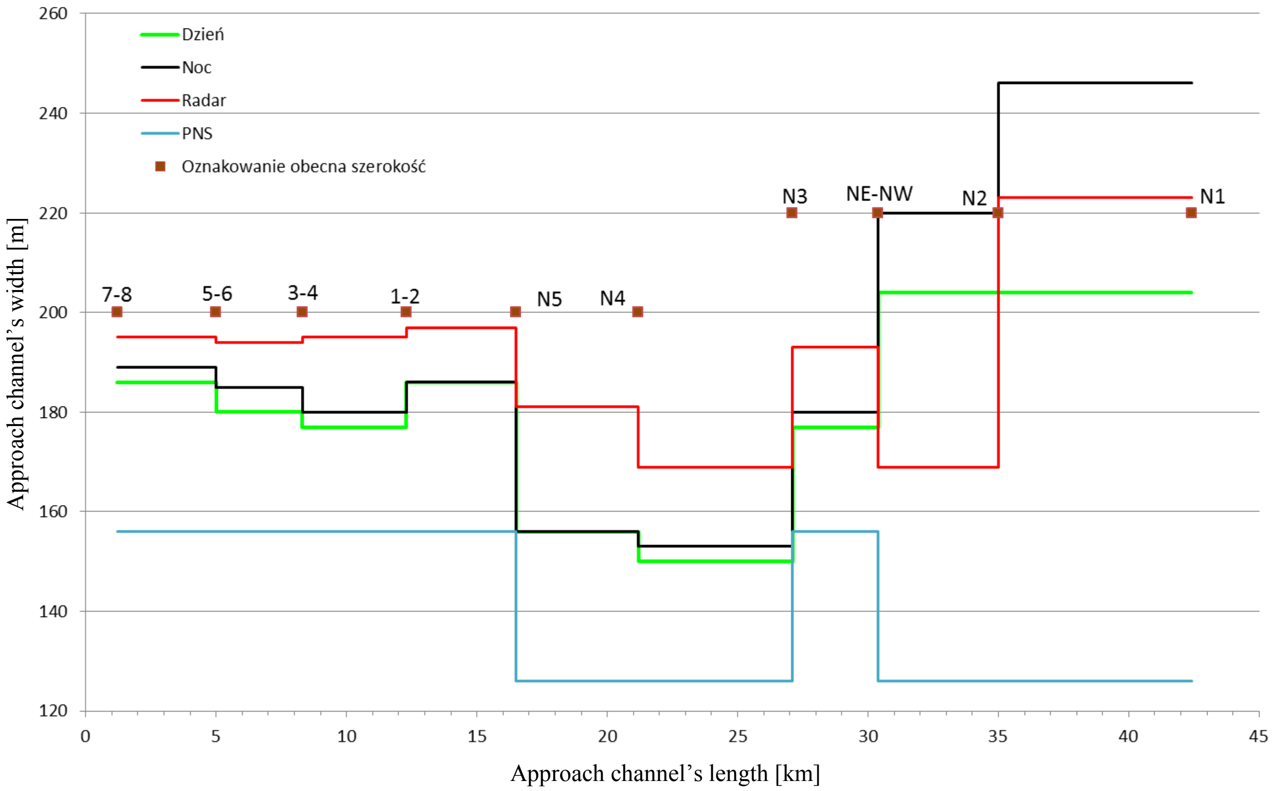

Fig. 5. Safe width of approach channel for an outgoing LNG tanker (speed 8 knots) – designed aids to navigation
Rys. 5. Bezpieczna szerokość podejściowego toru wodnego dla wychodzącego gazowca LNG (prędkość 8 w) – projekt oznakowania

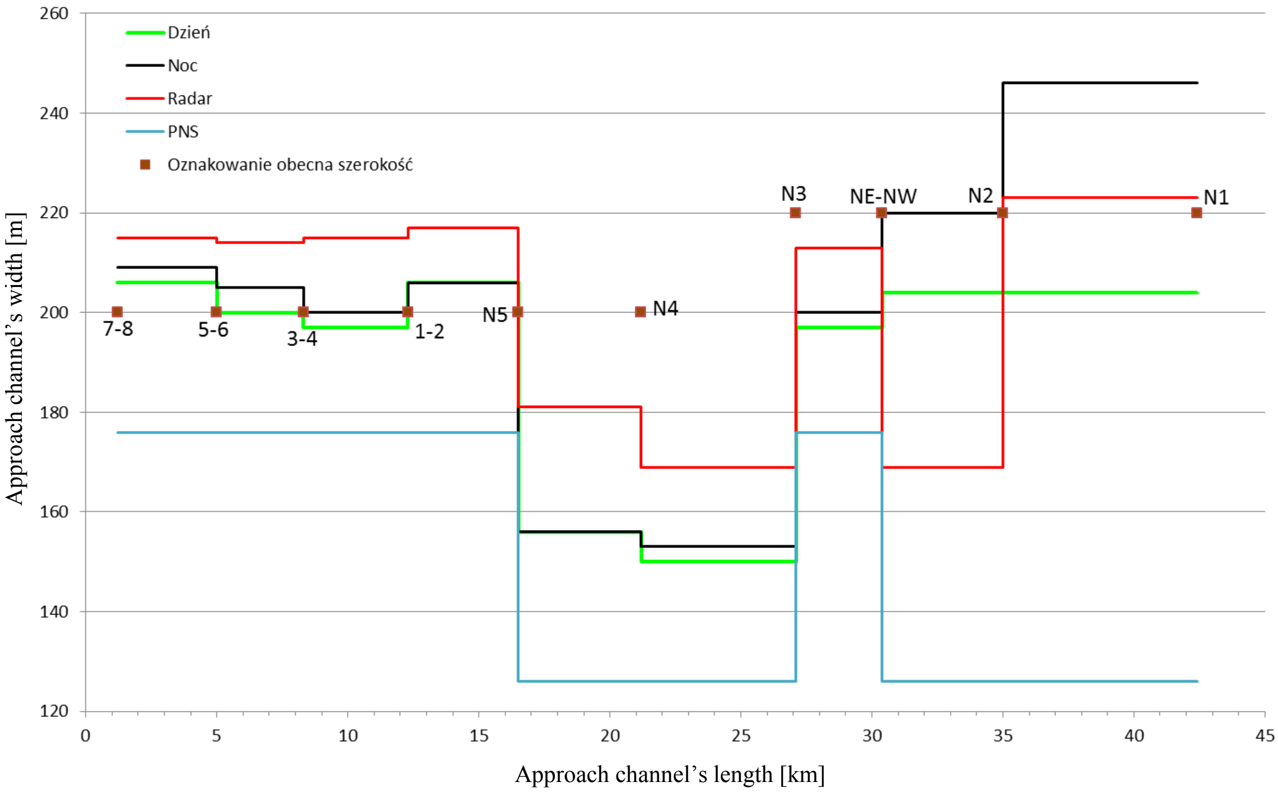

Fig. 6. Safe width of approach channel for an outgoing LNG tanker (speed 10 knots) – designed aids to navigation
Rys. 6. Bezpieczna szerokość podejściowego toru wodnego dla wychodzącego gazowca LNG (prędkość 10 w) – projekt oznakowania

Conclusions

The following conclusions can be drawn from an analysis of data on the navigational safety of LNG tankers of Q-flex type in the approach channel leading to the outer port in Świnoujście:

- present fairway parameters (width at the bottom) and its aids to navigation do not satisfy the accuracy requirements along the section from buoys 1–2 to buoys 7–8;
- the existing aids to navigation do not satisfy availability conditions for terrestrial and radar methods of position determination due to their possible drifting in ice conditions within a section from buoys 1–2 to buoys 5–6;
- the existing system of aids to navigation does not have a hydrometeorological survey station that would be part of the system for dynamic UKC determination assuring safe operations of LNG tankers.

The cost minimization criterion for the reconstruction of the existing waterway system of approaches to the outer port in Świnoujście was used, while satisfying all conditions of LNG tanker navigational safety, to determine the parameters of approach channel (minimum safe widths at the bottom for the depth h = 14.5 m) and parameters of aids to navigation. Thus, the minimum safe fairway width at the depth of 14.5 m is:

- 200 m between 0.0 km and 26.8 km;
- 220 m od 26.8 km do 35.6 km.

To implement designed changes to the existing aids to navigation for the approach channel of the outer port in Świnoujście, having widths as given above and providing for appropriate level of navigational safety (position accuracy, system availability, safe vessel operation), the following actions have to be taken:

- implement a pilot navigation and docking system (PNDS);
- replace buoys 3–4 by beacons and adjust their position;
- adjust the position of buoys: N-4, N-5, 1–2, 5–6 and 7–8 and replace them;
- build a hydrometeorological survey station on beacon No. 3 or 4 and implement the dynamic UKC determination system.

The layout and aids to navigation of the Świnoujście outer port entrance have been defined from simulation tests carried out at the Institute of Marine Traffic Engineering, Maritime University of

Szczecin (see [1]). The tests allowed to determine the layout and parameters of the outer port in Świnoujście and on that basis a technical design was made. The concept of aids to navigation for the same area was also based on the results of simulation tests [1].

The concept includes:

– moving buoys 7–8 two cables north;
– establishing a sector light on the head of the new breakwater to indicate the moment of course alteration;
– establishing a light on the head of the new western breakwater (spur).

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