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Maximum Safe Parameters of Ships in Complex Systems of Port Waterways

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Abstract: Context: From the perspective of marine traffic engineering, a system of port waterways is composed of a set of waterways (port areas), such as approach channels, port entrance, inner fairways (port channels, rivers, lakes), turning basins and port basins of various terminals. The sea waterway must be adjusted to the navigation of specific types of ships, characterized by length, breadth, draft and airdraft. The primary requirement for shipping in sea waterways is the safety of navigation. Each sea waterway has traffic restrictions for the ships using it. These restrictions are called conditions of sea waterway operation or conditions of ship operation in the sea waterway. Problem: There are a number of empirical, deterministic or probabilistic methods to determine the safe width of maneuvering areas on port waterways. The direct application of empirical methods to determine the conditions for the safe operation of ships on the complex waterway, such as the Świnoujście–Szczecin fairway, was impossible due to the complexity of the waterway and various restrictions on its individual parts. Method: The paper presents the assumptions and calculation procedure of a method allowing for the determination of maximum safe parameters of ships in existing complex waterways. Results: The proposed method was used in the preparation of port regulations for the dredged and widened Świnoujście–Szczecin waterway. The results of these calculations are presented as a practical application of the method. Conclusions: This article defines conditions for the safe operation of ships in complex port waterways systems and presents the methodology for determining maximum safe parameters of ships in existing complex port waterways systems.

Keywords: maritime transport routes; safety of navigation; maritime transport; design of waterways; marine simulation; full-mission ship simulator; maritime traffic engineering; safe maneuvering area; safe operation of the ship; navigational risk

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1. Introduction

1.1. Waterway System in Marine Traffic Engineering

The sea waterway must be adjusted to the navigation of specific type of ships, characterized by length, breadth, draft and airdraft [1]. The primary requirement for shipping in sea waterways is the safety of navigation [2]. Navigational safety comprises all of the issues related to smooth ship conduct from point A to point B of the sea route.

The sea waterway system in marine traffic engineering is composed of a number of separate sections (n). A complex port waterways system is usually composed of the following sections:

- Approach channel;
- Port entrance;
- A number of straight sections and bends in the fairway;
- Port basins of specific terminals and related turning basins.

Each of the waterway sections consist of three basic elements [3]:

- Waterway subsystem;

- Subsystem of ship position determination (navigational subsystem);
- Subsystem of traffic control.

These elements affect each other and have an important impact on the system characteristics.

Each sea waterway has traffic restrictions for the ships using it [4,5]. These restrictions are called conditions of sea waterway operation or conditions of ship operation in the sea waterway, and refer to:

- Parameters of ships using the waterway;
- Hydrometeorological conditions, in which, the traffic includes specific types of ships;
- Parameters of vessel traffic intensity in the waterway;
- Conditions of ship maneuvering in the waterway (tug assistance, allowable speeds).

The conditions for the safe operation of ships in a port regarded as a system composed of various types of waterways are dependent on the conditions of the safe operation of ships in each specific waterway section within the port. The parameters of each waterway within the port determine the conditions of the safe operation of ships maneuvering in that area [6].

There are a number of empirical, deterministic or probabilistic methods to determine the safe width of maneuvering areas on port waterways [3]. The most important methods include:

- PIANC;
- ROM (Spanish);
- Japanese;
- CIRM (Centrum Inżynierii Ruchu Morskiego).

They are widely used, in particular, at the preliminary stage of waterway design. For example, the most widely known PIANC method was used during the initial localization of the LNG terminal in India [7] to determine the approach fairway in the Chinese port of Panjin [8] and to determine the parameters of fairways in Korean waters [9]. However, the use of these methods was limited to determining the parameters of one or a maximum of several types (sections) of waterways (e.g., straight sections, bends, turning basins).

The direct application of the above methods to determine the conditions for the safe operation of ships on a complex waterway, such as the Świnoujście–Szczecin fairway, was impossible due to the complexity of the waterway and various restrictions on its individual parts.

This article:

- Defines conditions for the safe operation of ships in complex port waterways systems;
- Presents the methodology for determining maximum safe parameters of ships in existing complex port waterways systems.

1.2. Conditions of Safe Operation of Ships in Port Waterways Systems

From the perspective of marine traffic engineering, a system of port waterways is composed of a set of waterways (port areas), such as approach channels, port entrance, inner fairways (port channels, rivers, lakes), turning basins and port basins of various terminals.

In a port regarded as a system of sea waterways, different areas make up separate waterway sections that can be grouped into several criteria [3]:

- Technical parameters of the port area;
- Technical parameters of navigation systems used;
- Prevailing hydrometeorological conditions;
- Conditions of safe operation.

The conditions for the safe operation of ships in the *i*-th section of the waterway can be written as a set:

$$\boldsymbol{W}_i = \left[t_{yp}, L_{ci}, B_i, T_i, H_{sti}, V_i, C_i, \boldsymbol{H}_i\right] \tag{1}$$

where:

t_{yp} — Type of 'maximum ship';
L_{ci} — Overall length of 'maximum ship';
B_i — Breadth of 'maximum ship';
T_i — Draft of 'maximum ship' in i-th section of waterway;
H_{sti} — Airdraft in i-th section of waterway (useful while passing under a bridge or overhead power line);
V_i — Allowable speed of 'maximum ship' in i-th fairway section;
C_i — Tug assistance in i-th section of fairway, if it is required (required number and bollard pull of tugs);
$\boldsymbol{H}_i$ — Set of hydrometeorological conditions acceptable for 'maximum ship' in i-th fairway section.

$$\boldsymbol{H}_i = \left[d/n_i, s_i,\ \Delta h_i,\ V_{wi}, V_{pi},\ h_{fi}\right] \tag{2}$$

where:
d/n_i — Allowable time of day in *i*-th section of waterway;
s_i — Allowable visibility in *i*-th section of waterway;
Δh_i — Allowable drop of water level in *i*-th section of fairway;
V_{wi} — Allowable wind speed in *i*-th section of fairway;
V_{pi} — Allowable speed of current in *i*-th section of fairway;
h_{fi} — Allowable wave height in *i*-th section of fairway.

The conditions for the safe operation of ships passing through the waterways system consisting of a set of *n* sections can be written in this form:

$$\boldsymbol{W} = \left[t_{yp}, L_c, B, T, H_{st}, V_i, C_i, \boldsymbol{H}\right] \tag{3}$$

where:
t_{yp} — Type of 'maximum ship';
L_c — Maximum overall length of ships that can safely pass through the waterway system (port entrances);
B — Maximum breadth of ships that can safely pass through the waterway system;
T — Maximum draft of ships that can safely pass through the waterway system;
H_{st} — Maximum airdraft of ships that can safely pass through the waterway system.

$$\boldsymbol{H} = [d/n,\ s,\ V_w] \tag{4}$$

where:
d/n — Allowable time of day in the waterway system;
s — Allowable visibility in the waterway system;
V_w — Allowable wind speed in the waterway system.

Additional restrictions may occur, causing temporary changes in vessel traffic in the waterway system (or restrictions of maximum ship parameters). These are:

- Drop in water level in specific sections (Δh_i);
- Exceeded speed of the sea current in specific sections (V_{pi});
- Exceeded wave height in specific sections (h_{fi}).

The conditions for the safe operation of ships, defining the parameters of waterway system components, are defined separately for one-way and two-way traffic. In two-way traffic sections, the conditions for the safe operation of fairways can be written as follows:

$$\boldsymbol{W}_i = f_2\begin{bmatrix} t_{yp}^{in}, L_c^{in}, B^{in}, T^{in}, V_i^{in}, C_i^{in}, \boldsymbol{H} \\ t_{yp}^{out}, L_c^{out}, B^{out}, T^{out}, V_i^{out}, C_i^{out}, \boldsymbol{H} \end{bmatrix} \tag{5}$$

where *in* means a ship entering the port and *out* refers to a departing ship.

The state vector of safe ship operation conditions in waterway systems is a function of the parameters of this system [10,11]:

$$\mathbf{W} = F\begin{bmatrix} \boldsymbol{A}_i \\ \boldsymbol{N}_i \\ \boldsymbol{Z}_i \end{bmatrix} \quad (6)$$

where:

$\boldsymbol{W}$	—	Conditions of safe ship operation (state vector);
$\boldsymbol{A}_i$	—	Subsystem of i-th section of the waterway, determining the area parameters and the type of maneuver performed in that area (area subsystem);
$\boldsymbol{N}_i$	—	Subsystem of ship position determination, characterizing parameters of navigational systems in use (navigational system);
$\boldsymbol{Z}_i$	—	Subsystem of traffic control, characterizing its parameters and waterway capacity.

In cases where port waterways are covered by the identical system of regulations, each of the waterway sections consist of two basic components [12,13]:

1. Waterway subsystem;
2. Navigational subsystem (ship position determination subsystem).

These elements affect each other and have a vital impact on the system characteristics.

The parameters of subsystems of individual port waterway sections determine the conditions for the safe operation of ships in the waterway system:

$$\boldsymbol{W} = F\begin{bmatrix} \boldsymbol{A}_i \\ \boldsymbol{N}_i \end{bmatrix} \quad (7)$$

Conditions for the safe operation of ships in seaports are subject to two restrictions [11,12]:

1. The basic maximum parameters of ships that can safely pass through the waterway system cannot be greater than maximum parameters of ships safely passing through all of the sections of the system. Therefore:

$$\begin{aligned} L_c &= \min_i L_{ci} \\ B &= \min_i B_i \\ T &= \min_i T_i \end{aligned} \quad (8)$$

2. The hydrometeorological conditions that allow for maneuvering in the given waterway system of ships with maximum parameters are identical. This applies to the time of day (d/n), visibility (s) and wind speed (V_w).

2. Methods

The problem of maximum safe parameters of ships arises in the case of the construction, conversion or modernization of a port waterways system. This particularly applies to complex port waterways systems, composed of several port basins (cargo handling terminals), fairways (straight sections and bends) and turning basins.

Individual sections of waterways (system components) differ in technical and operational parameters:

- Cargo-handling terminals (port basins): type and maximum parameters of ships handled (t_{yp}, L_C, B, T);
- Fairways (bends and straight sections): depth (h), width at bottom (D) and slope angle;
- Turning basins: depth (h), length and width (l_{obr}, b_{obr},) or diameter.

In addition, mooring ships are taken into account in port basins and quays or piers located along the fairways of the system, anchorages and lay-by berths.

A complex port waterway system is usually composed of the following sections:

- Approach channel (from an anchorage);

- Port entrance;
- A number of inner fairway sections leading to various terminals;
- Port basins of the terminals;
- Turning basins for ships handled at a given terminal.

In order to take into account all constraints on individual sections of the fairway, the following procedure is proposed. It allows us to determine the maximum safe parameters of ships that may use the system between specific turning basins:

1. Preliminary determination of ships' maximum drafts in specific fairway sections:

$$T_{wi} = h_i - \Delta_{wi} \tag{9}$$

The underkeel clearance Δ_{wi} was determined for the pre-defined ship speed V_{wi}.

2. Determination of maximum overall lengths L_{co} of ships in turning basins, taking into account the possibility of turning in port basins of the terminals; location of turning basins in the fairway accounting for the length overall of ships safely turned:

$$L_{co}max, \ldots, \ L_{co}min \tag{10}$$

It was assumed that maximum lengths of turning ships decrease along with the increase in turning basin distance from the fairway entrance.

3. The division of the fairway into sections between the turning basins (j turning basins):
   - First section: from port entrance (into fairway) to the turning basin where the maximum length ship can be turned ($L_{co}max$);
   - Next sections were determined between subsequent turning basins in the fairway.

   Further calculations were made separately for each section between the turning basins.

4. Determination of length overall L_{cz} and breadth of B_z of ships safely maneuvering in fairway bends (z). Making calculations by starting from the turning basin where a vessel of greater length can turn, we should assume the safe overall length and breadth of the ship on the fairway section running from the considered turning basin as:

$$L_c^{zak} = \min_z L_{cz} \tag{11}$$

$$B^{zak} = \min_z B_z \tag{12}$$

5. Determination of maximum safe breadths of ships in straight one-way fairway sections (B_p); here, we should assume the safe ship breadth for all straight fairway sections (p) from the considered turning basin as:

$$B^{pr} = \min_p B_p \tag{13}$$

6. Determination of maximum safe lengths and breadths of ships in particular sections between the considered j-th turning basin:

$$L_{cj} = L_c^{zak} \text{ for } L_{cj} < L_{coj} \tag{14}$$

$$B_j = \min\left(B^{zak}, B^{pr}\right) \tag{15}$$

7. Determination of ship's safe draft and allowable speeds in specific fairway sections of the considered waterway, taking into account ship and fairway section parameters. The ship speed in individual waterway sections is calculated from this formula:

$$T_i = h_i - \Delta_i \tag{16}$$

The underkeel clearance is a function of ship speed and other parameters, fairway parameters and the performed maneuver:

$$\Delta_i = f(V_i) \tag{17}$$

The maximum safe draft of the ship in the considered *j*-th section of the waterway to be assumed:

$$T_i = \min_i T_i \tag{18}$$

8. Determination of maximum parameters of two-way traffic in each fairway section.
9. Determination of the conditions of safe operation of ships passing through the waterway system between the examined turning basins:

$$\boldsymbol{W}_j = \left[t_{ypj}, L_{cj}, B_j, T_j, H_{sr}, V_i, C_i, \boldsymbol{H}\right] \tag{19}$$

The algorithm of the parameters determination is shown in Figure 1.

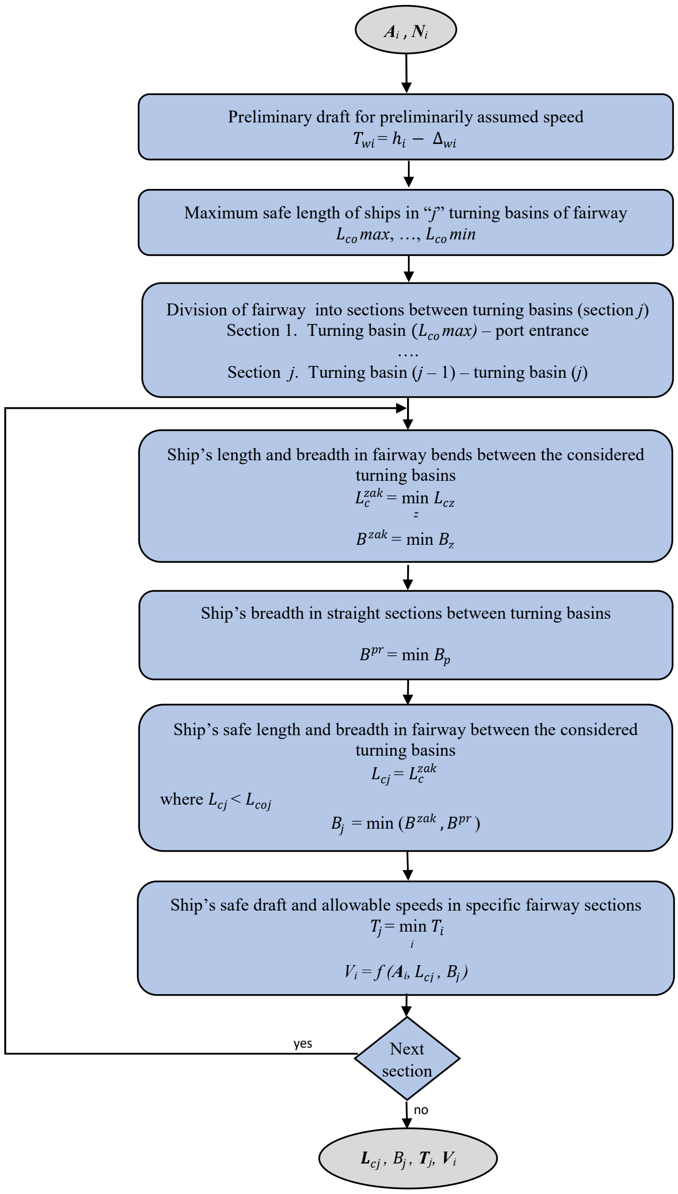

Figure 1. The algorithm of the process of determining maximum parameters of the ship in complex port waterways systems.

Notably, safe parameters of ships (L_c, B) maneuvering in turning basins and fairway bends can be determined by simulation or empirical methods [3,14,15]. Simulation methods using full mission bridge simulators are more accurate than empirical methods. In straight sections of the fairway, empirical methods are sufficiently accurate.

3. Results

The developed method for determining the maximum safe parameters of ships in complex port waterways systems was used for the calculation of the conditions for safe ship operations in the modernized Świnoujście–Szczecin fairway, dredged from 10.5 m to 12.5 m and widened. The requirements for determining the conditions for the safe operation of ships included parameters of 'maximum ships' passing through this fairway.

The modernized Świnoujście–Szczecin fairway is 68 km in length, and 12.5 m deep. It includes the Świnoujście entrance channel and a number of straight sections and bends with various technical parameters. The main sections of the fairway, together with their parameters, are shown in Table 1. The basic sections are connected with transition sections, on which, fairway parameters change. The whole waterway system comprises four turning basins. In addition, turning is possible in the Świnoujście–Szczecin fairway for ships entering and departing from two other ports (Figure 2):

- Police (49.4 km of the fairway), handling bulk carriers, chemical tankers and LPG tankers;
- Newly designed Skolwin port (55.7 km) to serve product, chemical and LPG tankers.

Table 1. Sections and the parameters of the modernized Świnoujście–Szczecin fairway.

Kilometer of Fairway		Type of Section	Radius [m]	Width Max [m]	Width Min [m]	Depth Max [m]	Depth Min [m]
from	to						
0	5.3	Port Świnoujście					
5.3	7.6	Straight		130	130	14.0	12.5
8.1	9.1	Straight		110	110	12.5	12.5
9.8	10.9	Bend	2300	120	120	14.0	12.5
11.4	17.0	Straight		110	110	18.0	12.5
17.4	23.0	Straight		100	100	12.5	12.5
23.8	28.8	Straight		250	250	12.5	12.5
29.6	40.9	Straight		100	100	12.5	12.5
41.2	43.0	Bend	2200	155	110	12.5	12.5
43.0	48.6	Straight		110	110	12.5	12.5
48.8	49.5	Bend + Turning basin		350	150	12.5	12.5
49.5	51.5	Straight		350	220	14.0	12.5
52.0	53.0	Bend	1680	150	150	13.0	12.5
53.2	54.4	Straight		130	130	12.5	12.5
54.7	55.4	Bend	1730	150	150	12.5	12.5
55.6	59.0	Straight		100	100	12.5	12.5
59.4	60.5	Bend	1600	150	150	12.5	12.5
60.8	62.9	Straight		100	100	12.5	12.5
63.4	64.0	Turning basin		360	360	12.5	12.5
64.3	66.6	Straight		100	90	12.5	12.5
66.7	67.0	Straight		130	130	12.5	12.5
67.1	67.4	Turning basin		330	330	12.5	12.5

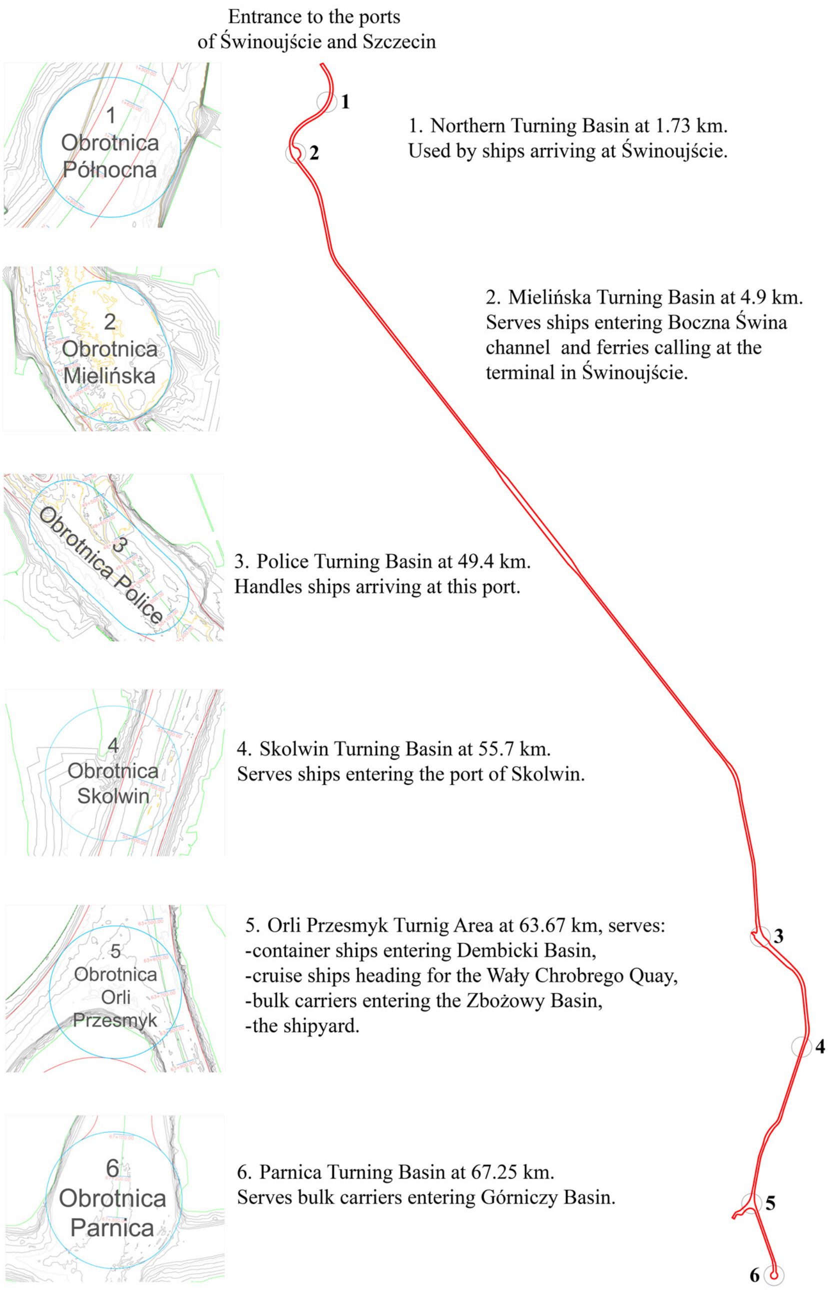

Figure 2. A simplified model of the complex port waterways system (four terminals).

Maximum safe parameters of ships passing through the Świnoujście–Szczecin fairway were determined in a procedure composed of the following steps:

1. Preliminary maximum draft of ships is:

$$T_w = 11 \text{ m}$$

where the underkeel clearance (Δ_{wi} = 1.5 m) was calculated using the method of components and adopting:

- Preliminary ship speed in individual sections V_i = 8 knots;
- Water level drop $\Delta h_i = -0.5$ m [16,17].

2. The maximum length of ships that can safely turn in four Świnoujście–Szczecin fairway turning basins is, respectively:

- Northern Turning Basin (1.7 km of the fairway), L_{co} = 300 m, B_o = 50 m—bulk carriers under ballast;
- Mielińska Turning Basin (4.9 km of fairway), L_{co} = 270 m, B_o = 40 m, T_o = 11.0 m;
- Przesmyk Orli Turning Basin (63.7 km), L_{co} = 260 m, B_o = 33 m, T_o = 9.0 m—cruise ships and L_{co} = 250 m, B_o = 33 m, T_o = 11.0 m—container ships
- Parnica Turning Basin (67.3 km of the fairway), L_{co} = 230 m, B_o = 33 m, T_o = 11.0 m—bulk carriers;
- Port of Police (49.4 km of the fairway), L_{co} = 230 m, B_o = 33 m, T_o = 11.0 m—bulk carriers and chemical tankers;
- Designed Skolwin Port (55.7 km of the fairway), L_{co} = 230 m, B_o = 35, T_o = 11.2 m—product tankers and LPG tankers.

The maximum ship lengths in the turning basins of Northern, Mielińska and Przesmyk Orli were determined using simulation methods, whereas the maximum ship length in the Parnica Turning Basin was estimated using the empirical method.

Example results of simulation tests are presented for the Northern Turning Basin. The tests were conducted on the FMBS simulator from Kongsberg. The preliminary assumed conditions for the safe operation of bulk carriers entering the Port of Świnoujście were as follows:

- Ingoing vessel entering and berthing port side alongside—loaded bulk carrier: L_c = 300 m, T = 13.2 m;
- Outgoing—bulk carrier under ballast: L_c = 300 m, T_D = 7.4 m, T_R = 9.0 m; the ship turns around the starboard side in the Northern Turning Basin.

Two simulation models of this bulk carrier were built to conduct three test series of ship arrivals and departures. The simulation experiment consisting of 12 passages in one series was performed by port pilots. Each test series was conducted in different least favorable hydrometeorological conditions. Figure 3 presents statistically developed test results of the port entry by a loaded bulk carrier, and Figure 4 depicts the turning of the bulk carrier under ballast, at wind N 10 m/s and ingoing current 0.8 knots. The test results are shown as safe maneuvering areas determined at three levels of confidence: maximum (red line), mean (green line) and 95% (magenta line).

3. The maximum overall length and breadth of ships safely maneuvering in fairway bends were determined for fairway sections between the turning basins. The calculations were made in this order:
    - Northern Turning Basin (1.7 km)—port entrance (0.0 km of the fairway). The maximum overall length and breadth of ships entering the port and approaching the Northern Turning Basin were determined by the simulation method (Figure 3), L_c = 300 m, B = 50 m, T = 13.2 m;
    - The Mielińska Turning Basin (4.9 km of the fairway)—Northern Turning Basin. The maximum overall length and breadth of ships safely passing from the Northern to Mielińska Turning Basins were determined by the simulation method L_c = 270 m, B = 40 m, T = 11.0 m [16]. In addition, the navigational risk of maximum ship passage was examined in connection with the planned arrivals of a ferry L_c = 220 m at berth No 2 of the ferry terminal in Świnoujście. The risk that the maneuvering ship moves out of the available navigable area and passenger fatalities occur R = 2.8×10^{-7} [year^{-1}] is lower than the acceptable risk [18].
    - Przesmyk Orli Turning Basin (63.7 km of the fairway)—Mielińska Turning Basin. The maximum overall length L_c^{zak} and breadth B^{zak} of ships safely maneuvering in the fairway bends (turns) between Mielińska and Przesmyk Orli Turning Basins were determined by the simulation method. The tests were conducted using a Kongsberg-made FMBS simulator in three fairway bends: Mańków, Ińskie-Babina and Święta. A simulation experiment was conducted for a cruise ship L_c = 260 m, B = 33.0 m, T = 9.0 m, and container ship L_c = 250 m, B = 33.0 m, T = 11.0 m [16]. Two series of tests were conducted in least favorable hydrom-

eteorological conditions for each bend. The simulation experiment consisting of 12 passages in one series was performed by port pilots. Figure 5 shows statistically processed test results for the Święta bend. The results refer to the safe maneuvering areas for a cruise ship L_c^{zak} sailing through the bend in the least favorable hydrometeorological conditions;

- There are no bends between Parnica (57.3 km) and Przesmyk Orli Turning Basins.

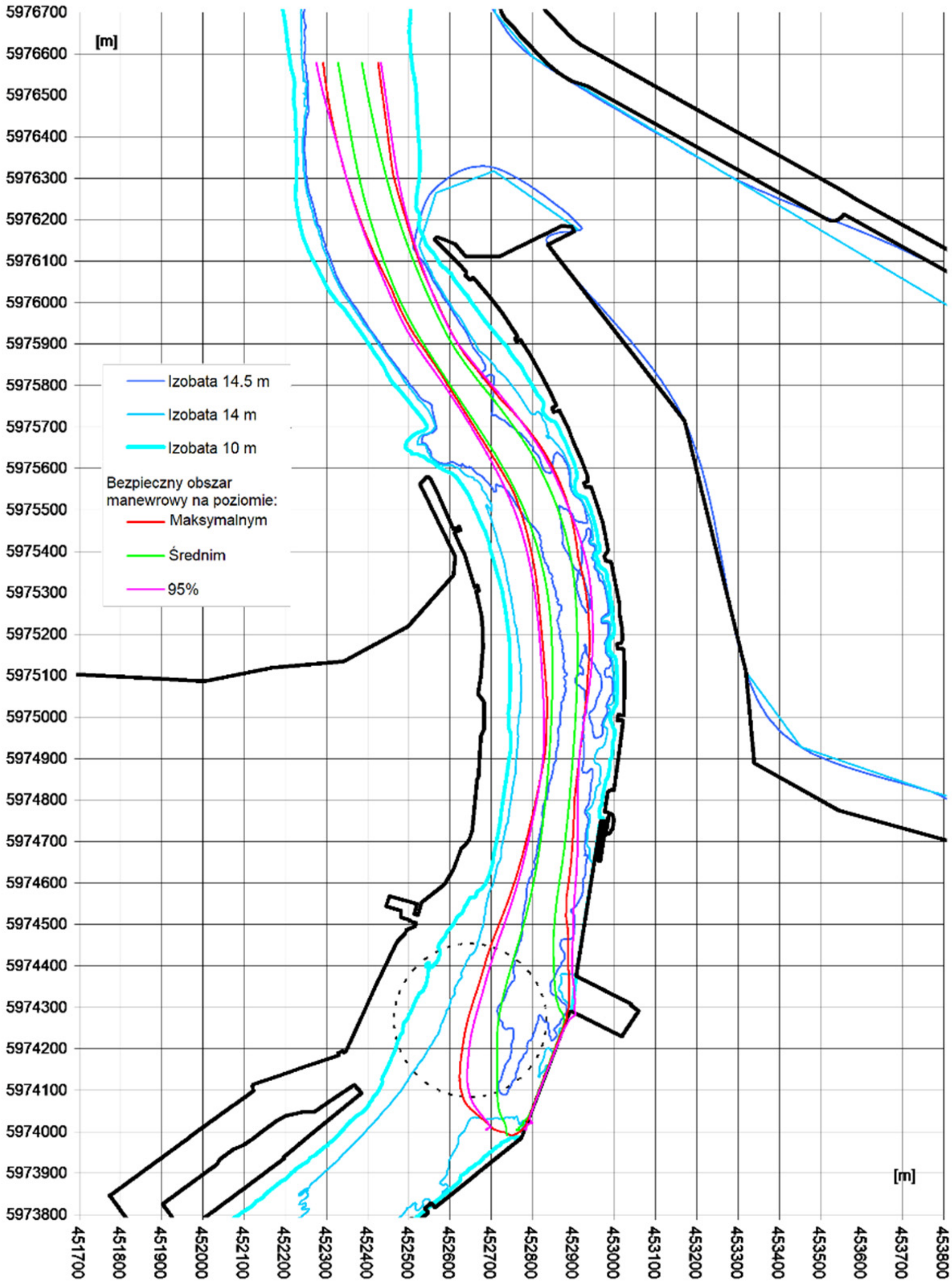

Figure 3. Safe maneuvering areas of the loaded carrier L_c = 300 m, T = 13.5 m at the entrance to Port Świnoujście. Wind N 10 m/s, ingoing current 0.8 knots, UTM coordinates (zone 33U).

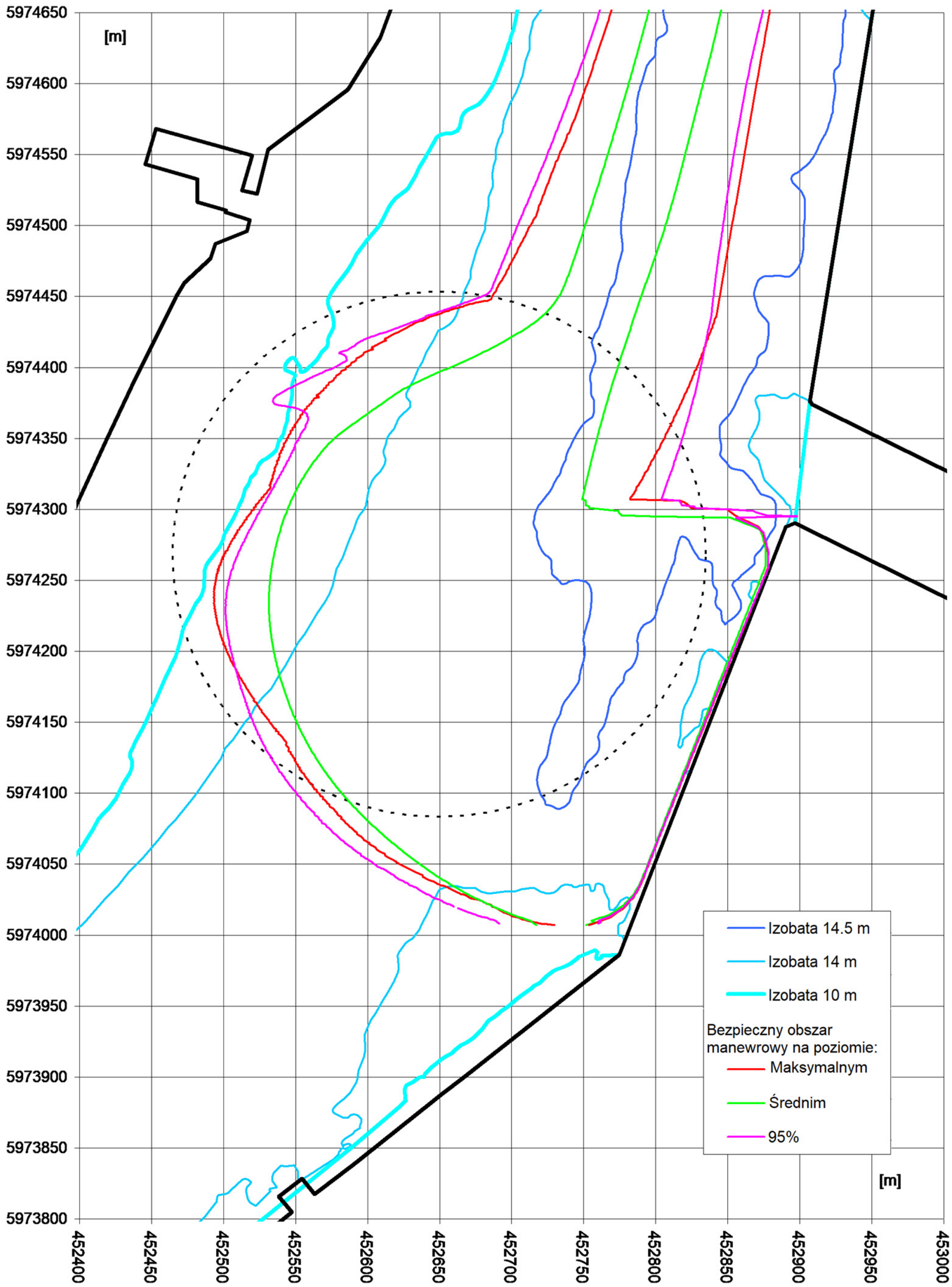

Figure 4. Safe maneuvering areas of turning in the Northern Turning Basin in Świnoujście, bulk carrier under ballast L_c = 300 m, T_D = 7.4 m, T_R = 9.0 m/s, ingoing current 0.8 knots, UTM coordinates (zone 33U).

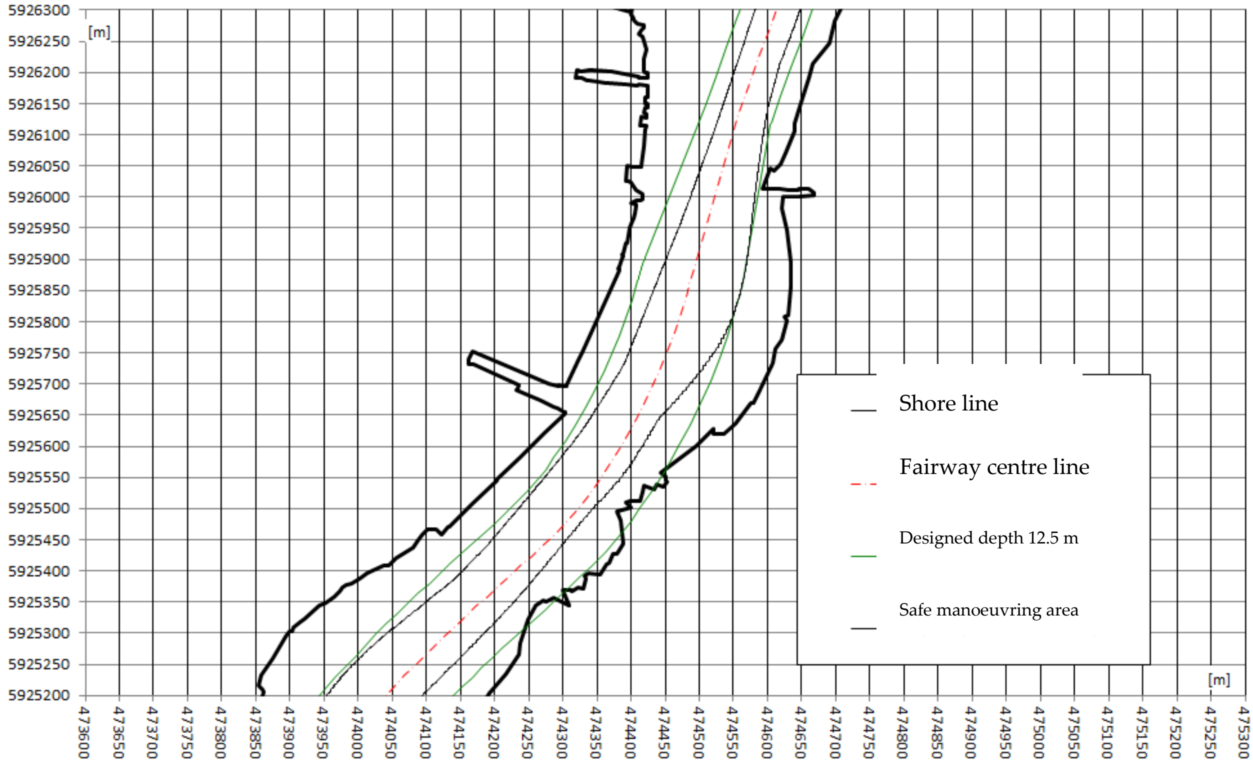

Figure 5. Święta fairway bend. Safe maneuvering area of cruise ship passage L_c = 260 m in least favorable hydrometeorological conditions. Wind S and W, 10 m/s, outgoing current 0.7 knots, UTM coordinates (zone 33U).

4. The maximum breadth of ships safely maneuvering in straight fairway sections was determined after transforming the condition of navigational safety, defined in the empirical CIRM method [3,15]. This condition can be written as:

$$D_j \geq d_m + 2d_{n(1-\propto)} + d_r^p + d_r^l \quad (20)$$

where:

D_j	—	Width at bottom of j-th point of the fairway center line for safe depth (available width of the navigable area) [m];
d_m	—	Deterministic maneuvering component of the swept path width [m];
$d_{n(1-\alpha)}$	—	Probabilistic navigational component of the swept path width [m] of the ship at a given confidence level $(1-\alpha)$ [m];
d_r^p	—	Reserve of maneuvering area width on the right-hand side [m];
d_r^l	—	Reserve of maneuvering area width on the left-hand side [m];

The maneuvering component is the sum of the basic width of the swept path d_{mp} and additional corrections of the swept path width d_{md}

$$d_m = d_{mp} + d_{md} \quad (21)$$

while:

$$d_{mp} = k \cdot B \quad (22)$$

where:

k	—	Coefficient determining the ship's maneuverability, dependent on ship type $k = f\ (t_{yp})$.

Additional corrections of the swept path width depend on the ship speed, technical parameters of the fairway and hydrometeorological conditions, i.e.:

$$d_{md} = f(V_i, A_i,\ H_i) \tag{23}$$

The width allowances depend on the ship speed and technical parameters of the fairway:

$$d_r = f(V_i,\ A) \tag{24}$$

The navigational component is determined by the subsystem of ship position determination in the given fairway section.

$$d_n = f(N_i) \tag{25}$$

Transforming this relationship (20) leads to the determination of the maximum safe width of the ship in straight fairway sections between the turning areas: (p sections):

$$B_p = \left(D_p - d_{md} - 2d_{n(1-\propto)} - d_r^p - d_r^l\right)/k \tag{26}$$

where all data necessary for determining the right-hand side terms of the equation are known:

$$B_p = f\ \left(A_i, N_i,\ H_i, V_{wi}, t_{yp}\right) \tag{27}$$

and these were used to determine the maximum safe breadths Bp of ships in each section and between the examined turning areas B^{pr}.

$$B^{pr} = \min_p B_p \tag{28}$$

5. Maximum safe lengths, breadths and drafts of ships between Świnoujście–Szczecin fairway turning areas were calculated as above and are equal to:
    - Northern Turning Area—port entrance channel: L_c = 300 m, B = 50 m, T =13.2 m;
    - Mielińska to Northern Turning Areas: L_c = 270 m, B = 40 m, T = 11.0 m;
    - Przesmyk Orli to Mielińska Turning Areas:

      L_c = 260 m, B = 33 m, T = 9.0 m—cruise carrier;
      L_c = 240 m, B = 33 m, T = 11.0 m—container ship;
      L_c = 230 m, B = 33 m, T = 11.0 m—bulk carrier;
    - Parnica to Przesmyk Orli Turning Areas: L_c = 230 m, B = 33 m, T = 11.0 m—bulk carrier.
6. Safe allowable speeds of ships in specific sections of the Świnoujście–Szczecin fairway were determined by starting from the basic condition of navigational safety

$$T \geq h - \Delta \tag{29}$$

where:

Δ – Underkeel clearance.

There are two methods for determining the underkeel clearance:

- Static method;
- Dynamic method.

The safe allowable speeds of ships in specific fairway sections were determined using the static method of components [15]. In the method, the allowance Δ was divided into two components: static allowance Δ_s and dynamic allowance Δ_d:

The static allowance does not depend on ship movement and is constant for the given area and the ship. Its components include:

Δ_1 — Water allowance for sounding error, depending on the depth of the area;
Δ_2 — Navigational allowance due to the discontinuity of soundings;
Δ_3 — Allowance for siltation, depending on the area;
Δ_4 — Allowance for the height of tide determination error, depending on the shipping area;
Δ_5 — Allowance for the error of water level determination due to water level fluctuations relative to chart datum;
Δ_6 — Allowance for the draft determination error, depending on the type of ship;
Δ_7 — Allowance for ship's list assessment error, depending on ship parameters.

The components of the dynamic allowance include:

Δ_8 — Allowance for moving ship squat, depending on ship's speed, draft, depth and other area parameters;
Δ_9 — Allowance for waves, depending on wave and ship parameters.

In the Świnoujście–Szczecin fairway, no water allowance for waves ($\Delta_9 = 0$) was made, so the condition of navigational safety can be written as:

$$T \leq h - \sum_{l=1}^{7} \Delta_l - \Delta_8 \tag{30}$$

The underkeel clearance was determined by five empirical methods recommended by PIANC in the given conditions [19]:

- Tuck;
- Huuska/Guliev;
- ICORELS;
- Barras3;
- Eryuzlu2.

It was calculated for container ships (block coefficient $C_b = 0.62$) and bulk carriers ($C_b = 0.8$) by adopting appropriate bottom profiles for individual fairway sections. Given the obtained results, specific safe allowable speeds were identified in all fairway sections. For ships T > 10 m, the following values apply:

- Container ships, general cargo ships, LPG tankers ($C_b \leq 0.65$) V = 8 to 12 knots;
- Bulk carriers, tankers ($Cb \geq 0.75$) V = 6 to 10 knots.

The guidelines were also formulated for the implementation of the dynamic underkeel clearance system, which will increase the allowable maximum draft to T = 11.2 m.

7. The passing of two ships in the Świnoujście–Szczecin fairway require the determination of maximum safe breadths of the meeting ships, depending on their draft and the fairway channel slope (Table 2).

The breadths of ships safely passing each other in straight fairway sections were determined based on the condition of the navigational safety of two-way traffic [13]:

$$D_{it} \geq d_m^{in} + d_m^{out} + 2d_{n(1-\propto)}^{in} + 2d_{n(1-\propto)}^{out} + d_r^{in} + d_r^{out} + d_r^s \tag{31}$$

where:

D_{it} — Width of available navigable area for ships with draft T in i-th section of the fairway;
d_r^s — Separation zone allowing for the suction force effect;
in, out — Indices marking incoming and outgoing ships.

Table 2. Determination of safe breadths of passing ships in straight sections of the Świnoujście–Szczecin fairway.

$T_1 + T_2$ [m]	$B_1 + B_2$ [m]		
	Slope Inclination		
	1:2	**1:3**	**1:4**
8	32	40	47
9	31	38	45
10	30	36	43
11	29	34	41
12	28	33	39
13	27	32	37
14	26	31	35
15	25	30	34
16	24	28	32
17	23	27	30
18	22	26	28
19	21	25	27
20	20	23	25

4. Discussion

The main objective of the research presented in the article is to develop a general method for determining the maximum parameters of ships in complex port water systems. This goal was achieved by developing a computational procedure (algorithm) that takes into account various constraints specific to individual sections of the fairway. The developed method stands out from the methods known in the literature (PIANC, ROM, Japanese, CIRM), which focus on determining the maximum parameters of a ship on individual types of waterways, but do not include the procedure for their use for complex waterways.

The developed method was used to determine the conditions for the safe operation of ships on the modernized Szczecin–Świnoujście fairway. The obtained results showed that the deepening and widening of the waterway will, obviously, allow for the passage of larger ships. However, the increase in ship dimensions relates more to the draft and length of the ship than to its breadth. For example, for the port of Szczecin, the maximum vessel draft increased from 9.15 m to 11.0 m and the length from 215 m to 260 m, and the width of the maximum vessel only increased from 31 m to 33 m. This is due to the fact that the horizontal dimensions of the safe maneuvering area depend not only on the width of the vessel, but also on its length, the draft ratio and the available depth.

The proposed method does not introduce new dependencies allowing for the determination of safe ship parameters, but, thanks to the systematization of calculations, it allows for the determination of these parameters on complex waterways. The limitations of its use result from the limitations of the detailed methods used; however, due to the possibility of using various methods (both empirical and simulation), it can be treated as a universal method allowing for the determination of safe parameters of ships on complex waterways. In the future, work on the development of this method will focus on the partial automation of calculations, which will allow us to shorten the time necessary to obtain results.

In conclusion, the developed method allows us to determine the maximum safe parameters of ships in complex port waters, which has been practically confirmed by defining the conditions for the safe operation of ships on the modernized Szczecin–Świnoujście fairway.

5. Conclusions

The article presents a new method for determining the maximum safe parameters of ships in existing complex port waterway systems and the conditions for safe ship operations.

The developed method can be described with the following general procedure:

1. The determination of maximum safe lengths of ships in specific turning basins and ship drafts;

2. The waterway division between turning basins, depending on the maximum length of ships turned there;
3. The determination of maximum lengths and breadths of ships safely maneuvering in fairway bends (turns) between the turning basins;
4. The determination of maximum safe breadths of ships in straight fairway sections between the turning basins;
5. The determination of the allowable speed of ships in specific fairway sections;
6. The determination of ship parameters in two-way traffic lanes;
7. The determination of conditions for the safe operation of ships in a complex port waterway system.

The prosed method was used for the determination of conditions for the safe operation of ships on the modernized 68-kilometer Świnoujście–Szczecin fairway. The modernization of the fairway resulted in deepening the channel from 10.5 m to 12.5 m and an appropriate widening of the channel. By dredging the fairway to 12.5 m, the maximum permissible draught of vessels calling at Szczecin was increased to approx. 11.0 m (before 9.15 m), and, thus, the availability of the Szczecin port to a certain group of large vessels was ensured. There will be no need for them to be discharged at Świnoujście before continuing on to the Szczecin port.

The results were used to draw up detailed port regulations defining the conditions for safe fairway operations of ships heading for the ports of Świnoujście, Szczecin, Police and Skolwin.

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