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Optimization of waterway bend widths using computer simulation methods of ship movement

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Abstract

The paper presents the development of a new simulation method to optimize bends in marine waterways. This method, using results of empirical research and simulation methods, would allow accurate determination of safe manoeuvring areas. The method was used at the stage of detailed design of parameters of the, which is undergoing modernization, to determine the optimum parameters of horizontal curves of the fairway. The study was conducted on the type of manoeuvring simulator called Polaris Kongsberg and attended by pilots from the Szczecin–Swinoujscie Pilot Station. Based on the studies carried out, the maximum safe ship length was determined for the redesigned waterway and the conditions for their safe operation. The maximum lengths of these ships are as follows: cruise $L_c = 260$ m, container $L_c = 240$ m and a bulk carrier $L_c = 220$ m.

Introduction

Horizontal parameters of a waterway bend can be determined by empirical or simulation methods (Gucma et al., 2015b), although empirical methods are less accurate than simulation methods. Empirical methods define the safe width of a manoeuvring area (d) as constant over the entire length of the bend:

$$d = \text{const} \tag{1}$$

Simulation methods determine the safe width of a manoeuvring area as a variable of the function of bend length (l):

$$d = f(l) \tag{2}$$

Methods of computer simulation were used to optimize horizontal parameters of bends in the modernized Świnoujście–Szczecin fairway. To determine the parameters of the components of the waterway system, an optimization method was used in which the objective function is the cost of building and operating a system of marine waterways, which can be written as follows (Gucma, 2013; Gucma et al., 2015b):

$$Z = (A_1 + A_2 + N_1 + N_2 + S_k) \rightarrow \min \tag{3}$$

with the constraint:

$$\left.\begin{array}{l} \mathbf{d}_{\mathrm{ijk}}(1-\alpha) \subset \mathbf{D}_{\mathbf{i}}(t) \\ \underset{p(x.s)\in\mathbf{D}(t)}{\wedge} h_{xy}(t) \geq T_{xy}(t) \cdot \Delta_{xy}(t) \end{array}\right\} \tag{4}$$

where:
$\mathbf{D}_\mathbf{i}(t)$ – navigable area at i-th section of the waterway (the condition of safe depth at moment t is fulfilled);
$\mathbf{d}_{\mathrm{ijk}}(1 - \alpha)$ – safe manoeuvring area of j-th ship manoeuvring in i-th section of the waterway

under k-th navigational conditions, the area being determined at confidence level $1–\alpha$;

Z – cost of construction and operation of waterways;
– cost of construction (reconstruction) of the waterway;
A_2 – cost of operation of the waterway;
N_1 – cost of the construction of a subsystem for determining ship position (navigation systems);
N_2 – cost of navigation systems operation;
S_k – vessel operating costs associated with waterway passage (pilotage, tug assistance, etc.);
h_{xy} – water depth at point (x, y);
T_{xy} – ship's draft at point (x, y);
Δ_{xy} – underkeel clearance at point (x, y).

Computer simulation methods used for the optimization of safe width of waterway bends

Computer simulation methods are used at the stage of detailed design of waterways. The application of these methods results in an accurate determination of safe manoeuvring areas for ships in service or those expected to operate therein. This refers to the determination of the width of safe manoeuvring areas for intended "maximum ships" in particular sections of the waterway and operating conditions allowable for these ships, at a preset confidence level $\mathbf{d}_{ijk}(1–\alpha)$. Using the basic navigational condition, a navigable area of the waterway $\mathbf{D}_i(t)$ is defined as a set of maximum available widths in each (i) section of the waterway.

In computer simulation methods for determining the width of safe manoeuvring areas of ships, the results were taken from the preliminary design stage where empirical methods are used (PIANC 2014; Gucma et al., 2015b).

The procedure of simulation tests used in the design of marine waterways is carried out in the following order (Gucma, Gucma & Zalewski, 2008):

1. formulation of the research problem, including identification of the design objective, simulation methods used and the type of simulators;
2. construction or choice of models of ship movement on the chosen simulator and their verification;
3. design of experimental system and conduct of an experiment;
4. processing and statistical analysis of test results.

The formulation of the research problem of the simulation experiment in the design of marine waterways is reduced to these steps:

1. determine the research objective;
2. determine the level of confidence or acceptable risk for safe manoeuvring area
3. choose a simulation method;
4. detect the type of shiphandling simulator.

Simulation tests used at the stage of detailed design of marine waterways employ the preliminary waterway design results. On this basis, the vectors of the parameters of safe operation of "maximum ships" that are used at the initial stage are determined to define parameters of waterway elements (Gucma, 2013):

$$\mathbf{W}_{\max} = [t_{yp}, L_c, B, T, H_{st}, V, C, \mathbf{H}_\mathbf{i}] \qquad (5)$$

where:

t_{yp} − type of "maximum ship";
L_c − length overall of "maximum ship";
B − breadth of "maximum ship";
T − draft of "maximum ship";
H_{st} − air draft of "maximum ship";
V_i − allowable speed of "maximum ship" in i-th section of the waterway;
C_i − tug assistance in i-th section of the waterway (number of tugs and bollard pull of each tug);
$\mathbf{H}_\mathbf{i}$ − vector of hydrometeorological conditions allowable for "maximum ship" in i-th section of the waterway.

When several "maximum ships" obtain comparable widths of safe manoeuvring areas at the initial design stage, all such ships qualify for simulation studies. The following may be a case in which simulation studies will be conducted for a number of models with the following vectors of safe operation of the ship:

$$\begin{array}{c} \mathbf{W}_\mathbf{i}\,(L_c = \max) \\ \mathbf{W}_\mathbf{i}\,(B = \max) \\ \mathbf{W}_\mathbf{i}\,(T = \max) \end{array} \qquad (6)$$

"Maximum ships" that qualify for simulation tests are called "characteristic ships" of the waterway under examination.

Arranging the experiment and processing the simulation test results are two parts of the simulation research procedure that require the researchers to have experience, deep insight, and understanding of the principles of manoeuvring and marine traffic engineering. Statistical analysis of the results of simulation studies must be based on specially designed programs for determining safe manoeuvring areas of a ship at a certain confidence level or at a certain level of acceptable risk.

Designing a simulation experiment system consists of:

- determining the scope of simulation studies;
- determining the number of simulation tests in each series;
- defining the characteristics and professional qualifications of the navigators performing simulated manoeuvres.

Simulation tests of the Świnoujście-Szczecin fairway bends

Deepening the Świnoujście–Szczecin fairway to 12.5 m will result in a deeper channel, drawing, longer and broader ships entering the port of Szczecin, hence the problem of determining the optimal width of the Świnoujście–Szczecin fairway for its dredged depth to 12.5 m.

In the initial stage of designing the modernized Świnoujście–Szczecin fairway three "maximum ships" were examined (Gucma et al., 2015a):

- container ship $L_{OA} = 210$ m;
- cruise ship $L_{OA} = 260$ m;
- bulk carrier $L_{OA} = 195$ m.

Two of these "maximum ships", the cruise ship and bulk carrier, require the widest path to safely manoeuvre through the bend. The container ship can safely manoeuvre through the bend on a narrower path. Therefore, the two ships that were accepted for simulation tests on the fairway bends are:

- cruise ship $L_{OA} = 260$ m;
- bulk carrier $L_{OA} = 195$ m.

Maximum ships qualified for simulation tests are called "characteristic ships" (or calculation ships) in reference to the examined waterway.

The aim of the simulation tests was to determine safe manoeuvring areas of "characteristic ships" on the bends and turning basins along the Świnoujście–Szczecin fairway. The simulation study included the following bends:

- Mańków (41.0 km ÷ 43.0 km);
- Ińskie and Babina (51.5 km ÷ 55.5 km);
- Święta (58.5 km ÷ 61.0 km).

The width of safe manoeuvring areas was determined at a confidence level of $1–\alpha = 0.95$. The study used a simulation method of vessel movement in real time (RTS) using non-autonomous models, meaning one in which the ship movement is controlled by a person (pilot or captain).

The simulation tests were conducted on a multi-bridge, shiphandling simulator called Polaris from Kongsberg Maritime AS, with 3D projection visualization. This Full Mission Bridge Simulator (FMBS) is operated at the Marine Traffic Engineering Centre (MTEC), Maritime University of Szczecin.

MTEC's ship navigation and manoeuvring simulator is composed of:

- FMBS with 270° visual projection, equipped with live marine and on-screen simulated navigational and manoeuvring equipment, including ARPA, ECDIS and DP Class 2 consoles;
- two multitask navigation bridge simulators with 120° visual projection, equipped with live marine and on-screen simulated navigational and manoeuvring equipment, including one Voith-Schneider tug console and one with azimuth propeller tug console;
- two part-task desktop PC simulators with one-display visual projection and on-screen simulated navigational and manoeuvring equipment;
- instructor room for designing and monitoring simulations.

The hydrodynamic modelling application enables users to build their own ships Available options for these ship models include: control function for two engines, two fixed pitch propellers, controllable pitch propellers, azimuth propellers; conventional and active rudders, as well as bow and stern thrusters with six degrees of freedom (pitching, rolling, yawing, heaving, surging and swaying).

User defined, target ships, and navigable waters are visualized in the 3D graphic, using high resolution textures, implemented into the simulator via Creator software from Presagis (Multigen). Testing areas are composed of databases combined with live or on-screen simulated navigational, ship handling equipment, and hydrodynamic models of ships and floating objects. The data bases comprise depths, aids to navigation, vision display, charts, wind, waves, currents, tides, fenders, locks, shores, Navtex data, DGPS, VTS, and positioning systems (DGPS, HPR, Artemis, Radius etc.).

The research team built and verified two models of "characteristic ships" with the following parameters (Gucma et al., 2015a):

The cruise ship:

- $L_{OA} = 260$ m – length overall;
- $L_{BP} = 220$ m – length between perpendiculars (also designated as L);
- $B = 33$ m – breadth;
- $T = 9$ m – draft;
- $m = 45{,}500$ t – displacement (corresponding to the deadweight capacity of approx. 8000 t);
- $A_L = 8{,}700$ m^2 – lateral windage area;
- propulsion: twin propellers; 4 x 7875 kW engines (diesel, total 31 500 kW); propeller type – cpp, turning inwards; stern rudders – Becker; thrusters: 3 x 1400 kW (bow) and 2 x 1400 kW (stern).

The bulk carrier:

- L_{OA} = 195 m – length overall;
- L_{BP} = 185 m – length between perpendiculars (also designated as L);
- B = 29 m – breadth;
- T = 11 m – draft;
- m = 47,000 t – displacement, laden ship (corresponds to deadweight capacity of approx. 38 000 t);
- A_L = 1,200 m^2 – lateral windage area;
- propulsion: single-propeller; diesel engine of 8500 kW; controllable pitch propeller, left-handed; conventional rudder; thrusters: none.

Designing an experimental system for simulation tests on FMBS comes down to the following tasks:

1. Defining the scope of simulation research. Determination of the number of characteristic series of tests, navigational conditions, and manoeuvring tactics adopted in each series of tests. These conditions should be selected so as to maximize the widths of safe manoeuvring areas of "characteristic ships".
2. Determination of the number of simulated manoeuvres (passages) in each series of tests.
3. Selection of the pilots for simulation tests. Determination of the qualifications of persons performing the manoeuvres and maximum numbers of simulations performed by one person in a given series of tests.

The following ranges have been developed for simulation tests of cruise ship and bulk carrier, proceeding along the Świnoujście–Szczecin fairway (V = 8 knots):

1. Mańków bend 41.0 km ÷ 43.0 km / ± 250 m:
   - passage to Szczecin;
   - current = 0;
   - wind = 10 m/s NW and SW.

   2 series of tests for each "characteristic ship" at two different wind directions NW and SW.
2. Ińskie-Babina bend 51.5 km ÷ 55.5 km / ± 250m:
   - passage to Świnoujście;
   - current = outgoing, 0.7 knot;
   - wind = 10 m/s, S and W

   2 series of tests for each "characteristic ship" at two different wind directions S and W.
3. Święta bend 58.5 km ÷ 61.0 km / ± 250 m:
   - passage to Świnoujście;
   - current = outgoing, 0.7 knot;
   - wind = 10 m/s, S and W.

   2 series of tests for each "characteristic ship" at two different wind directions S and W.

The minimum number of manoeuvre simulations in a test series was twelve for a specific wind direction (Gucma, 2001). The simulated manoeuvres were performed by pilots from Szczecin Pilot Station, captains experienced in manoeuvring large vessels. Each captain performed two simulated manoeuvres in a test series.

Analysis of simulation test results for optimization of horizontal Parameters of the Świnoujście–Szczecin fairway bends

Analysis of the results of the simulation studies using best fit tests has showed that:

1. There is no statistically significant difference (significance level $\alpha = 0.05$) between the widths of the paths swept by the cruise ship and bulk carrier for these winds:
   - NW and SW in the Mańków bend;
   - S and W in the bends: Ińskie, Babina and Święta.

   Accordingly, it was assumed, in further analysis that safe manoeuvring areas for individual vessels refer to all directions of wind speeds up to 10 m/s.
2. The biggest widths of safe manoeuvring areas in all the bends are swept by the cruise ship, L_{OA} = 260 m.
3. In all the examined bends the widths of safe manoeuvring areas determined by simulation methods are smaller than the widths defined by empirical methods (preliminary design).

The results of simulation tests, in the form of safe manoeuvring areas of the cruise ship and bulk carrier that were determined at a significance level of 0.95, are presented for the following Świnoujście-Szczecin fairway bends (Gucma et al., 2015a):

- Mańków bend – Figure 1;
- Ińskie bend – Figure 2;
- Babina bend – Figure 3;
- Święta bend – Figure 4.

Figures 1 to 4 include preliminary depth contours of 12.5 m superimposed at the stage of preliminary design using the MTEC method and safe depth contours of 12.5 m determined from simulation tests involving the cruise ship and bulk carrier, in the diagrams identified as swept paths of 95%.

The navigable area meeting the criteria of the minimum cost of construction and operation and navigational safety conditions designed on the basis of safe manoeuvring areas determined using simulation tests studies (see relations 3 and 4).

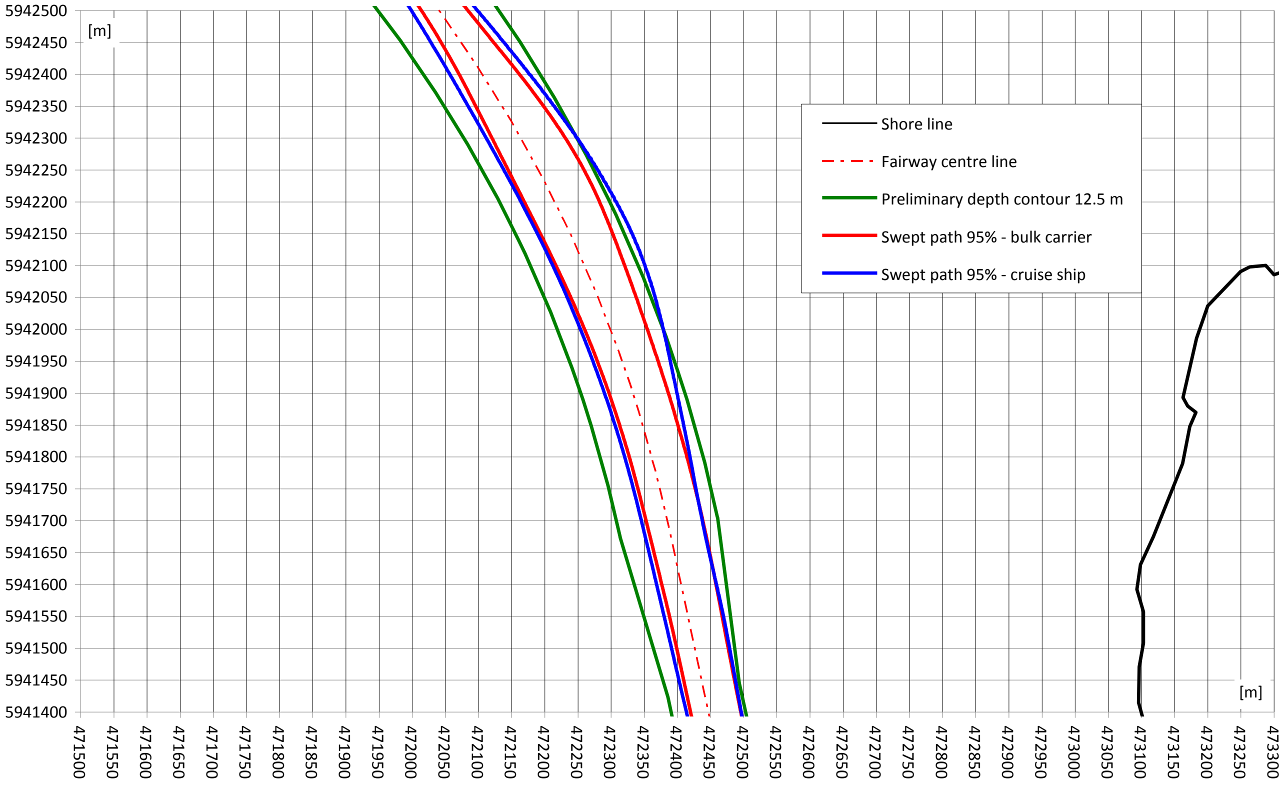

Figure 1. Safe manoeuvring areas of the cruise ship and bulk carrier in Mańków bend (41.0 km ÷ 43.0 km of Świnoujście–Szczecin fairway). Wind speed of 10 m/s (Gucma et al., 2015a)

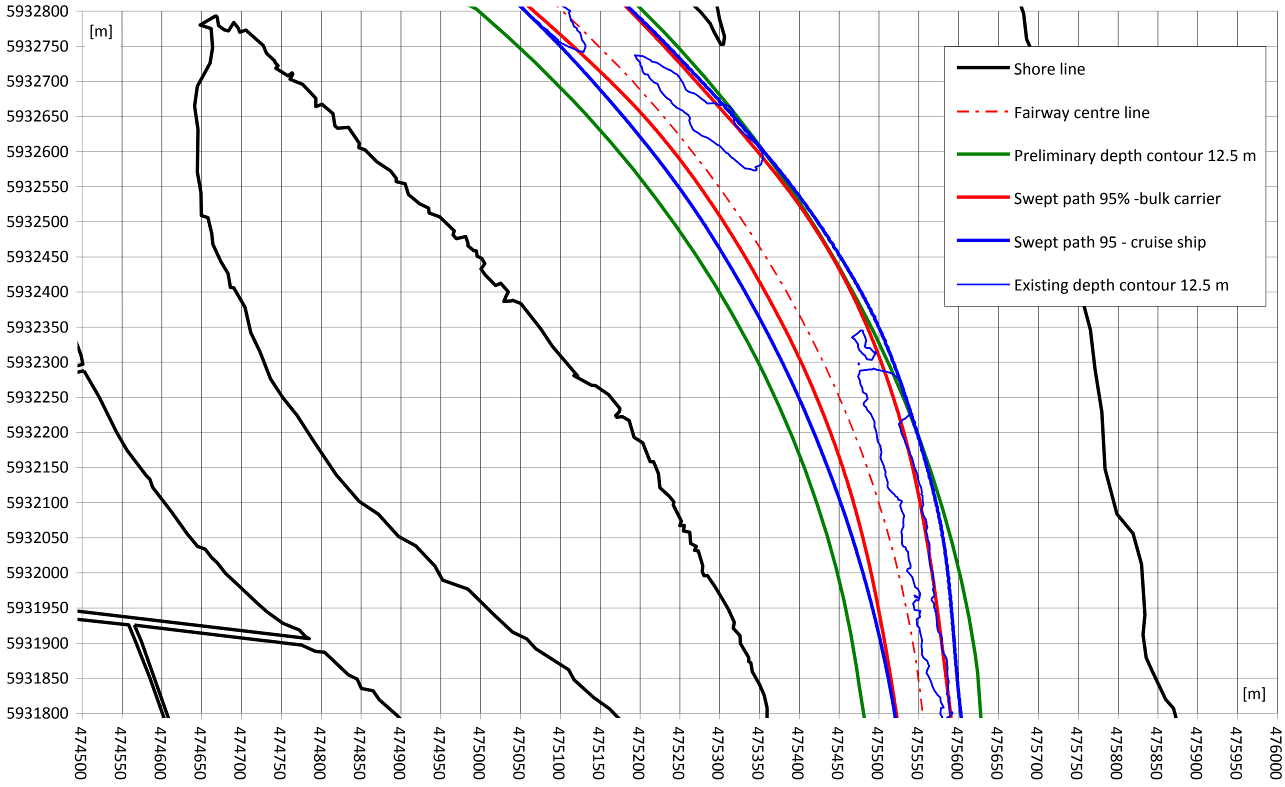

Figure 2. Safe manoeuvring areas of the cruise ship and bulk carrier in Ińskie bend (51.5 km ÷ 53.0 km of Świnoujście–Szczecin fairway). Wind speed of 10 m/s (Gucma et al., 2015a)

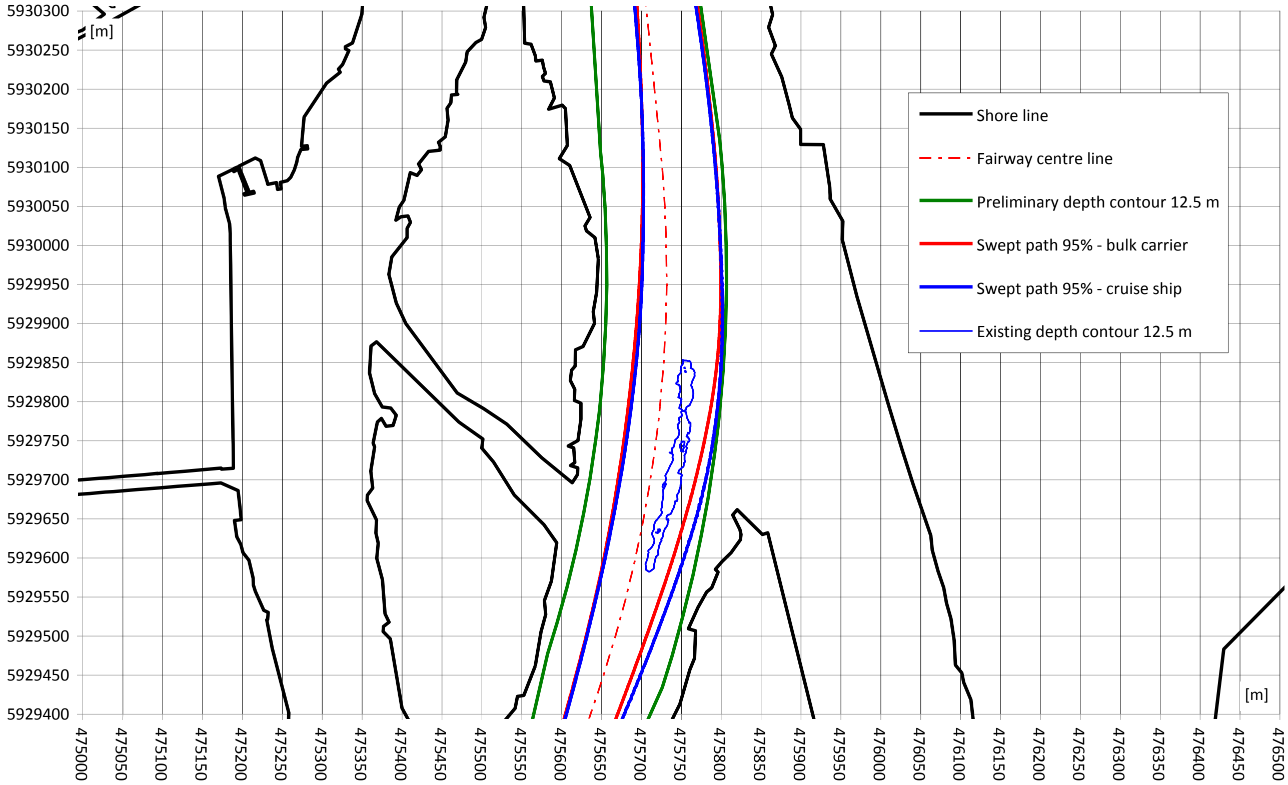

Figure 3. Safe manoeuvring areas of the cruise ship and bulk carrier in Babina bend (54.5 km ÷ 55.5 km of Świnoujście–Szczecin fairway). Wind speed of 10 m/s (Gucma et al., 2015a)

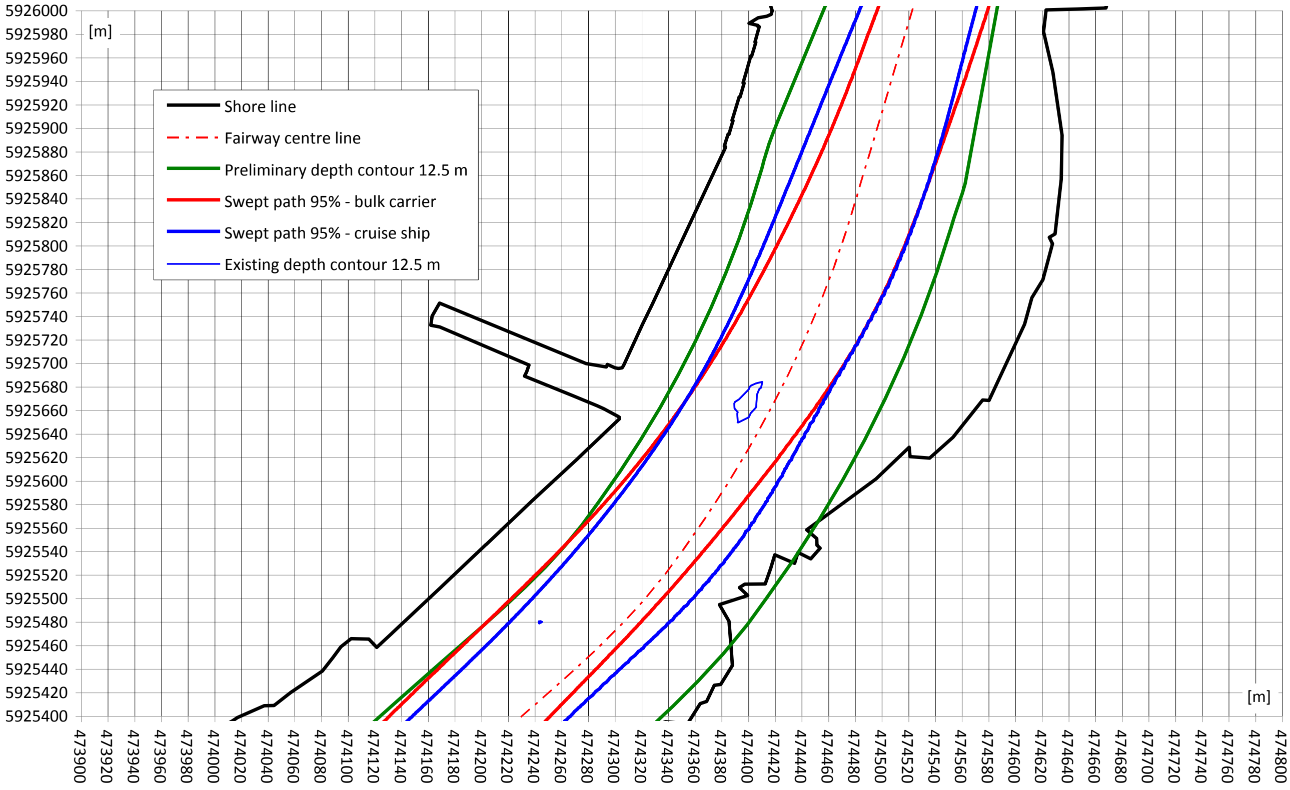

Figure 4. Safe manoeuvring areas of the cruise ship and bulk carrier in Święta bend (58.5 km ÷ 61.0 km of Świnoujście–Szczecin fairway). Wind speed of 10 m/s (Gucma et al., 2015a)

Conclusions

Based on simulation tests, the authors have determined the optimal horizontal parameters of bends making up sections of the Świnoujście-Szczecin fairway (Figures 1, 2, 3 and 4). These parameters are determined on the basis of safe manoeuvring areas of the cruise ship, $L_{OA} = 260$ m, as the widths of those areas were greater than the widths of safe manoeuvring areas of the bulk carrier, $L_{OA} = 195$ m.

Taking into account the different manoeuvring capabilities of the examined types of ships (cruise ship, container ship and bulk carrier), and having analyzed the widths of their safe manoeuvring areas defined by empirical and simulation methods, the authors have determined conditions for safe operation of these vessels on the Świnoujście–Szczecin fairway.

Given the above analysis, we have determined the maximum safe parameters of ships to be operated on the modernized Świnoujście–Szczecin fairway to be:

1. cruise ship
   $L_{OA} = 260$ m, $B = 33.0$ m, $T = 9.0$ m;
2. container ship
   $L_{OA} = 240$ m, $B = 32.3$ m, $T = 11.0$ m;
3. bulk carrier
   $L_{OA} = 220$ m, $B = 32.3$ m, $T = 11.0$ m;

As well as, the conditions for their safe operation:

- time of day – without restrictions;
- visibility – greater than 2 Nm;
- ship's speed – $V \leq 8$ knots;
- wind speed – $V_W \leq 10$ m/s;
- wind direction – without restrictions;
- current speed – $V_C \leq 1$ knot;
- current direction – outgoing (river);
- wave height – $h_{wa} = 0.0$ m;
- ice conditions – brash ice;
- margin for low water level – $\Delta h \leq 0.5$ m;
- tug assistance – not required.

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