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PARAMETER OPTIMIZATION OF SEA WATERWAY SYSTEM DREDGED TO THE SPECIFIED DEPTH CASE OF THE MODERNIZED ŚWINOUJŚCIE-SZCZECIN FAIRWAY

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Abstract: *The paper presents a methodology for designing and optimizing the parameters of reconstructed marine waterways dredged to a certain depth. The reconstruction comes down to a particular deepening and widening of the waterway to permit operation of longer, broader and deeper drawing ships. The methodology, based on a systemic approach to the design and optimization of waterways, uses the method developed at the Marine Traffic Engineering Centre (MTEC), Maritime University of Szczecin and methods of computer simulation. The optimization criterion used is the minimization of the aggregated costs of construction and operation of the waterway and its navigation systems*

Key words: *sea waterways, optimization of waterway parameters.*

1. Introduction to the optimization of sea waterway systems

One of the tasks of marine traffic engineering is to optimize the system of waterways which are to be deepened to a specific depth. Dredging of the waterway opens opportunities for increasing the vessel traffic by allowing bigger ships, with greater draft, length and width, to enter the fairway. This raises issue relating to deepening the modernized waterway and the determination of its optimal width. The problem herein considered refers to the optimization of sea waterway systems undergoing modernization.

A system of maritime waterways in terms of marine traffic engineering consists of a number of separate sections (*n*). Each of the sections of the waterway consists of three basic elements (Gucma, 2013a):

1) Waterway subsystem.
2) Subsystem of vessel position determination (navigation subsystem).
3) Vessel traffic control subsystem.

These elements interact with each other and have a significant effect on the properties of the system.

The sections of the waterway are distinguished using the following comparative criteria:

- performed maneuver;
- technical parameters of the waterway;
- technical parameters used in navigation systems;
- prevailing weather conditions;
- port regulations and traffic control systems.

Individual sections are separated so that the same comparative criteria are applicable along the whole length of a section.

If the entire area through which the individual section of the waterway is covered by the same traffic control system, a model of waterway system can be simplified to two elements. Then each of the sections of the waterway consists of two basic elements (Gucma, 2013b):

1) Waterway subsystem.
2) Navigation subsystem.

A simplified model of waterway system is shown in Figure 1.

Conditions for safe operation of ships on the waterway are described by the state vector of conditions of safe operation of 'maximum ship' at *i*-th section of the examined waterway, written as (Gucma, 2013a):

$$\mathbf{W_{ij}} = [typ_{ij}, L_{c\,ij}, B_{ij}, T_{ij}, H_{st\,ij}, V_{ij}, C_{ij}, \mathbf{H_{ij}}] \qquad (1)$$

where:

typ_{ij} – type of *j*-th 'maximum ship for *i*-th waterway section;

$L_{c\,ij}$ – length overall of *j*-th 'maximum ship for *i*-th waterway section;

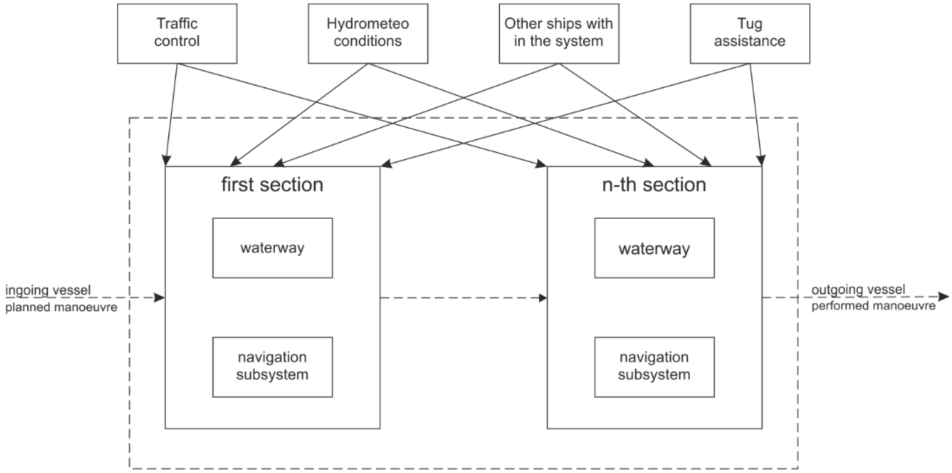

Fig. 1. A simplified model of the system of waterways including *n* sections

B_{ij} – breadth of *j*-th 'maximum ship' for *i*-th waterway section;
T_{ij} – draft of *j*-th 'maximum ship' for *i*-th waterway section;
$H_{st\,ij}$ – air draft of *j*-th 'maximum ship' for *i*-th waterway section;
V_{ij} – permissible speed of *j*-th 'maximum ship' on *i*-th waterway section;
C_{ij} – tug assistance on *i*-th waterway section (required number of tugs and bollard pulls);
$\mathbf{H_{ij}}$ – vector of hydrometeorological conditions acceptable for *j*-th 'maximum ship' at *i*-th section of the waterway.

The system of waterways is defined by parameters of its components (subsystems). Two elements of the marine waterway system at each of its sections are a function of the state vector of the conditions of safe operation of 'maximum ship':

$$\begin{bmatrix} \mathbf{A_i} \\ \mathbf{N_{in}} \end{bmatrix} = \mathbf{F}\left(\mathbf{W_{ij}^n}\right) \tag{2}$$

where:
$\mathbf{A_i}$ – subsystem of *i*-th waterway section;
$\mathbf{N_{in}}$ – navigation subsystem of *i*-th waterway section;
$\mathbf{W_{ij}^n}$ – state vector of safe conditions of operating *j*-th 'maximum ship' for *n*-th navigation system.

The *i*-th section of the waterway is characterized by four parameters (matrix elements):

$$\mathbf{A_i} = \begin{bmatrix} t_i \\ l_i \\ D_i \\ h_i \end{bmatrix} \tag{3}$$

where:
t_i – type of *i*-th section of the waterway;
l_i – length of *i*-th section;
D_i – width of the navigable area of *i*-th section;
h_i – minimum depth of *i*-th section.

A few (n) navigational systems, characterized by three parameters, may be operated on each of the waterway sections:

$$\mathbf{N_{in}} = \begin{bmatrix} \sigma_{in} \\ m_{in} \\ n_{in} \end{bmatrix} \tag{4}$$

where:
σ_{in} – accuracy of *n*-th navigation system at *i*-th section of the waterway (standard deviation);
m_{in} – availability of *n*-th navigation system at *i*-th section (depending on the time of day and visibility);
n_{in} – reliability of *n*-th navigation system at *i*-th section of the waterway (technical reliability).

It should be noted that for a specific system of marine waterways defined by relevant parameters of the subsystems there exist a number of (j) types of 'maximum ships' that fulfil the conditions of safe operation.

To determine the parameters of waterway elements we use optimization methods where the objective function is the cost of construction and operation/maintenance of sea waterway system, which can be written as follows (Gucma, 2013b):

$$Z = \sum_{i=1}^{m} \left(A_{bi} + A_{ei} + N_{bi} + N_{ei} + S_i^k \right) \rightarrow \min \tag{5}$$

subject to the constraint, the condition of the safety of navigation:

$$\forall P_{xy} \in \mathbf{D}(t) \quad \left. \begin{aligned} \mathbf{d}_{ijk(1-\alpha)} &\subset \mathbf{D_i}(t) \\ h_{xy}(t) &\geq T_{xy}(t) + \Delta_{xy}(t) \end{aligned} \right\} \tag{6}$$

where:

- $\mathbf{D_i}(t)$ – navigable area at i-th section of the waterway (the condition of safe depth at moment t is fulfilled);
- $\mathbf{d}_{ijk(1-\alpha)}$ – safe manoeuvring area of j-th ship manoeuvring at 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 composed of m-sections;
- A_{bi} – cost of construction (reconstruction) of the i-th waterway section;
- A_{ei} – cost of operation of i-th waterway section;
- N_{bi} – cost of the construction of a subsystem for determining ship position (navigation systems) on i-th waterway section;
- N_{ei} – cost of navigation systems operation on i-th waterway section;
- S_i^k – ship operating costs associated with waterway passage (pilotage, tug assistance, etc.) on i-th waterway section;
- h_{xy} – water depth at point (x,y);
- T_{xy} – ship draft at point (x,y);
- Δ_{xy} – underkeel clearance at point (x,y);
- P_{xy} – point at (x, y) coordinates.

2. Methodology of the design and optimization of reconstructed sea waterways dredged to a specific depth

Using a systemic approach to the optimization of waterways, the Marine Traffic Engineering Centre (MTEC) developed a method of optimizing parameters of the reconstructed waterway. The reconstruction, which consists in specified deepening and broadening of the fairway, will allow operation of larger ships: with greater draft, length and breadth.

The process of designing marine waterways system is divided into two stages (Gucma et al., 2015):

- concept design;
- detailed design.

The phase of concept design of waterways consists of:

- preliminary determination of the matrix $\mathbf{M^w}$ of conditions of safe operation of 'maximum ships' on the designed waterway;
- preliminary determination of the matrix of the intensity $\mathbf{I^w}$ of vessel traffic for the designed waterway;
- preliminary determination of parameters $\mathbf{A_i^w};\mathbf{N_{in}^w}$ of the elements of waterway system.

The underkeel clearance (UKC) and widths of safe manoeuvring areas of individual 'maximum ships' are determined by preliminary approximate methods.

Detailed design stage comes down to these steps:

- choose 'characteristic ships' (for calculations) and determine their vectors of safe operation conditions $\mathbf{W}_{\mathbf{ij}\max(T_j+\Delta_j)}$ – ship with the maximum draft; $\mathbf{W}_{\mathbf{ij}\max d_j}$ – ship with the maximum width of a safe manoeuvring area;
- determine the level of confidence $(1-\alpha_i)$ at which calculations are made of UKCs and safe manoeuvring areas for each 'characteristic ship';
- determine optimum parameters of the waterway system elements $\mathbf{A_i};\mathbf{N_{in}}$;
- determine the matrix $\mathbf{M}$ of conditions of safe operation of ships on the designed waterway;
- determine the matrix of intensity $\mathbf{I}$ of vessel traffic for the designed waterway.

Concept design and optimization stage

For the 'maximum ships' a matrix is built with preliminary conditions of safe operation of the fairway. The rows of this matrix are the conditions of safe operation of 'maximum ships' of types intended for operation:

$$\mathbf{M}^{w}=\begin{bmatrix} typ_1, & L_{c1}, & B_1, & T_1, & V_1, & C_1, & \mathbf{H}_1 \\ typ_2, & L_{c2}, & B_2, & T_2, & V_2, & C_2, & \mathbf{H}_2 \\ typ_3, & L_{c3}, & B_3, & T_3, & V_3, & C_3, & \mathbf{H}_3 \end{bmatrix}=\begin{bmatrix} \mathbf{W}_1^{w} \\ \mathbf{W}_2^{w} \\ \mathbf{W}_3^{w} \end{bmatrix} \quad (7)$$

At the concept design and optimization stage we define a minimum UKC and safe widths of manoeuvring areas (minimum safe width of the fairway at the bottom). The minimum UKC was determined by the component margin method and the probabilistic method. The UKC unambiguously defines the permissible drafts of maximum ships.

The parameters for safe manoeuvring area of 'maximum ships' on the waterways with one-way traffic lanes were determined using the following deterministic methods (Determination …, 2008):

- PIANC;
- Canadian;
- IMN (Institute of Marine Navigation);
- method of generalizing the results of simulation studies.

Safe waterway widths are determined for:

- straight (rectilinear) sections of fairway;
- bends in the fairway;
- transition sections between a bend and straight section.

Detailed design and optimization stage

The stage of detailed design and optimization of parameters of deepened waterway system takes place in the following order:

A. determination of the optimal safe widths of the waterway for maximum ship one-way traffic.
B. determination of the location and safe widths of passing places on the designed waterway.
C. determination of the location and optimal parameters of turning basins on the designed waterway (see article Gucma & Ślączka, 2015b).

A. Determination of fairway parameters for one-way traffic

In order to determine the optimum waterway widths an algorithm was developed for calculations at this stage, which differentiates the straight sections and bends because they require different methods of calculation. The inputs to this algorithm are:

- preconditions for safe operation of 'maximum ships' $\mathbf{M}^{w}$;
- preliminary navigation subsystem of individual sections of the fairway $\mathbf{N}_{\mathbf{i}}^{w}$;
- preliminary waterway (fairway) subsystem $\mathbf{A}_{\mathbf{i}}^{w}$ defined as follows:

$$\mathbf{A}_{\mathbf{i}}^{w}=\begin{bmatrix} t_i \\ l_i \\ D_i^{w} \\ h_i \end{bmatrix} \quad (8)$$

where three types of waterway (t_i) are distinguished:

- straight fairway section;
- bend;
- transition section between the bend and the straight section, 250 m long.

The parameters h_i and $D_i^{w}=d_i^{w}$ were adopted from the concept design stage (for different types of waterway).

The algorithm of detailed design of the modernized fairway is shown in Figure 2. This algorithm can be described as follows:

1) Determination of safe manoeuvring area width (fairway width) of 'maximum ships' at each section of the Świnoujście-Szczecin using MTEC deterministic-probabilistic methods (Gucma & Ślączka, 2015a). The width of safe manoeuvring areas is determined at a confidence level of 1-α=0.95 for three 'maximum' ships manoeuvring in three conditions of visibility and appropriate navigation system and in hydrometeorological conditions pre-determined at the design stage. For further calculations, we select the maximum safe width of the data set encompassing all ships and navigation conditions:

$$d_i^{MTEC}=\max_{jk} d_{ijk}^{MTEC}$$

2) Determination of the width of safe manoeuvring areas on the bends and transition sections of the fairway, using computer simulation methods for two 'characteristic ships'. Simulation tests are performed on models of these ships. 'Characteristic ships' are two ships selected for calculations from the set 'maximum ship' tested at a concept stage. These vessels have the following characteristics:
   - maximum width of safe manoeuvring area:
   $d_i^{MTEC} = \max_{jk} d_{ijk}^{MTEC}$;
   - maximum safe draft:
   $\max(T_j + \Delta_j)$.

   State vectors of safe operation conditions for 'characteristic ships' are built:

   $\mathbf{W}_{\mathbf{ij}\, d_{MTEC}}$

   $\mathbf{W}_{\mathbf{ij}\max(T_j+\Delta_j)}$

   The widths of safe manoeuvring areas are defined at a confidence level of 1-α=0.95. The study used a simulation method of movement in real time (RTS) using non-autonomous models, in which the movement of the ship is controlled by a human (pilot, captain). Simulation tests are carried out on a full mission bridge simulator with 3D projection-type visualization, such as the one installed at the Marine Traffic Engineering Centre (MTEC), the Maritime University of Szczecin. The computer simulation methods for determining widths of safe manoeuvring areas of ships utilized the widths determined by the MTEC method. The simulation test procedure used in the design of sea waterways requires the following steps (Gucma S., Gucma L.& Zalewski P., 2008):
   - formulate the research problem, and identify the design objective, simulation methods to be used and simulator type;
   - build models of ship movement on the chosen simulator and verify them;
   - design an experimental system and conduct the experiment;
   - design and statistically analyze test results.
3) Available widths of the reconstructed waterway are determined for rectilinear sections using the MTEC method:

   $D_i \le d_i^{MTEC}$

   while for the bends and transition sections simulation tests are used:

   $D_i(l) \le d_i^{SYM}(l)$

   where these widths are determined as a function of fairway length (l).
4) The two waterway subsystem parameters are optimized on the basis of precise estimates of reconstruction and operation/maintenance costs of individual waterway solutions regarded as a system. Given that:

   $Z_i \to \min$

   and having the fulfilled basic condition for safe navigation we determine the waterway system parameters:

   $\mathbf{A_i}\,;\mathbf{N_{in}}$

   At the detailed design stage the navigation subsystem $\mathbf{N_{in}}$ is expanded to two basic navigation systems for three different visibility conditions.
5) Determination of operational conditions for 'maximum ships' of all types included in the matrix of preconditions for safe operation of ships. In this step, we increase L_{oa} and B at $T = const$ of smaller ships in such a way as to obtain equal safe manoeuvring areas of all types, i.e.

   $d_{ij} = d_i$ - rectilinear section;

   $d_{ij}(l) = d_i(l)$ - fairway bend.

   This will allow determining the matrix M of safe operation of maximum ships.

B. Determination of the location and parameters of passing places

Designers of passing places for one-way traffic lanes have to solve two problems:
- determine a safe width of the passing place for a particular ship size;
- locate the sites of the passing places on the fairway.

A safe width of a passing place for a specific vessel size is determined with the MTEC method for two-way fairways.

The determination of passing place location on a one-way fairway is carried out by computer simulation of vessel traffic streams for predefined parameters of predicted traffic and has the following algorithm:

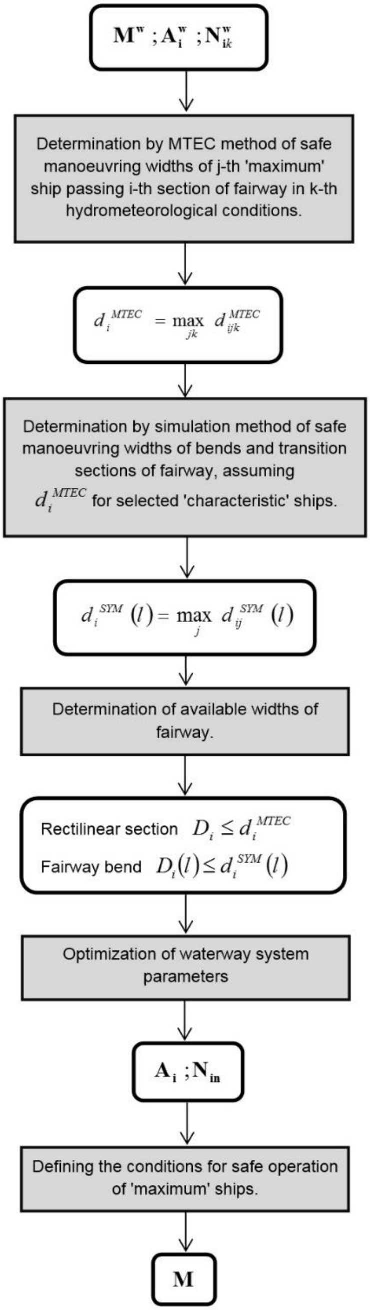

Fig. 2. The algorithm of detailed design of waterway reconstruction and dredging

1) Predict vessel traffic by ship sizes and types.
2) Determine realistic variants of passing place locations and their parameters.
3) Estimate construction costs of the different options of passing places.
4) Perform computer simulation of anticipated vessel traffic streams on the fairway, to specify:
   - the likelihood of queues of ships in different ship size groups;
   - total annual times of ships waiting to enter the fairway.
5) Choose the optimal location of passing places, taking into account two criteria:
   - minimization of passing place construction costs;
   - minimization of yearly waiting times of vessels intending to enter the fairway.

3. Optimized parameters of the reconstructed Świnoujście-Szczecin fairway dredged to 12.5 m

The basic premise of the reconstruction of the Świnoujście-Szczecin fairway was its deepening to 12.5 m and widening allowing safe navigation of 'maximum ships' in the one-way traffic with the possibility of passing another ship (construction of passing places) that would not pose traffic restrictions.

The Świnoujście-Szczecin fairway is a sea waterway of varying features, stretching from the Pomeranian Bay through the Świna, Kanał Mieliński, then across Zalew Szczeciński, through the Odra River and Przekop Mieleński to the Port of Szczecin. The fairway, 68 km long, has already been modernized along its 0.0-16.5 km section and adapted to 'maximum ships' (deepened to 12.5 m). Therefore, this article considers only the fairway stretch from 16.5 km to 68.0 km. Applying a systemic approach and the above-specified comparative criteria, we divided the Świnoujście-Szczecin fairway into nine characteristic sections (Gucma, et al., 2015; PIANC 2014).

Three 'maximum ships' were examined in the concept stage of redesigning the Świnoujście-Szczecin fairway (Navigational analysis ..., 2015):

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

Using the MTEC method, we determined minimum safe widths of the Świnoujście-Szczecin fairway sections at a confidence level of 0.95, for three types of 'maximum ship' described above, manoeuvring under three different hydrometeorological conditions. Calculations were made for two directions of traffic: Szczecin and Świnoujście.
The largest safe fairway widths are required by the cruise ship L_{OA} = 260 m, and these widths as d_i^{MTEC} were accepted for further studies. The calculation results for the cruise ship proceeding from Świnoujście to Szczecin are shown in Figure 3.
Two of these 'maximum ships', cruise ship and bulk carrier, produced on the fairway bends comparable widths of safe manoeuvring areas (MTEC method). The container ship swept smaller widths of safe manoeuvring area. Therefore, the two characteristic ships were qualified for further simulation studies on fairway bends:

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

The simulation tests were aimed at determining safe manoeuvring areas of 'characteristic ships' on the bends and turning basins of the Świnoujście-Szczecin fairway. The simulations included the 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 widths of manoeuvring safe areas were determined at a confidence level of 1-α=0.95. The study used a simulation method of ship movement in real time (RTS) using non-autonomous models, in which the ship is steered by a human (pilot, captain). The simulations were performed on a full mission bridge simulator with 3D projection-type visualization, namely a Kongsberg Maritime Polaris AS simulator, installed at the MTEC, the Maritime University of Szczecin.
Two computer models of 'characteristic ships' were built and verified: cruise ship L_{OA} = 260 m, bulk carrier L_{OA} = 195 m (Navigational analysis ..., 2015).

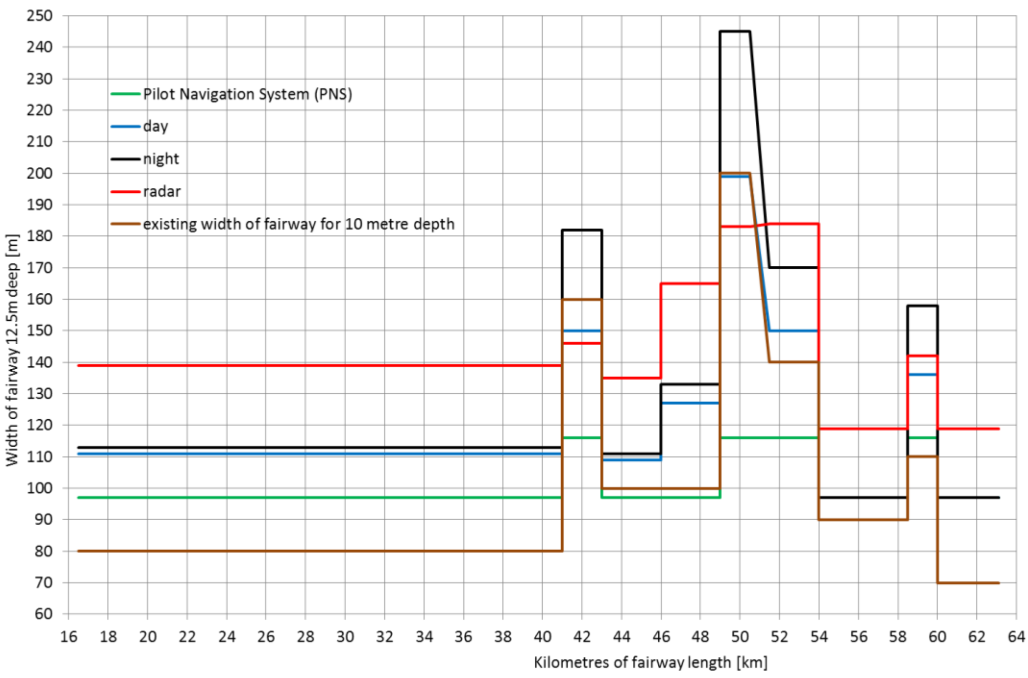

Fig. 3. Safe width of the Świnoujście-Szczecin fairway for a cruise ship bound for Szczecin for the existing aids to navigation, at a confidence level of 0.95

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

1. Mańków 41.0 km ÷ 43.0 km / ± 250 m: - passage to Szczecin - current = 0. - wind = 10 m/s NW and SW	Two series of tests for each 'characteristic ship' manoeuvring under two different wind directions, NW and SW.
2. Ińskie-Babina 51.5 km ÷ 55.5 km / ± 250 m: - passage to Świnoujście - current = outgoing, 0.7 knot - wind = 10 m/s S and W	Two series of tests for each 'characteristic ship' manoeuvring under two different wind directions, S and W.
3. Święta 58.5 km ÷ 61.0 km / ± 250 m: - passage to Świnoujście - current = outgoing, 0.7 knot - wind = 10 m/s S and W	Two series of tests for each 'characteristic ship' manoeuvring under two different wind directions S and W.

The minimum number of simulated manoeuvres in a test series was *n* = 12 for one wind direction (Gucma S., Gucma L., Zalewski P., 2008). Manoeuvre simulations were performed by ship pilots from Szczecin Pilot Station, captains experienced in manoeuvring large ships. Each navigator performed two simulated manoeuvres in a given test series.

An analysis of the simulation results using statistical conformity tests has shown that:

1) the biggest widths of safe manoeuvring areas on all the fairway bends are swept by the cruise ship, L_{OA} = 260 m;
2) in all examined bends the widths of safe manoeuvring areas determined by simulation methods are smaller than those determined by the MTEC method.

Example results of simulation studies, i.e safe manoeuvring areas of the cruise ship and bulk carrier defined at a significance level of 0.95 are shown for two bends of the Świnoujście-Szczecin fairway (Navigational analysis ..., 2015; Artyszuk et al., 2015):

- Mańków - Fig. 4;
- Ińskie - Fig. 5.

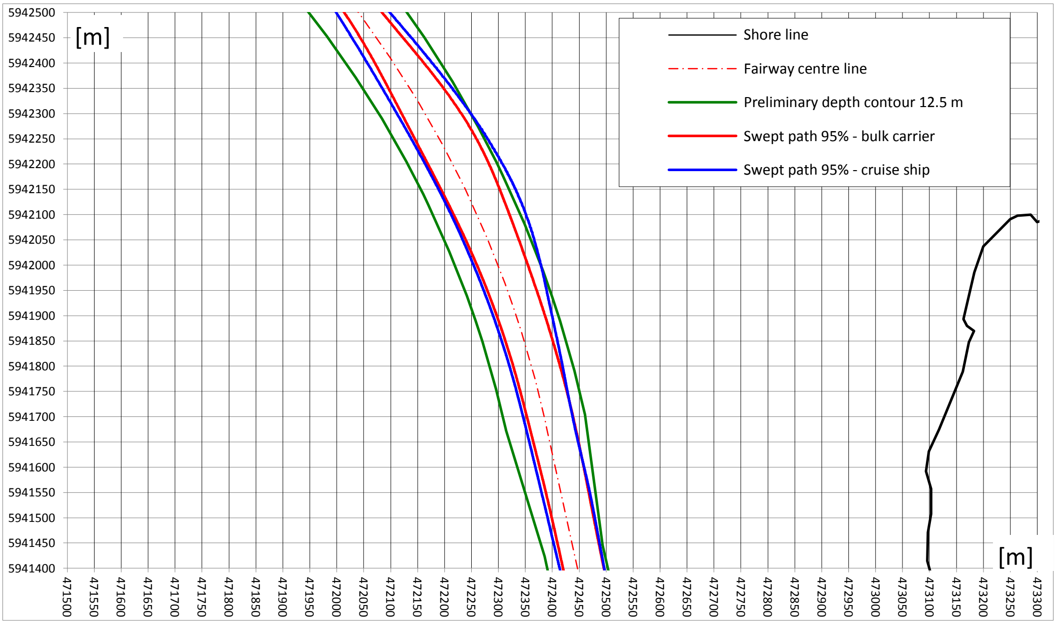

Fig. 4. Safe manoeuvring areas of the cruise ship and bulk carrier on the Mańków Bend (41.0 km ÷ 43.0 km of Świnoujście-Szczecin fairway). Wind speed of 10 m/s

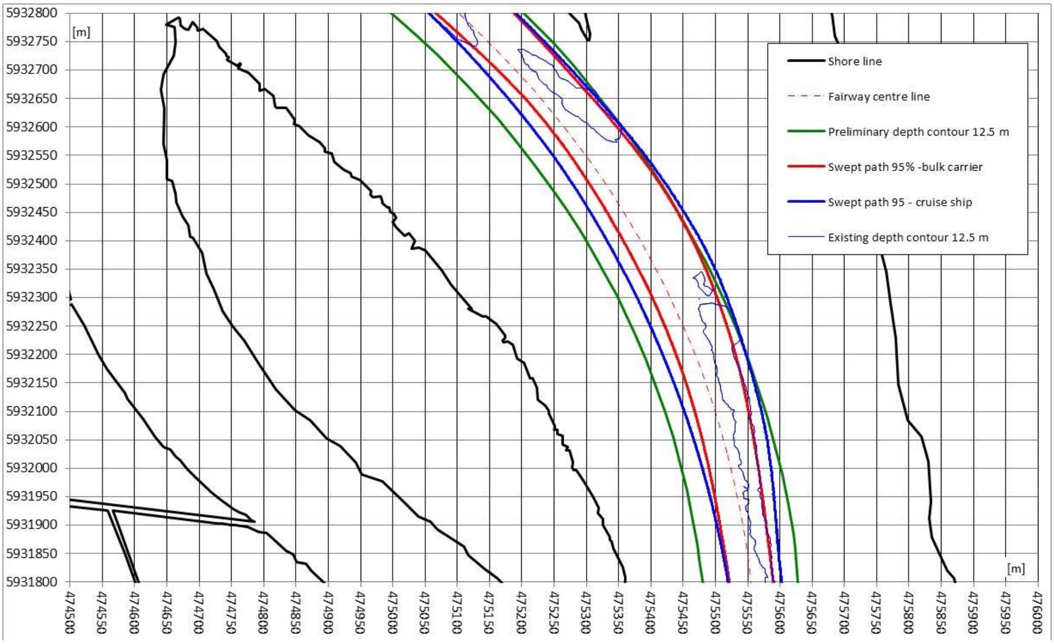

Fig. 5. Safe manoeuvring areas of the cruise ship and bulk carrier on the Ińskie Bend (51.5 km ÷ 53.0 km Świnoujście-Szczecin fairway). Wind speed of 10 m/s

These diagrams show theoretical preliminary depth contours 12.5 m determined at the concept design stage with the MTEC method and safe depth contours 12.5 m determined through simulated passages of the cruise ship and bulk carrier, marked as 95% swept paths. The navigable area meeting the criteria of the minimum construction and operation costs and navigation safety conditions was designed on the basis of safe manoeuvring areas determined through simulations.

The optimal horizontal parameters of Świnoujście-Szczecin fairway bends were determined from results of simulated passages. These parameters were defined on the basis of safe manoeuvring areas of the cruise ship L_{OA} = 260 m, because their widths were greater than the corresponding widths swept by the bulk carrier L_{OA} = 195 m.

Taking into account the manoeuvring differences of the examined ship types (cruise ship, container ship and bulk carrier) and regarding the widths of their safe manoeuvring areas identified by the MTEC and simulation methods, we defined the conditions for safe operation of these vessels on the Świnoujście-Szczecin fairway. Accordingly, the ships' parameters were increased (L_{OA} and B) for the container ship and bulk carrier so as to meet:

$$d_{ij} = d_i$$

$$d_{ij}(l) = d_i(l)$$

These analyses permitted to determine both 'maximum' safe parameters of particular types of ships for the modernized Świnoujście-Szczecin fairway:

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,

and the conditions for their safe operation **M**. For these ships, simulations were also used to determine safe parameters of turning basins on the Świnoujście-Szczecin fairway and lay out optimal location and parameters of passing places.

Based on the results presented in this article, a mathematical model of the fairway was developed

(Navigational analysis ..., 2015), a basis for the technical design of its modernization. The investment project is currently being implemented.

4. Conclusions

The article describes a newly developed methodology for the design and optimization of sea waterway system parameters in case of fairway deepening to a specific depth. The methodology involves determining safe widths of the waterways for 'maximum' ships using different navigation systems under different hydrometeorological conditions. Safe widths of waterways are determined using:

- MTEC method (Marine Traffic Engineering Centre, Maritime University of Szczecin) for rectilinear sections of the waterway;
- computer simulation methods for bends and transition sections of the waterway.

This methodology also takes into account the optimization of the location and width of passing places and turning basin parameters. The criterion used for the optimization of sea waterway system parameters is minimized total cost of rebuilding the waterway and its navigation systems.

This methodology has been applied recently in the design of the reconstructed Świnoujście-Szczecin fairway to be dredged to 12.5 meters along its entire length.

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