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Ship movement simulation studies used to optimize waterway system elements comprising the Przesmyk Orli Turning Basin in the Port of Szczecin

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Abstract

This paper presents a simulation method for identifying optimal parameters for turning basins on waterways. This method has been used for the detailed design of the Przesmyk Orli Turning Basin in the Port of Szczecin. Methods of this type allow the parameters of a turning basin to be optimized so long as the facility is fixed in one location.

Introduction

The Przesmyk Orli Turning Basin is part of the Świnoujście–Szczecin Fairway (63.0 km ÷ 64.0 km). It is located within the Port of Szczecin, in the forks of the Odra River, the *Kanał Grabowski*, and the *Przekop Mieliński*. The largest vessels entering the port of Szczecin are turned at Przesmyk Orli Turning Basin.

Conditions for safe operation of ships on the waterway are described by the vector of conditions of safe operation for a "maximum ship" in *i*-th section of the waterway being considered, a vector which Gucma (Gucma, 2013) and Gucma et al. (Gucma et al., 2015) wrote as follows:

$$\mathbf{W_i} = [t_{yp}, L_c, B, T, H_{st}, V, C, \mathbf{H_i}] \qquad (1)$$

where:

- t_{yp} – type of "maximum ship";
- L_c – overall length of "maximum ship";
- B – breadth of "maximum ship";
- T – draft of "maximum ship";
- H_{st} – air draft of "maximum ship";
- V_i – admissible 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);
- $\mathbf{H_i}$ – vector of hydrometeorological conditions allowable for a "maximum ship" in the *i*-th section of the waterway. In turn, the vector $\mathbf{H_i}$ is defined as follows:

$$\mathbf{H_i} = [d/n, \Delta h_i, V_{wi}, KR_{wi}, V_{pi}, h_{fi}, KR_{fi}] \qquad (2)$$

where:

- d/n – allowable day time (daylight or unrestricted);
- Δh_i – allowable drop of water level;
- V_{wi} – allowable wind speed in *i*-th section;
- KR_{wi} – wind direction restrictions (if any, if any, in *i*-th section);
- V_{pi} – current speed restriction in *i*-th section;
- h_{fi} – permissible wave height at *i-th* section;
- KR_{fi} – restrictions of wave direction (if any).

The vector of conditions of safe operation for a "maximum ship" in the *i*-th section of the waterway unequivocally defines an under keel clearance, Δ, and the width of the safe maneuvering area of a "maximum ship", *d*. Therefore,

$$\Delta_i = f_1(\mathbf{W_i}) \text{ and } d_i = f_2(\mathbf{W_i}) \qquad (3)$$

The conditions for safe operation of ships in the Przesmyk Orli Turning Basin cannot be worse than the conditions of safe operation of ships along the entire Świnoujście–Szczecin fairway (Analiza, 2015). Taking into account possible increase of the length of certain "maximum ships" on the Szczecin–Świnoujście Fairway, we have increased the overall length of a "maximum" container ship and bulk carrier in the Przesmyk Orli Turning Basin. Ultimately, the following **conditions for safe operation of ships** in Przesmyk Orli have been summarized as follows:

1. "Maximum ships" that can safely turn in the turning basin have the following parameters:
   - cruise ship L_{OA} = 260 m; B = 33.0 m; T = 9.0 m;
   - container ship L_{OA} = 250 m; B = 32.3 m; T = 11.0 m ;
   - bulk carrier L_{OA} = 230 m; B = 32.3 m; T = 11.0 m.
2. Required navigational systems include:
   - Pilot Navigation System (PNS);
   - terrestrial navigation system.

   A visibility of 2 Nm should be considered as the minimum visibility for which **terrestrial navigation system is available** in certain sections of the Świnoujście–Szczecin Fairway. The terrestrial navigation system is one of two primary navigation systems that meet the conditions of safe navigation.
3. Minimum tug assistance:
   - 3 tugs with combined bollard pull Σ 130 tons;
   - tugs must have azimuth or cycloidal propellers.
4. Allowable hydrometeorological conditions:
   - time of day: no restrictions;
   - visibility over 2 Nm;
   - wind speed, V_w, ≤ 10 m/s;
   - wind direction unrestricted;
   - current speed, V_c, ≤ 1 knot;
   - current direction = outgoing (river);
   - wave height, h_{wa}, = 0.0 m;
   - ice conditions = brash ice;
   - margin for low water level, Δh, ≤ 0.5 m.

Simulation methods for optimizing turning basins

The existing methods of optimizing turning basins all entail simulations that focus on specific elements of waterways or their specific system. These methods entail optimization procedures that place one to four constraints on manoeuvring safety (Gucma et al., 2015).

One method is a detailed simulation method of optimizing parameters of the turning basin in which the objective function is written in the form:

$$Z = (a \cdot w + b \cdot t) \rightarrow \min \qquad (4)$$

with the constraints set out by the basic condition of navigation safety:

$$\left.\begin{array}{l} d_{ijk}(1-\alpha) \subset \mathbf{D} \\ \underset{p(x,y)\in\mathbf{D}}{\wedge} \Delta_{ijkxy} \geq h_{xy} - T_i \end{array}\right\} \qquad (5)\ (6)$$

where: $(x, y) \in \mathbf{X1} \times \mathbf{Y1}$ – A subset of water areas.

In practice, the constraints are written as:

$$R^s_{\alpha ijk} \leq R^s_{\alpha} \qquad (7)$$

$$R^h_{\alpha ijk} \leq R^h_{\alpha} \qquad (8)$$

on the bearing intervals α = 1°, ..., 360°,

where:

- R^s_{α} – minimum radius-vector of turning basin for safe depth at the bottom (h_s) for ships;
- R^h_{α} – minimum radius-vector of turning basin for safe depth at the bottom (h_s) for tugs;
- $R^s_{\alpha ijk}$ – radius-vector of safe manoeuvring area in the turning basin for i-th type of vessel, j-th type of manoeuvre, with k-th variation of navigation conditions at 95% level of confidence;
- $R^h_{\alpha ijk}$ – radius-vector of safe manoeuvring area in the turning basin for tugs assisting i-th type of vessel, j-th type of manoeuvre, k-th variant of navigation conditions at 95% level of confidence.

The values $R^s_{\alpha ijk}$ and $R^h_{\alpha ijk}$ were determined from simulation tests of real-time models, carried out for the maximum operating vessel types, at different speeds and directions of current and wind. The tests consisted of a series of passages (simulated manoeuvres) of reliable number, under varied navigation conditions.

This method has been repeatedly used in the design of various turning basins with a well-defined area location $(x, y) \in \mathbf{X1} \times \mathbf{Y1}$ (Gucma, Gucma & Zalewski, 2008).

The area under examination is defined by a set $x \in \mathbf{X}$, $y \in \mathbf{Y}$, which has the following subsets: water areas $\mathbf{X1} \subset \mathbf{X}$. $\mathbf{Y1} \subset \mathbf{Y}$; shoreline $\mathbf{X2} \subset \mathbf{X}$. $\mathbf{Y2} \subset \mathbf{Y}$. The coordinates describing these subsets are Cartesian products: $\mathbf{X1} \times \mathbf{Y1}$; $\mathbf{X2} \times \mathbf{Y2}$.

In the case of modernizing the Przesmyk Orli Turning Basin, two problems arose:

- selection of the best location for a turning basin in the Świnoujście–Szczecin Fairway;

- determination of the optimal horizontal parameters of the turning basin in its best location.

To solve these problems, a simulation method of optimizing turning basins in waterways was used. The procedure can be described as follows:

1. Determine at least two viable preliminary candidates for the location of the turning basin.
2. For each candidate, make at least two assumptions concerning manoeuvring tactics.
3. Determine at least two combinations of the least favourable hydrometeorological conditions: two different wind directions at allowable speeds in conjunction with allowable speeds for currents.
4. Specify initial horizontal parameters for two turning basin candidates by the MTEC deterministic-probabilistic method (Gucma, Gucma & Zalewski, 2008). The safe manoeuvring areas identified by the MTEC method in simulation tests are used as the basis.
5. Carry out simulation tests in six series of turning manoeuvres of the "maximum ship" for each of the candidate locations for the turning basin. For each candidate, employ two assumed maneuvering tactics, each of which uses two sets of the least favourable hydrometeorological conditions.
6. Analyse the simulation test results, identifying the best location and optimal parameters of the turning basin.

Optimizing Przesmyk Orli Turning Basin by simulation tests

Simulation tests were conducted on the Polaris multi-bridge manoeuvring and handling ship simulator. This is a Full Mission Bridge Simulator (FMBS), located at the Marine Traffic Engineering Centre, at the Maritime University of Szczecin. The elements of the procedures implemented were typical of simulation studies carried out in the design of marine waterways:

- formulation of the research problem, including identification of the design objective, simulation methods to be used, and the type of simulators to be used;
- building models of ship movement on the chosen simulator and verifying intended movements;
- designing an experimental system and conducing an experiment;
- processing and statistical analysis of test results.

From the set of "maximum ships", two "characteristic ships" were selected for simulation tests on the Przesmyk Orli Turning Basin:

- cruise ship, with L_{OA} = 260 m; B = 33.0 m; T = 9.0 m;
- container ship, with L_{OA} = 250 m; B = 32.3 m and T = 11.0 m.

Mathematical (simulation) models of "characteristic of ships" and tugs employed for the manoeuvres were built and verified. The two tugs, with azimuth propellers, had bollard pulls of 45 tons and 55 tons, respectively. A three-dimensional geometric model of the examined water area was built on the Polaris simulator.

Simulation tests consisted of the characteristic ship's entry into Przesmyk Orli from the Świnoujście–Szczecin Fairway, turning around the port side, and sternway movement towards *Kanał Grabowski*. The manoeuvre was assisted by two tugs with 45 ton bollard pull – fore and aft towing lines were used.

The simulation experiment system was designed as follows:

Variant I. Przesmyk Orli Turning Basin in the existing location (63.0 km ÷ 63.6 km) without compromising the shoreline of Ostrow Grabowski Island. The turning manoeuvre was carried out in the northern and central parts of the turning basin:
- Series 1, wind W 10 m/s;
- Series 2, wind S 10 m/s.

Variant II. Przesmyk Orli Turning Basin in the existing location (63.0 km ÷ 63.6 km) without compromising the shoreline of Ostrow Grabowski. The turning manoeuvre was carried out in the central and southern parts of the turning basin:
- Series 3, wind W 10 m/s;
- Series 4, wind S 10 m/s.

Variant III. Przesmyk Orli Turning Basin shifted south (63.3 km ÷ 64.0 km), the shoreline of Ostrow Grabowski moved about 150 m. The manoeuvre carried out in the southern part of the turning basin:
- Series 5, wind W 10 m/s;
- Series 6, wind S 10 m/s.

Variant IV. Przesmyk Orli Turning Basin shifted south (63.3 km ÷ 64.0 km), the shoreline of Ostrow Grabowski moved about 120 m. The manoeuvre carried out in the central and southern parts of the turning basin:
- Series 7, wind W 10 m/s;
- Series 8, wind S 10 m/s.

The series comprised n = 12 tests, each of which was carried out in the least favourable hydrometeorological condition:
- wind speed of 10 m/s;
- outgoing current of 0.7 knots.

Simulated manoeuvres were performed by pilots from the Szczecin Pilot Station. Each navigator performed two simulated manoeuvres in one series.

The results of each series of simulation tests were statistically analysed using the polar method of manoeuvring area determination (Gucma, Gucma & Zalewski, 2008). By using this method, the authors identified three manoeuvring areas (swept paths) of "characteristic ships", operated under various conditions: maximum, average and at the 95% confidence level. Safe manoeuvring areas for each kind of test are shown in Figures 1, 2, 3 and 4 (Analiza, 2015; Określenie, 2015).

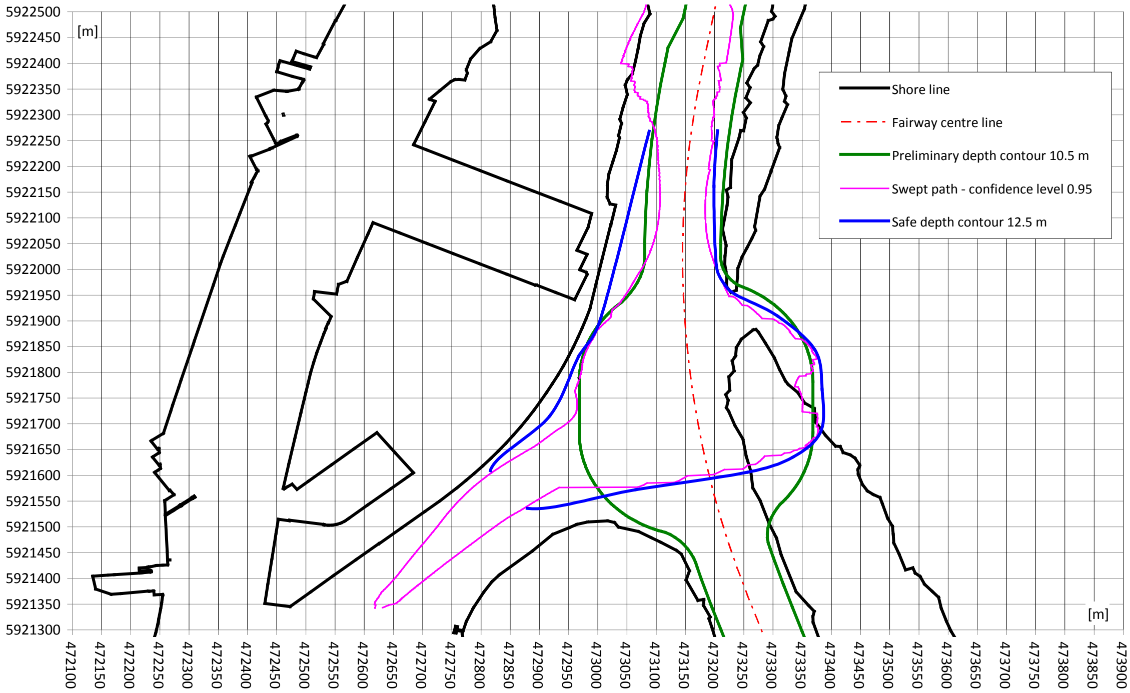

Figure 1. Variant I. Locations and manoeuvring tactics in Przesmyk Orli Turning Basin. Safe manoeuvring area of the cruise ship with L_{OA} = 260 m and navigable area (safe depth contour of 12.5 m)

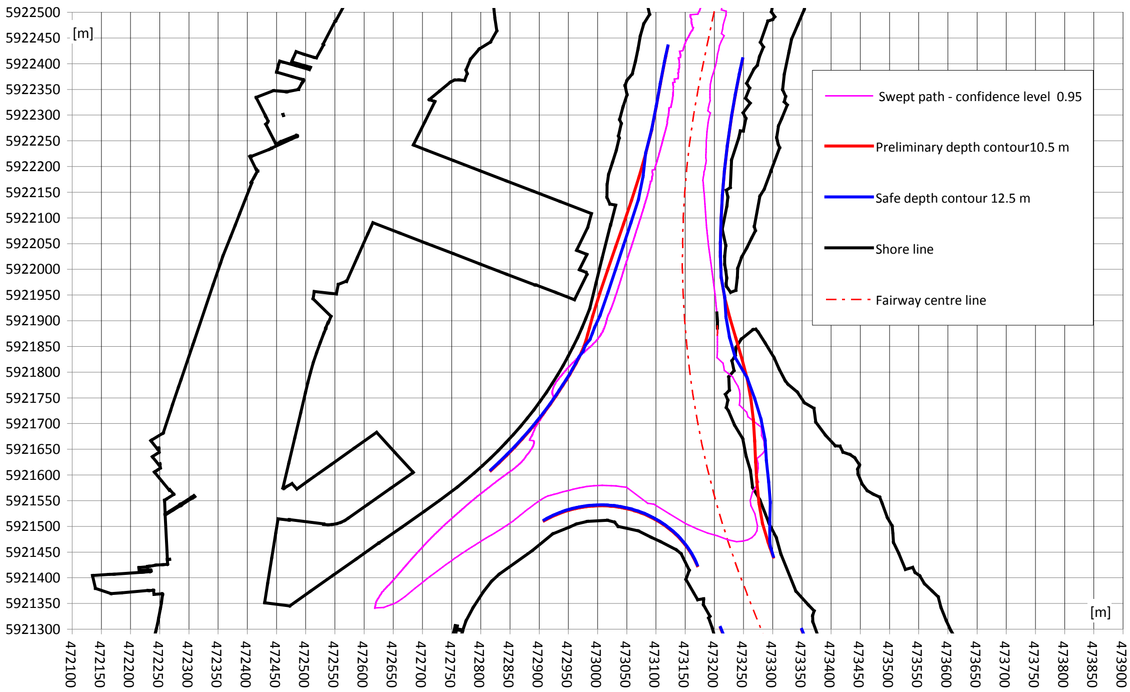

Figure 2. Variant II. Locations and manoeuvring tactics in Przesmyk Orli Turning Basin. Safe manoeuvring area of the cruise ship L_{OA} = 260 m and navigable area (safe depth contour 12.5 m)

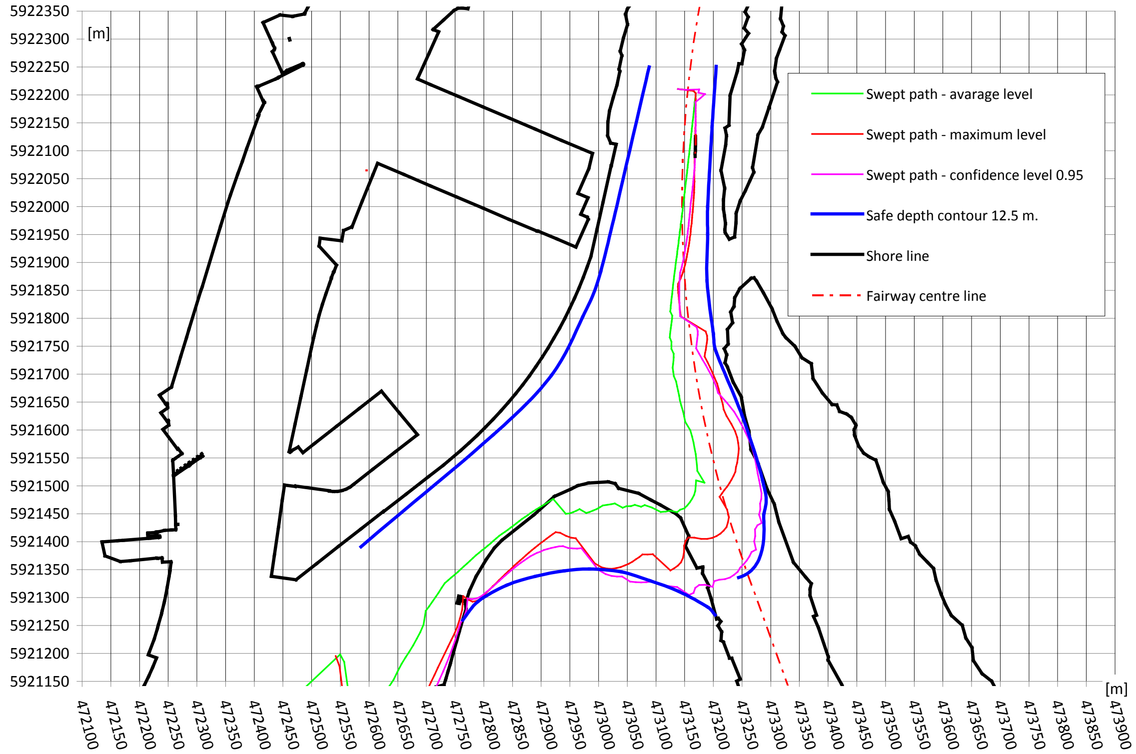

Figure 3. Variant III. Locations and manoeuvring tactics in Przesmyk Orli Turning Basin. Safe manoeuvring area of the container ship L_{OA} = 250 m and navigable area (safe depth contour 12.5 m)

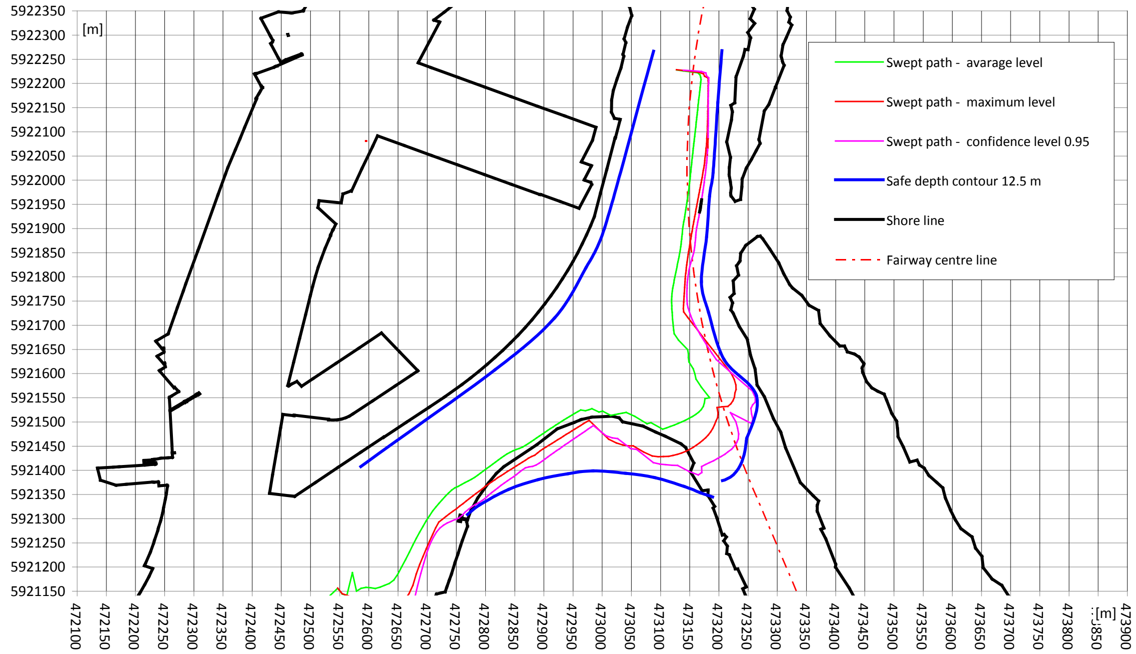

Figure 4. Variant IV. Locations and manoeuvring tactics in Przesmyk Orli Turning Basin. Safe manoeuvring area of the container ship L_{OA} = 250 m and navigable area (safe depth contour 12.5 m)

Analysis of the results of simulation studies

An analysis of results of the simulation including different variants (stages) is outlined below.

1. Comparing variant II (southern) and variant I (northern), while maintaining the same level of safety (confidence level 0.95), we found that:
   - variant II is less expensive to implement than variant I because:

  - a smaller area of the basin must be deepened to 12.5 m;
  - a smaller land area must be transformed into a water area, consequently elimination a measure of dredging;
- variant II is more environmentally friendly:
  - less impact to land areas;
  - does not encroach on areas covered by the Natura 2000 Program.

At the same time it was found that:
- neither of the two variants is a long-term solution because neither take accounts for possible increases of cruise ship and container ship parameters after tests in real conditions;
- both variants obstruct, to a greater or lesser extent, the existing connection between Lake Dąbie and the Szczecin–Świnoujście Fairway. This problem entails expensive engineering solutions to secure the connecting canal.

2. Comparing variant III (southern) and variant IV (northern), while maintaining the same level of safety (confidence level 0.95), we found that:
   - variant IV is cheaper to implement than variant III because:
     - a smaller area of the basin requires must be deepened to 12.5 m;
     - smaller land areas must be transformed into water areas, reducing the amount of dredging required;
   - variant IV is more environmentally friendly:
     - less impact on land areas.

   At the same time it was found that:
   - both variants are long-term solutions that account for the possibility of increasing the parameters of "maximum ships" after tests in real conditions.
3. Comparing all the test variants, it was found that:
   - the best solution is to move the Przesmyk Orli Turning Basin south (63.3 km 64.0 km ÷ fairway):
     - variants III and IV.
   - Przesmyk Orli Turning Basin presented in variant IV is the optimal solution.

Conclusions

The presented simulation method of optimizing waterway system elements allows marine traffic engineers:
- to select the best location for a turning basin;
- to determine the optimal horizontal parameters of the selected turning basin.

This process makes use of a four stage method primarily based on simulations examining specific variants of turning basin location and manoeuvring tactics, with the assumed conditions of safe operation of a "maximum ship". The design of each subsequent simulation experiment (variant) involves an analysis of the previous experiment.

This method was successfully used for the detailed design of the Przesmyk Orli Turning Basin located on the Świnoujście–Szczecin Fairway, within the perimeter of the Port of Szczecin.

So far, methods of this type have been used only to determine optimal parameters of a turning basin, with no consideration of a change in location.

It should be noted that the method requires from that the researcher deep have a deep theoretical and practical knowledge of the principles of model tests in marine traffic engineering if confidence is to be placed in the results obtained.

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