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Algorithms for analytical method of waterway design parameters determination

Algorytmizacja metody analitycznej określenia parametrów toru wodnego

Paweł Zalewski

Maritime University of Szczecin, Faculty of Navigation, Centre of Marine Traffic Engineering
Akademia Morska w Szczecinie, Wydział Nawigacyjny, Centrum Inżynierii Ruchu Morskiego
70-500 Szczecin, ul. Wały Chrobrego 1–2, e-mail: p.zalewski@am.szczecin.pl

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Abstract
The paper presents an algorithm of recommended waterway parameters determination based on relationships derived from actual empirical research (a combination of PIANC and Canadian methods). These relationships are mostly discontinuous functions (e.g.: of ship type variable, speed, method of determining the position, etc.), which can be approximated by continuous spline functions. Application built in the C# allows determining the recommended minimum width of the waterway, width increase due to the accuracy of the vessel positioning method, and the radius of waterway bends for the five input variables of the ship and from ten to sixteen input variables of the area.

Słowa kluczowe: parametry toru wodnego, zarządzanie bezpieczeństwem

Abstrakt
W artykule przedstawiono algorytm wyznaczenia zalecanych parametrów toru wodnego oparty o pozyskane z badań rzeczywistych zależności empiryczne (kombinacja metody PIANC i kanadyjskiej). Zależności te są przeważnie funkcjami nieciągłymi (np. zmiennej typu statku, prędkości, metody określenia pozycji itd.), które można aproksymować ciągłymi funkcjami sklejanymi. Zbudowana aplikacja w środowisku C# umożliwia wyznaczenie zalecanej minimalnej szerokości toru, powiększenia szerokości ze względu na dokładność określenia pozycji statku oraz promienia łuku zakola dla pięciu zmiennych wejściowych statku i od dziesięciu do szesnastu zmiennych wejściowych akwenu.

Introduction

Analytically, the minimum width of a waterway, comprised to straight sections and bends of specified safe depth, depends on the size and manoeuvrability of the vessel navigating the fairway, type of fairway, bank, effects of other vessels in the fairway, and effects of wind and currents [1]. Therefore, channel width design must account for the following factors: vessel's speed, cross winds, cross current, longitudinal current, significant wave height and length, aids to navigation, bottom surface, depth of waterway, cargo hazard level, traffic density, and shape of waterway as presented in the figure 1.

The width required consists of three distinct zones [2]: manoeuvring lane, ship's clearance lane, and bank clearance which can be grouped into manoeuvring component and navigation component (see [3]). The algorithm presented in the following chapters leads to probabilistic measure of a required waterway width.

1. Analytical method of waterway width determination

In the developed method, the manoeuvring component of a waterway width (ship's lane width) (d_m) is deterministically defined (derived from empirical research), and the navigational component is

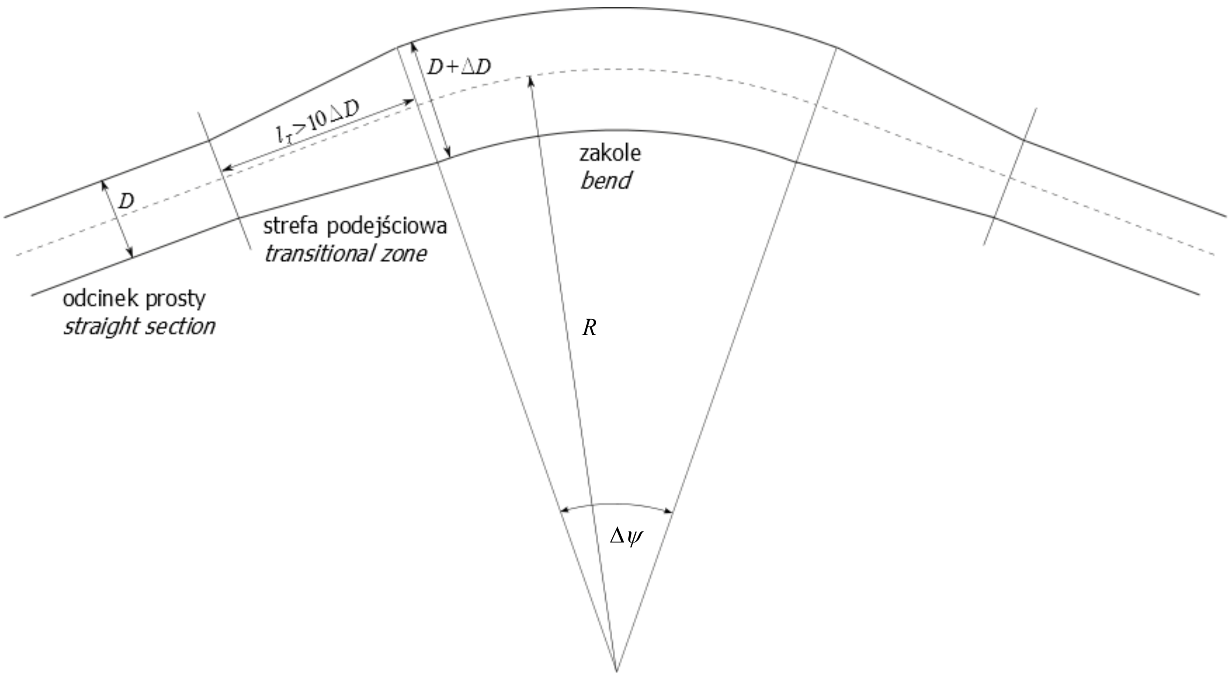

Fig. 1. Change of waterway width from straight section to bend [4]
Rys. 1. Zmiana szerokości drogi wodnej od odcinka prostego do zakola [4]

of probabilistic nature and it is defined at the specified confidence level as $d_n(1-\alpha)$.

The algorithm for determination of manoeuvring component of a waterway width has been based on PIANC method [5] modified by CMA method [2] for bends and expert method for manoeuvring with tugs.

For a vessel manoeuvring without tugs, the relations for the following parameters have been adopted directly from PIANC:

- basic manoeuvring lane width d_{mp};
- additional widths for bank clearance d_{rr} and d_{rg};
- additional widths: d_2, d_3, d_4, d_5, d_8.

And the relations for the following parameters have been adopted directly from CMA:

- additional manoeuvring width at bend ΔD;
- transitional zone length l_T;
- radius of waterway bend R.

For a ship sailing up to 12 knots, the manoeuvring component takes form:

$$d_m = \begin{cases} d_{mp} + d_2 + d_3 + d_4 + d_5 + d_8 + d_{rr} + d_{rg} \\ \qquad\qquad \text{if } i_{dt} \in \{1, 3, 5\} \\ d_{mp} + d_2 + d_3 + d_4 + d_5 + d_8 + d_{rr} + d_{rg} + \Delta D \\ \qquad\qquad \text{if } i_{dt} \in \{2, 4, 6\} \end{cases} \tag{1}$$

where:

d_{mp} – basic manoeuvring lane width [m];
d_2 – additional width for prevailing cross wind [m];
d_3 – additional width for prevailing cross current [m];
d_4 – additional width for prevailing longitudinal current [m];
d_5 – additional width for significant wave height [m];
d_8 – additional width for depth of waterway [m];
d_{rr}, d_{rg} – additional widths for bank clearance to port and starboard side [m];
ΔD – additional manoeuvring width at bend [m];
i_{dt} – index of waterway type (odd numbers for straight sections, even numbers for bends).

For a vessel manoeuvring with tugs, the formula for basic manoeuvring lane width [5] is modified as follows:

$$d_{mp} = k \cdot B$$
$$\text{where } k = \begin{cases} 1.3, \text{ if good and moderate manoeuvrability} \\ 1.5, \text{ if poor manoeuvrability} \end{cases} \tag{2}$$

and $d_8 = 0$.

The algorithm for determination of navigational component of a waterway width has been based on RMS (root mean square) relations presented by Gucma in [6]. At straight section of a waterway the navigational component is equal to a directional error of shipboard farthest position at specified confidence level. This error is perpendicular to a fairway axis and given by the formula (3):

$$d_n(1-\alpha) = p_{yB}(1-\alpha) = \\ = \pm\sqrt{p_y(1-\alpha)^2 + \left(\frac{m_{KR}(1-\alpha)\cdot L_D}{57.3^{\circ}}\right)^2} \qquad (3)$$

where:

- $d_n(1-\alpha)$ – directional error of shipboard position at confidence level of $(1-\alpha)$ [m];
- $p_y(1-\alpha)$ – directional error of ship's position (observer's position) at confidence level of $(1-\alpha)$ [m] dependable on w_t;
- $m_{KR}(1-\alpha)$ – ship's heading estimation error at confidence level $(1-\alpha)$ [°] dependable on i_{dt};
- L_D – distance from ship's bridge to bow [m], for most ships approximated to $0.75\times LOA$.

Directional errors in the formula (3) have been defined:

– for eight main positioning methods in restricted water areas: PNS (Pilot Navigation System based on DGPS), leading lights (Fig. 2), mid-channel marks as leading marks (Fig. 3), mid-channel marks as distance marks, lateral marks as leading marks (Fig. 3), lateral or mixed marks

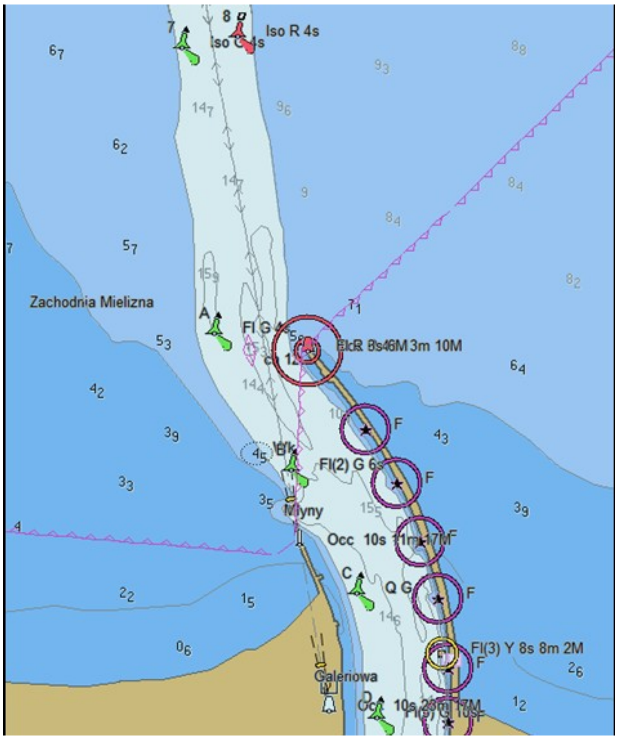

Fig. 2. Example of Leading (or Range) Lights Galeriowa–Mlyny in Świnoujście (firm line is a fairway axis) [7]
Rys. 2. Przykład głównych (lub tylnych) świateł Galeriowa–Młyny w Świnoujściu (stałą linią jest oś toru wodnego) [7]

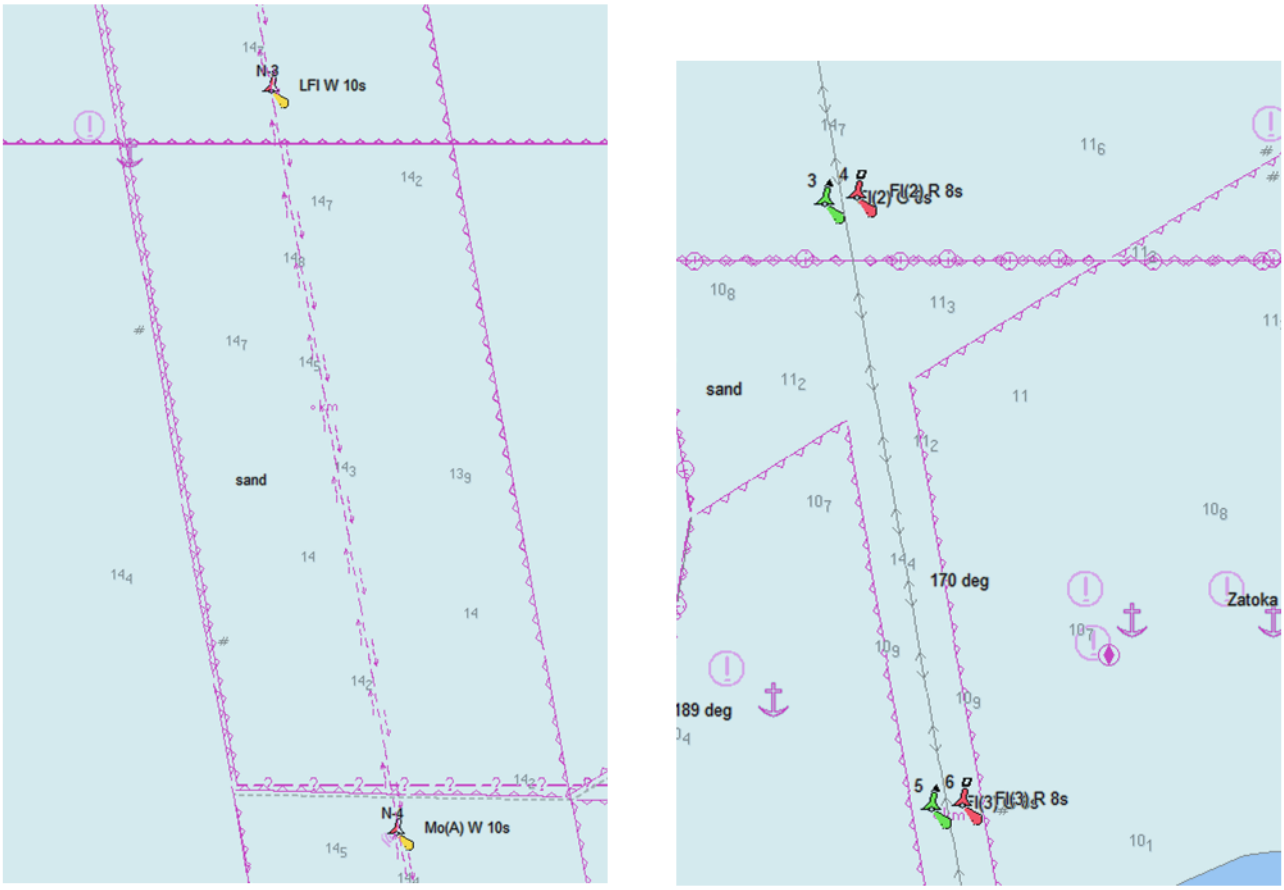

Fig. 3. Example of Midchannel (Fairway) Buoys or Beacons (left) and Lateral Buoys (right) [7]
Rys. 3. Przykład boi lub znaków nawigacyjnych (po lewej) i boi bocznych (po prawej) środkowego kanału (toru wodnego) [7]

as distance marks, mixed marks (sight leading marks – Fig. 4), bridge leading marks (pair of buoys or beacons);

– two sub-methods: buoys or beacons (except where PNS or leading lights are used);
– four types of visibility (> 2 Nm at day, at night, at night with no navigation or cultural lights, restricted visibility < 2 Nm).

All directional errors of methods using navigation marks or bank lines / structures have been further divided into terrestrical (optical), and radar (see Fig. 2).

Sight Leading Marks consist of three navigation marks located at triangle apexes – the ship's position relative to a fairway axis is determined by position of rear mark relative to front marks. Such marks are usually met at places where buoyage system changes from lateral to midchannel (central) or vice-versa (Fig. 4).

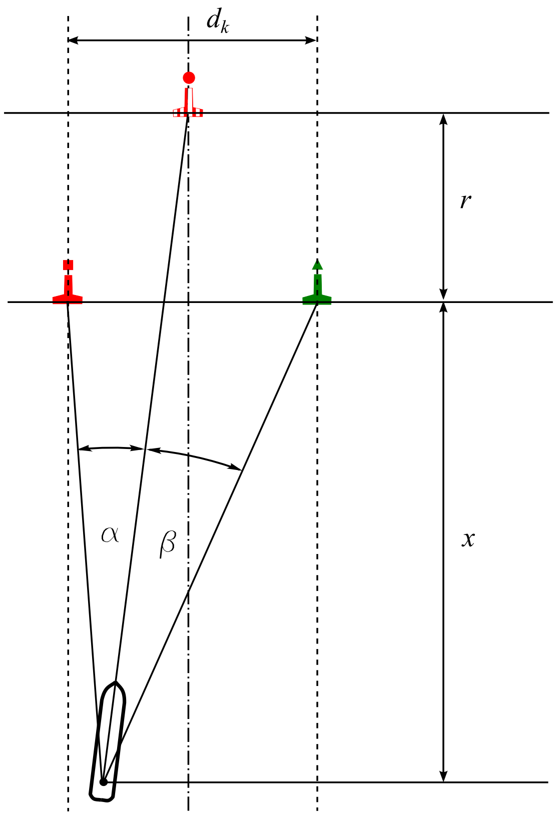

Fig. 4. Usage of buoys and beacons as Sight Leading Marks (Mixed Marks) [6]
Rys. 4. Użycie boi i znaków nawigacyjnych jako Głównych Znaków Obserwacyjnych (znaki mieszane) [6]

Taking into account that port and starboard navigational components are usually equal (similar assumption can be made for additional widths for bank clearance):

$$d_n(1-\alpha)=d_{nr}(1-\alpha)=d_{ng}(1-\alpha) \tag{4}$$

the width of the manoeuvring area (ship's manoeuvring lane width) at confidence level of $(1-\alpha)$ is yielding form:

$$D \geq d(1-\alpha)=d_m+2d_n(1-\alpha) \tag{5}$$

where:

$d(1-\alpha)$ – the width of the manoeuvring area (ship's path) at confidence level of $(1-\alpha)$ [m];

D – the recommended width of the manoeuvring area.

The used formulas are mostly discontinuous functions (e.g.: of ship's type variable, waterway's type variable, speed, method of determining the position, etc.). The example can be navigational component of ship's lane width determined for method of distance measurement to midchannel beacons [6]:

$$d_n(0.95)=\sqrt{p_y(0.95)^2+\left(\frac{1.5\,LOA}{57.3}\right)^2} \tag{6}$$

where:

$$p_y(0.95)=\begin{cases}5, & \text{if } x=100\text{m}\\ 6, & \text{if } x=200\text{m}\\ 10, & \text{if } x=500\text{m}\\ 20, & \text{if } x=1000\text{m}\\ 30, & \text{if } x=1\text{Nm}\end{cases} \quad [\text{m}] \tag{7}$$

x – distance to the beacon.

Such discontinuous functions as (7) have been approximated by continuous spline functions in the algorithm. In general, the i^{th} spline function for a cubic spline can be written as:

$$s_i(x)=a_i+b_i(x-x_i)+c_i(x-x_i)^2+d_i(x-x_i)^3 \tag{8}$$

For n data points, there are $n-1$ intervals and thus $4(n-1)$ unknowns to evaluate to solve all the spline function coefficients a_i, b_i, c_i, d_i. One condition requires that the spline function goes through the first and last point of the interval, yielding $2(n-1)$ equations of the form:

$$\begin{aligned} & s_i(x_i)=f_i \Rightarrow a_i=f_i \\ & s_i(x_{i+1})=f_i \Rightarrow s_i(x_{i+1})= \\ & =a_i+b_i(x_{i+1}-x_i)+c_i(x_{i+1}-x_i)^2+d_i(x_{i+1}-x_i)^3= \\ & =f_i \end{aligned} \tag{9}$$

Another condition requires that the first derivative is continuous at each interior point, yielding $n-2$ equations of the form:

$$s_i'(x_{i+1}) = s_{i+1}'(x_{i+1}) \Rightarrow$$
$$b_i + 2c_i(x_{i+1} - x_i) + 3d_i(x_{i+1} - x_i)^2 = b_{i+1} \quad (10)$$

A third condition requires that the second derivative is continuous at each interior point, yielding $n-2$ equations of the form:

$$s_i''(x_{i+1}) = s_{i+1}''(x_{i+1}) \Rightarrow 2c_i + 6d_i(x_{i+1} - x_i) = 2c_{i+1} \quad (11)$$

These give $4n-6$ total equations. Two additional equations are derived assuming clamped end conditions – the first derivatives at the first and last knots are known or in other words the slope of the function at the first and last knots is set according to expertly presumed extrapolation.

2. Algorithm

The general algorithm for analytical method of waterway design parameters determination is presented at block diagram in the figure 5.

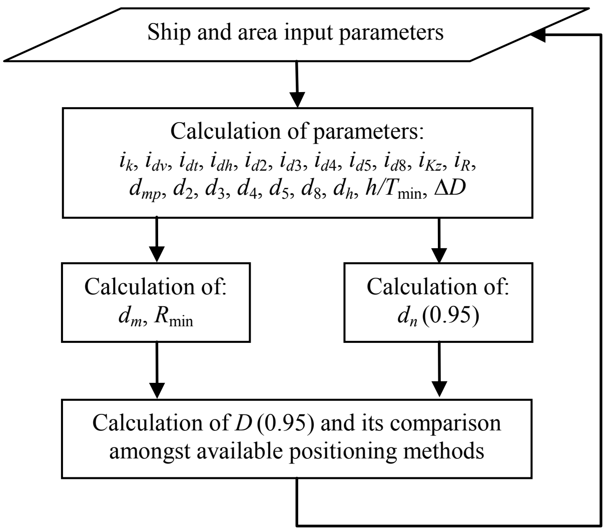

Fig. 5. Block diagram of analytical method of waterway design parameters determination
Rys. 5. Schemat blokowy metody analitycznej określania parametrów projektowania toru wodnego

Calculation of waterway width's manoeuvring component (d_m, R_m) and navigation component (d_n) is done independently of each other, but based on the common deterministic parameters defined in arrays accessible by indexes, index of parameters' array depending on:

i_k – ship's type;
i_{dv} – ship's speed;
i_{dt} – waterway's type;
i_{dh} – tugs availability;
i_{d2} – prevailing cross wind;
i_{d3} – prevailing cross current;
i_{d4} – prevailing longitudinal current;
i_{d5} – significant wave height;
i_{d8} – depth of a waterway;
i_{dK} – course change at bend;
$i_{R/L}$ – bend radius to ship's LOA ratio.

The discontinuity of the indexed parameters is solved by usage of spline functions as presented in chapter 1 (one example of cubic spline approximation of discontinuous function of bend radius is shown in the figure 6).

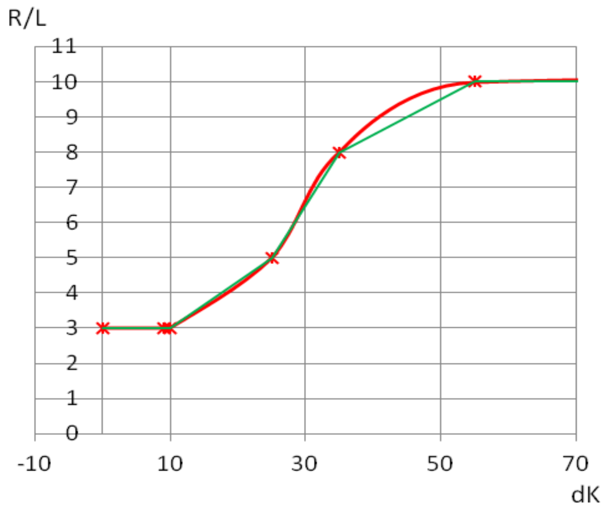

Fig. 6. Line and cubic spline approximation of discontinuous function of bend radius
Rys. 6. Zbliżenie liniowe i sześcienne pasa funkcji nieciągłej promienia wygięcia

In the algorithm, the following steps must be performed consecutively:

- uploading up-to-date database of waterway parameters;
- choice of area type, ship's type, hydrometeorological conditions, tugs' assistance (defined by several parameters);
- calculation of deterministic waterway parameters – manoeuvring width component, bend radius;
- calculation of navigation width component depending on waterway type, aids to navigation, visibility;
- eventual risk analysis based on confidence level set in p. 4 – calculation of grounding probability and its consequences.

The test interface of the algorithm implemented in Visual C# programming environment is presented in the figure 7.

The preliminary graphical interface is optimized according to criterion of inputs data number – therefore, more user / operator friendly (Fig. 8). It enables:

– choice from predefined parameters;
– graphical choice from predefined waterway's segments and their parameters readout.

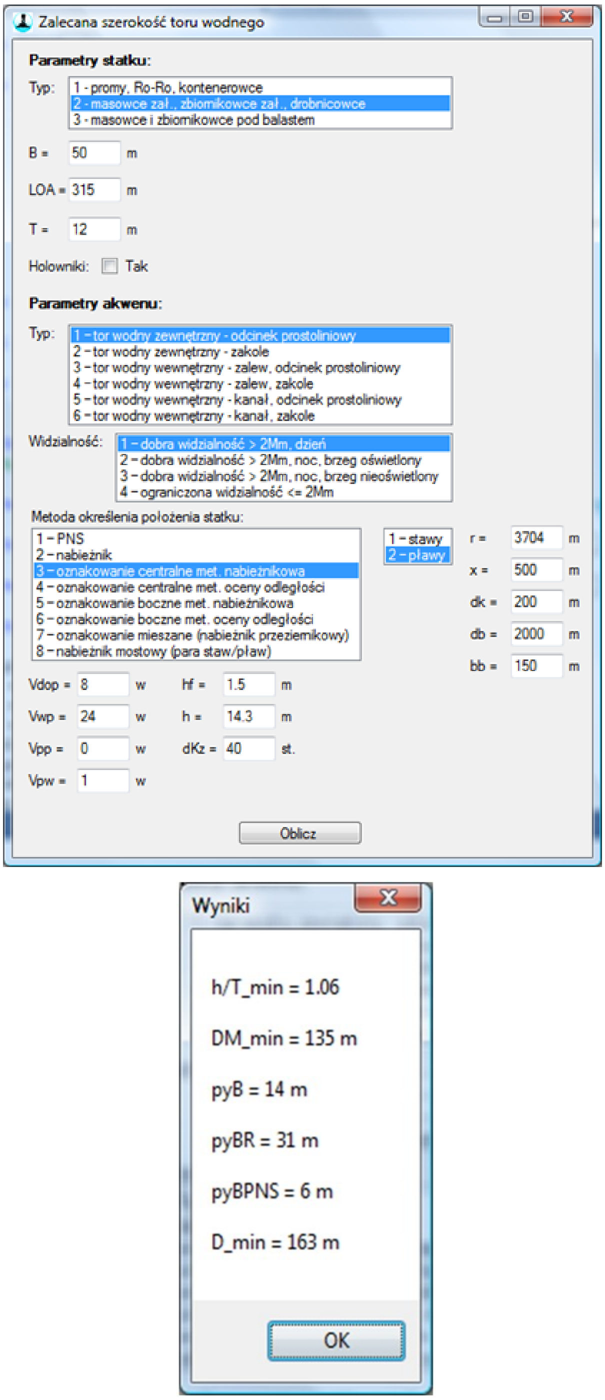

Fig. 7. Input test interface
Rys. 7. Interfejs wprowadzania danych testowych

Conclusions

In the developed algorithm for analytical method of waterway design parameters determination, the two components have been formulated:

– the manoeuvring component of a waterway width by deterministic formulas;
– the navigational component of a waterway width, probabilistically at the specified confidence level.

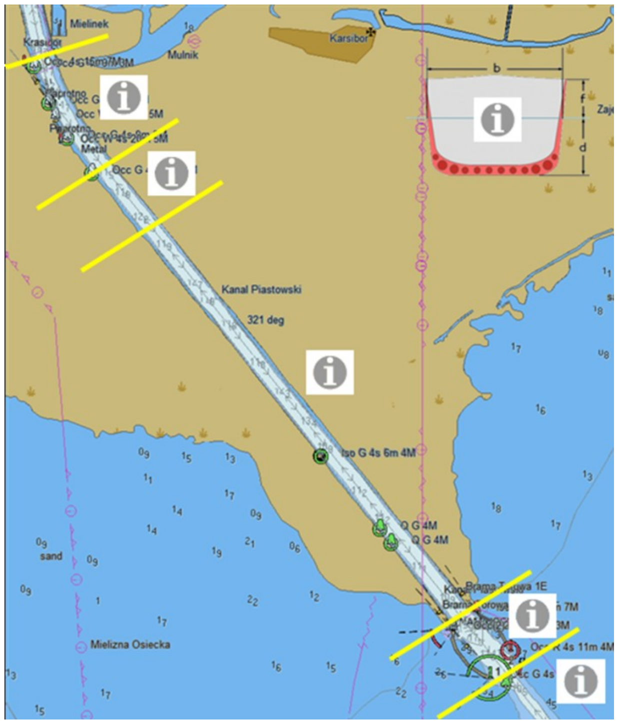

Fig. 8. Preliminary graphical operator's interface
Rys. 8. Wstępny graficzny interfejs operatora

This algorithm has been implemented in the C# allowing operator determining the recommended total minimum width of the waterway, width increase due to the accuracy of the vessel positioning method – so the total width at specified confidence level, and the radius of waterway bends. The discontinuity of the empirical and approximate functions used has been solved by means of cubic spline functions.

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