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Hydrodynamic influences induced by ships passing the navigable canals - the new navigation safety criteria

SUMMARY

Paper presents problems of defining ship--induced loads on navigable canals. New safety criteria are proposed for navigation in restricted waters, based on ship-induced reverse current speed and wave height. The new approach is illustrated by example calculations for a modernized part of Szczecin – – Świnoujście waterway. The paper presents also more commonly used criterion-speed of propeller stream at the bottom.

INTRODUCTION

Optimization of designed waterway parameters by means of simulation methods demands considering a set of constraints, called navigation safety criteria, which control realization of optimizing function. At present the most commonly used criteria are the following :

- ⇨ horizontal width of manoeuvring lane (path swept by the vessel)
- ⇨ dimensions of manoeuvring area (e.g. turning place diameter)
- ⇨ kinetic energy of ship impact on the quay
- ⇨ duration time of a given manoeuvre
- ⇨ propeller stream impact on the manoeuvring area bottom.

The new navigation safety criteria are proposed to be applied because of the complexity of the investigated problem. The loads induced by ships during their passage through the canal, destructive for the canal banks, embankments and the bottom, should be properly taken into account.The effects of the interaction between the ship and fairway are mainly due to propeller - induced hydrodynamic pressure and water stream. The main hydrodynamic effects are the primary and secondary wave systems and return current (backflow). Values of the effects are of primary significance for lowering the damage risk to canal construction as well as lowering the cost of waterway maintenance or modernization. The possibility of ship grounding due to degradation of waterway infrastructure should also be considered. As it results from engineering practice, neglecting the propeller stream action onto hydro-technical structures could cause serious ship traffic accidents connected even with human casualties.

The paper presents an attempt to describe three navigation safety criteria for ships manoeuvring in navigable canals :

- propeller stream on the bottom
- speed of reverse current on the bottom and embankments
- height of waves on the canal banks.

RESEARCH ASSUMPTIONS

The presented research was carried out for the reason of modernization works to be conducted on Szczecin–Świnoujście waterway. It is intended to bring into service on the waterway much bigger ships (L=250 m, B=38.5 m, d=10.5 m) than those permitted to navigate on it till now (L=210 m, B=31 m, d=9.15 m). The modernized area extends between Mielin and Paprotno bends (Fig.1).

The computer simulation model of manoeuvring the ships in that area was elaborated by the research group on marine traffic engineering, Maritime University of Szczecin.

This was the real-time ship motion simulation model applied to the investigated ships, in which the real navigators (captains and pilots) were employed in the research as no reliable mathematical model of human navigator's behaviour was available at that moment.

Series of simulation trials were executed in the number satisfying the assumed confidence level, and data recorded during the trials were processed with taking into account the below described mathematical models of the involved phenomena.

The analysis of ship-induced loads was performed with the consideration of :

- reverse current speed on the canal bottom and embankments
- height of waves on canal banks
- propeller stream speed on the canal bottom.

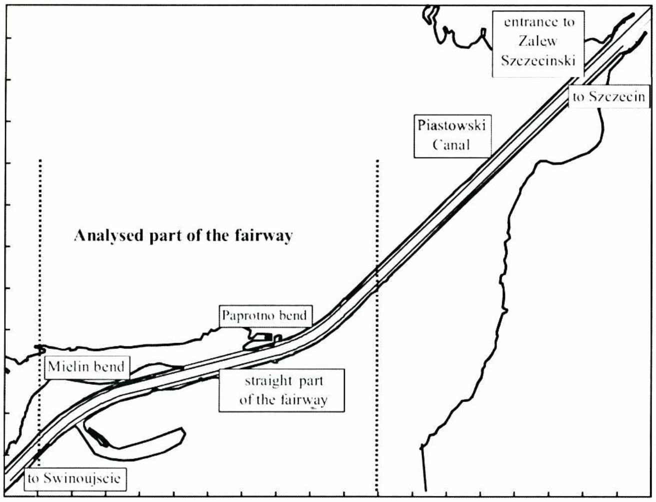


Fig.1. The investigated part of the Szczecin–Świnoujście waterway

The following ship parameters were taken into account :

$L = 250$ m
$B = 38.5$ m
$d = 10.5$ m
$A_s = 330.7$ m^2
$\delta = 0.818$
$P_n = 12\,814$ kW
k_m – (dependent on main engine setting)
$D = 6.5$ m
$h_s = 4.35$ m
$n = 1.96$ s^{-1} (at manoeuvre full speed)
K_T – (dependent on main engine setting)
$w \approx 0.8$.

The canal parameters were assumed in compliance with the planned canal arrangement (Fig.1 and 2). Canal cross sections were put into the simulation program at every 100 m of canal length.

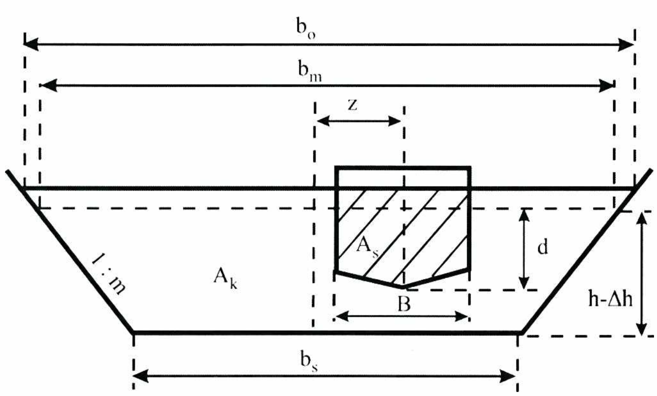


Fig.2. Definition of canal parameters and vessel-canal relationship

The following values of the canal parameters were considered :

$b_0 = 210 \div 280$ m
$b_s = 120 \div 150$ m
$h = 12.5$ m
$m = 3 \div 5$
A_k – (calculated in compliance with planned canal arrangement)
$\eta = A_k/A_s$
$h_m = A_k/b_0$

PROCESSING METHODS OF SIMULATION RESULTS

Ship-induced reverse current and waves

After 15 simulation trials the following ship parameters were calculated at each of 140 sections of the fairway (of the total investigated length of 7000 m) :

V_s - ship speed on the waterway
z - distance from the ship centre plane to that of the waterway (off-centre displacement, eccentricity)
β - ship drift angle.

Their average values and 95% confidence intervals were also computed. The values were then used as input data to the mathematical models in question.

Propeller stream loads on the bottom

The investigated area was divided into 10 m x 10 m squares. For each of them speed and duration time of propeller stream on the bottom was recorded during each of the simulation trials. After completing all the simulation trials the maximum and average speed values of the propeller stream on the bottom, as well as its duration times were determined. Also points of location of the propeller stream impact were calculated by using the below presented method.

APPLIED CALCULATION METHODS OF SHIP-INDUCED CURRENT SPEED AND WAVE HEIGHT IN NAVIGABLE CANALS

Reverse current (backflow)

Speed of the reverse current between ship and the bottom, generated by the ships moving through navigable canals, increases with ship speed until ship reaches the critical speed. Values of the critical speed for the investigated ship and canal parameters were calculated in advance by two methods. The results were contained within the range of 4.2 to 4.6 m/s. The navigators taking part in the simulation were obliged to maintain the optimum speed between 3.4 and 3.8 m/s (as port regulations limit it to 3.6 m/s for the investigated area).

The average backflow speed V_R was calculated by means of the following equations [5] :

$$V_R = \frac{A_s + \Delta h\, b_m}{A_k - (A_s + \Delta h\, b_m)} V_s \qquad (1)$$

where :

$$\Delta h = \frac{1}{g}\left(V_s V_R + \frac{V_R^2}{2}\right) \qquad (2)$$

The maximum backflow speed V_{Rmax} was calculated by using the following formulas [5] :

$$V_{R\,max} = V_s\left\{\left[1 + \alpha(\varepsilon^2 - 1)\left(\frac{0.08 g h_m}{\varepsilon^2 - 1}\right)^{-0.85} V_s^{1.7}\right]^{0.5} - 1\right\} \qquad (3)$$

where :

$$\alpha = 0.114\frac{b_r}{B} + 0.715 \qquad \text{for: } \frac{b_r}{B} \geq 2.5$$

$$\alpha = 1.0 \qquad \text{for: } \frac{b_r}{B} < 2.5$$

$$b_r = \frac{b_o + b_s}{2} \qquad \varepsilon = \frac{1}{0.96 - \frac{1}{\eta}}$$

The reverse current speed V_{Ra} due to ship position eccentricity relative to the fairway centre plane was calculated as follows [5] :

$$V_{Ra} = V_R \sqrt{\frac{\Delta h_a}{\Delta h}} \qquad (4)$$

where :

$$\Delta h_a = \Delta h (0.0086 \eta^{2.5(\frac{2z}{b_s})} + 1) \qquad (5)$$

Waves

When ship moves with the undercritical speed the primary wave system dominates. Therefore the secondary wave system was neglected. The wave height close to the canal bank was calculated as follows [5] :

$$H = c V_s^{3.5} \qquad (6)$$

where :

$$c = \varphi k (0.1 \zeta g h_m)^{-0.75}$$

$$\varphi = 0.6 e^{2.8\left(\frac{h_m}{b_0}\right)}$$

$k = f(\eta)$ - computed with the use of the following function :

η	2	4	6	8	10	12	14	16	18	20	22
k	∞	0.07	0.045	0.032	0.025	0.021	0.019	0.017	0.016	0.015	0.014

$$\zeta = \frac{(1-\alpha)^2}{1-(1-\alpha^2)}$$

In the case when ship is in an off-centre position on the fairway ($z \neq 0$) the coefficient φ was used [5] :

$$H_a = \varphi_a H \qquad (7)$$

where :

$$\varphi_a = 0.0086 \eta^{2.5\left(\frac{2z}{b_s}\right)} + 1$$

In the situation when ship moves with the drift angle β relative to the centre plane of the fairway η was replaced by η_k [5] :

$$\eta_k = \frac{A_k}{d(B + 0{,}15 L \sin\beta)} \qquad (8)$$

APPLIED CALCULATION METHOD OF PROPELLER STREAM LOAD ON THE CANAL BOTTOM AND EMBANKMENTS

Water stream velocity just behind the propeller was calculated by using four methods and their results were finally averaged :

1. by formula (9) [5] :

$$V_0 = 1.6 n D \sqrt{K_T} \left(1 + \frac{2V_P}{V_0}\right)^{-0.5} \qquad (9)$$

where :

$$V_P = V_S(1-w)$$

2. by formula (10) [9] :

$$V_0 = 1.6 n D \sqrt{K_T} \qquad (10)$$

3. with the use of formula (11) in which the main engine power P_n is applied [9] :

$$V_0 = c_p \left(\frac{k_m P_n}{\zeta_o D^2}\right)^{\frac{1}{3}} \qquad (11)$$

where :
- c_p = 1.48 for open-water propeller
- c_p = 1.17 for tunnel propeller.

4. with the use of formula (12), well-known from ship hydrodynamics, in which the propeller pitch h_s is applied :

$$V_0 = n h_s K_T \qquad (12)$$

The above specified methods yielded very similar results for the analyzed ship.

Most methods of propeller stream determination near the bottom is intended for ships not moving or moving with a slow speed. In such circumstances the following formulas were applied to determine speed of propeller stream on the bottom :

❖ formula (13) according to the recommendation Z30/14 of [9] :

$$V_{B\max} = V_0 E \left(\frac{h_p}{D}\right)^{-1} \qquad (13)$$

where :
- E = 0.42 for ship without central rudder
- E = 0.71 for ship with central rudder
- E = 0.25 for river barge with tunnel stern.

❖ formula (14) according to [2] :

$$V_{B\max} = 0.95 E n \frac{D^2}{h_p} \qquad (14)$$

❖ formula (15) according to [1] :

$$V_{B\max} = 1.88 e^{0.092\frac{h_p}{D}} \left(\frac{X}{D}\right)^{0.6} \qquad (15)$$

where :
- x - distance from the projection on the bottom of the propeller hub mid-length point to the point of location of the maximum propeller stream impact on the bottom (see Fig.3).
- e - Napierian base

When ship moves through a navigable canal with constant speed the propeller stream impacting the bottom is negligible. However, as the engine set is increased in order to increase water inflow to propeller and thus to improve ship manoeuvrability the propeller stream action on the bottom can be considerable. The maximum speed of the propeller stream on the bottom was calculated by the following formula [5] :

$$V_{B\max} = V_0 E \left(\frac{h_p}{D} \right)^{-1} \left(1 - \frac{V_s}{nD} \right) \qquad (16)$$

The maximum stream impact location on the bottom was calculated in accordance with [6,7] (Fig.3) :

$$X_p = \mathrm{ctg}25^0 h_p = 2.14 h_p \qquad (17)$$

In the calculations twisting effect of rudder angle was also taken into account by assuming that the propeller-stream horizontal deflection angle from the ship central plane is equal to that of the rudder.

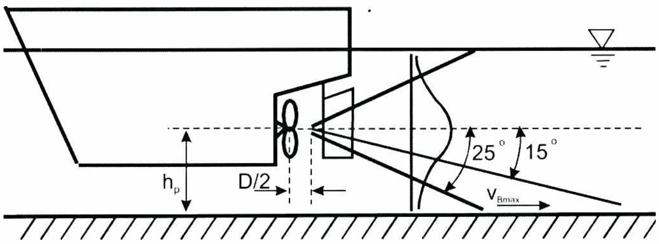


Fig.3. Location of the maximum propeller stream impact on the bottom at the engine set „ahead"

RESULTS OF THE EXAMPLE CALCULATIONS

Ship-induced reverse current

The example calculations of the reverse current by using the described calculation model for the analyzed part of the fairway is presented in Fig.4.

The maximum current speed calculated by means of (3) is that at the middle plane of the waterway. In the area of port - side and starboard canal banks the reverse current speeds were calculated with the use of (4) with accounting for ship's off-centre displacement. The greater current speed close the port-side bank means that the ship was off-centred toward this side. On the other side of the canal the current speed was determined by using (1) and (2).

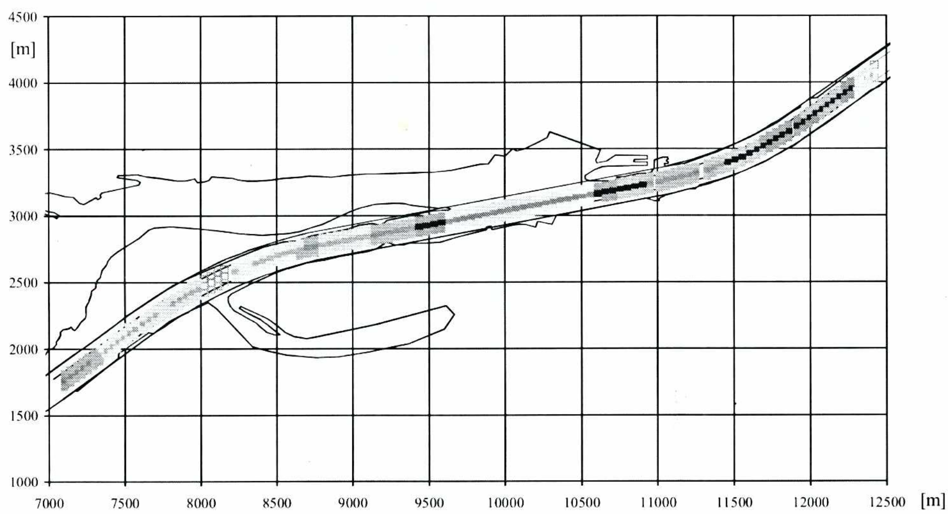
Ship-induced waves

Calculation results of the primary wave system are presented in Fig. 5. The wave height for ship's off-centre position near closer bank was calculated by using (7). On the other bank the average wave height was calculated by means of (6).

Propeller stream impact

Determination of the propeller stream impact on the bottom was carried out for 600 m x 600 m bottom areas divided into 10 m x 10 m squares. The analyzed waterway region was split into the following parts :

* Paprotno bend
* straight part of the canal between bends
* Mielin bend.



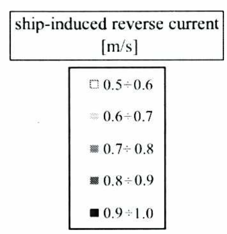
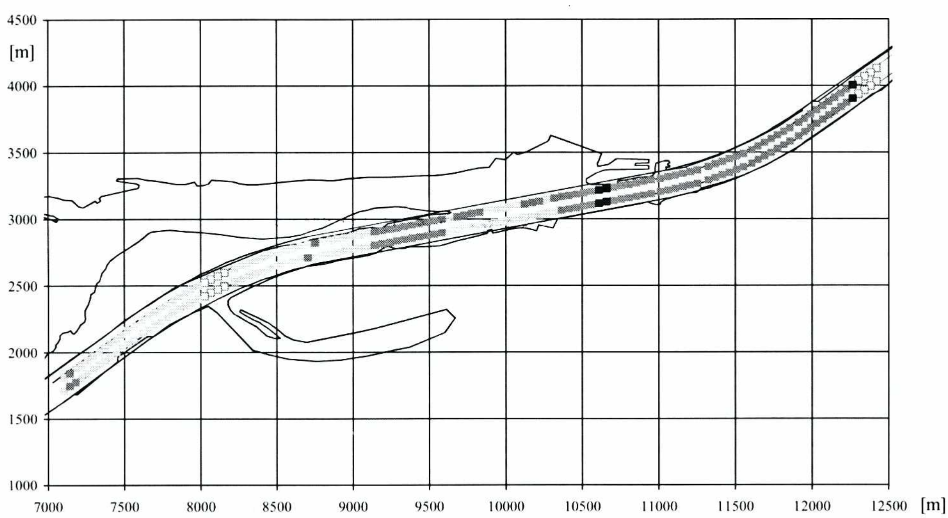
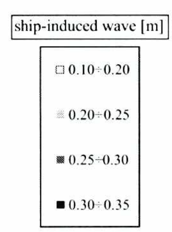


***Fig.4.** The simulated ship-induced reverse current speed in the area of Paprotno and Mielin bends.*
***Conditions :** Ship arrival in Szczecin, NE wind of 5 m/s velocity, sailing downstream, 15 simulation passages.*





The maximum values of the propeller stream speed at the bottom, obtained during simulation passages are presented in Fig.6.

***Fig.5.** Wave height of the primary wave system in the area of Paprotno and Mielin bends, simulated with accounting for ship's off-centre displacement.*
***Conditions :** Ship arrival in Szczecin, NE wind of 5 m/s velocity, sailing downstream, 15 simulation passages.*

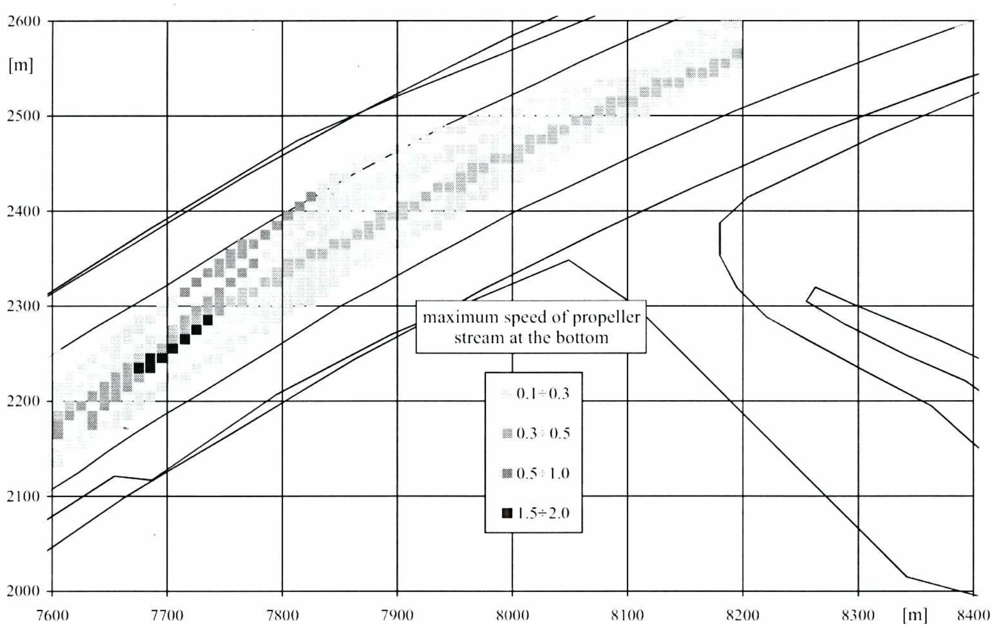


Fig.6. *The simulated maximum speed of the propeller stream at the bottom in the area of Mielin bend.*
Conditions : *Ship arrival in Szczecin, NE wind of 5 m/s velocity, sailing downstream, 15 simulation passages.*

Conclusions

- The presented research results can be used for determining the necessary strengthening of the canal bottom, banks and embankment. (Size of protective stones can be calculated from appropriate formulas used in coastal engineering).
- The results can also be applied to determine the areas of the waterway most exposed to ship-induced, destructive influences.
- The reverse current and waves induced by ships passing the navigable canals should also be considered in waterway design.
- In the extreme cases the ship speed limitation should also be taken into account as a way for decreasing the ship-induced current and waves. Moreover, captains and pilots should be made aware of ship's critical speed in particular canal areas as remarkable increase of ship-induced waves and current can be observed while ship moves close to that speed.

Appraised by Jerzy Hajduk, Assist.Prof.,D.Sc.

NOMENCLATURE

A_k	[m²]	wet cross section area of canal
A_s	[m²]	wet midship cross section area
b_m	[m]	canal width with accounted for water level decrease due to passing ship: $b_m \cong b_0$
b_o	[m]	canal width measured at the highest water level
b_s	[m]	canal bottom width
B	[m]	ship moulded breadth
c_p	[-]	coefficient for propeller stream calculation, in [11]
d	[m]	maximum ship draught
D	[m]	propeller diameter
E	[-]	coefficient of stern shape and rudder layout, in [13]
g	[m/s²]	gravity acceleration
h	[m]	canal depth
h_m	[m]	mean depth of the equivalent rectangle: $h_m=A_k/b_0$
h_p	[m]	height of the propeller centre above the canal bottom: $h_p=0{,}6D+[h-d]$
h_s	[m]	propeller pitch
H	[m]	maximum wave height of the primary wave system
H_a	[m]	wave height of the primary wave system with ship off-centre displacement accounted for
k_m	[-]	power efficiency factor, in [11]
K_T	[-]	propeller thrust coefficient
L	[m]	overall ship length
m	[-]	bank inverse slope
n	[s⁻¹]	propeller revolutions
P_n	[kW]	nominal engine power output
V_{Bmax}	[m/s]	maximum speed of propeller stream at the bottom
V_0	[m/s]	water stream velocity behind propeller
V_p	[m/s]	propeller water inflow velocity
V_R	[m/s]	average speed of reverse current
V_{Ra}	[m/s]	reverse current speed with ship off-centre displacement accounted for
V_{Rmax}	[m/s]	maximum speed of reverse current
V_s	[m/s]	ship speed
w	[-]	propeller effective wake factor
x	[m]	distance from the projection on the bottom of the propeller hub midlength point to the point of location of the maximum propeller stream impact on the bottom
z	[m]	distance from ship centre plane to that of the waterway [off-centre displacement]
δ	[-]	midship section coefficient
η	[-]	canal blockage factor: $\eta=A_k/A_s$
β	[°]	ship drift angle relative to the centre plane of the waterway
α, ε	[-]	coefficients for reverse current speed calculation, in [3]
φ, ζ, κ	[-]	coefficients for wave height calculation, in [6]
ζ_0	[kg/m³]	water density
φ_a'	[-]	coefficient for wave height calculation in the case of ship off-centre displacement, in [7]
Δh	[m]	water level decrease due to passing ship
Δh_a	[m]	water level decrease due to passing ship in the case of ship off-centre displacement
η_k	[-]	canal blockage factor in the case of ship off-centre displacement

BIBLIOGRAPHY

1. Fuehrer M., Römish K. : *Effects of modern ships traffic on inland - and ocean waterways and their structures.* Proceedings of the 24th International Navigation Congress PIANC. Leningrad, 1977
2. Fuehrer M., Römish K., Engelke G. : *Criteria for dimensioning the bottom and slope protection and for applying the new methods for protecting navigation channels.* Proceedings of the 25th International Navigation Congress PIANC. Edinburgh, 1981
3. Gucma S., Kopczyński P. : *Distribution of propeller stream at the bottom – – simulation method* (in Polish). Proceedings of the 6th International Scientific and Technical Conference on Marine Traffic Engineering. Szczecin, 1995
4. Kopczyński P. : *The limitation to ship's manoeuvring due to propeller streams* (in Polish). Proceedings of the 6th International Scientific and Technical Conference on Marine Traffic Engineering. Szczecin 1995
5. Mazurkiewicz B. : *Ship-induced loads on navigable canals* (in Polish). WSM Publishing. Szczecin, 2000
6. Masel S. (Ed.). : *Coastal Engineering Handbook* (in Polish). Maritime Publishing. Gdańsk, 1992
7. Schmidt E. : *Ausbreitungsverhalten und Erosionwirkung eines Bugpropellerstrahles von einer Kaiwand.* Doctoral dissertation. University of Carolo Wilhelmin. Brunswick, 1999
8. Uliczka K. : *Interaction between sea going ship and estuary fairway.* Proceedings of the 29th International Navigation Congress PIANC. The Hague, 1998
9. Mazurkiewicz B. (Ed.) : *Recommendations for Design of Coastal Engineering Structures* (in Polish). Gdańsk, 1993