Physical Phenomena and Safety in Inland Waterborne Transport

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The paper presents an analysis of the impact of the physical phenomena occurring during the movement of a vessel in shallow water on the number of accidents on inland waterways. On the basis of data on the accidents on German waterways it has been established that the phenomenon of ship squatting significantly contributes to accidents connected with the suction of the vessel to the bottom of the waterway. Such failures are the cause of over 35% of all the accidents on inland waterways. Another factor increasing the probability of a failure is the negative impact of the waves produced by the movement of the vessel and of the screw race. The size of squatting and the intensity of the negative impact of the waves and the screw race depend on the sailing speed and the waterway restrictions.

Keywords: inland waterborne transport, accidents, squatting.

1. INTRODUCTION

Inland waterways are routes with a limited depth and width. The limitations have several negative effects on the vessel-waterway system. As regards the vessel, its resistances increase whereby it may get sucked to the waterway bottom. Besides suction, vessel trim occurs. Typically it is trim by stern, which can contribute to damage to the steering-propulsion system. Suction with trim leads to damage to the vessel's plating and its immobilization. On the other hand, the moving vessel produces negative pressure areas on the waterway bottom and a system of waves. These phenomena are considered to adversely affect the waterway and are played up by environmentalists. Negative pressure is closely connected with reverse flow velocity. At the waterway bed this velocity can be higher than the scouring velocity, resulting in bed load movement and changes in the waterway parameters.

The system of waves generated by the movement of the vessel, and the screw race impact the waterway banks, causing the washing out and degradation of the bank protections. This is phenomenon is particularly adverse when the vessel sails on a canal. In order to limit this adverse effect the allowable sailing speeds are administratively restricted.

The main constraint for inland waterborne transport in Poland are low and variable water stages, resulting in recommended shallow transit depths, whereby the fleet is operated at a minimum waterway depth/vessel draught tolerance. This contributes to an increased hazard of the vessel getting sucked to the waterway bottom and the subsequent damage to the plating or the steering-propulsion system. The phenomena involved have a dynamic character. There is a close interdependence between the waterway parameters, the sailing speed, the shape of the vessel hull and the propulsion system operating parameters. The contribution of all the above parameters to the vessel getting sucked to the bottom (running aground), which is closely connected with safety in inland waterborne transport, is discussed in this paper.

2. STRUCTURE OF FAILURES AND ACCIDENTS ON INLAND WATERWAYS

The physical phenomena occurring during the movement of a vessel on a waterway with a limited depth can be the cause of such accidents as:

- running aground (stranding),
- damage to and destruction of waterway wharfs and banks,
- a change in the waterway bed structure.

Running aground is the result of vessel squatting and trimming, to which an excessive sailing speed and the minimization of the binding transit depth/allowable vessel draught tolerance contribute. Running aground has a significant share in the structure of the accidents which occur on free flowing rivers.

Damage to wharfs and banks results from the impact of the waves produced by the movement of the ship. The conducive factors here are: an excessive sailing speed and the vessel hull shape contributing to a high percentage of wave resistance in the total vessel movement resistance. Also the impact of the screw race should be included in the group of factors having a destructive effect on wharfs and banks. The adverse effects of vessel movement have a significant bearing on the waterway maintenance costs. Another major factor responsible for damage to watersides are collisions of the vessel with a bank, a wharf or other hydro-engineering structure (a lock, a bridge pier, etc.). The most common cause of such accidents are the crew's inattention or error. Damage to banks and elements of hydro-engineering structures most often occurs on stretches of channelized rivers and on navigable canals.

The literature on the subject lacks a uniform classification of failures and accidents on inland waterways. The existing classifications cover waterway types and the authorities administering the particular waterway regions. In Poland a register of accidents and failures is kept by Inland Navigation Inspectorates. A wide analysis of accidents on Polish waterways was carried out as part of the INBAT research project [2]. The analysis was based on data for the period of 1980-2000, made available by the Inland Navigation Offices in Kędzierzyn-Koźle, Wrocław and Szczecin. 773 navigation accidents were registered in this period. 275 of them can be classified as strandings (107 on the stretch of the channelized Oder and 168 on the free flowing Oder). This amounts to 35.5% of the total number of accidents.

2.1. ACCIDENTS IN NAVIGATION ON GERMANY'S WATERWAYS

Data on failures and accidents on the German waterways with the highest traffic volume in the years 2012 and 2013 [3], [7], [8] are presented below. The data are for the following regions:

- WSD Südwest – the Upper and Middle Rhine, the Moselle, the Neckar, the Lahn, the Saar,
- WSD West – the Lower Rhine up to the border with the Netherlands and the West German canals within the Ruhr region,
- WSD Mitte – the Mittelland Canal with the adjoining branches, the Weser, the Lateral Canal connecting the Mittelland Canal with the Elbe and Hamburg.

  This count of accidents does not cover two areas of Germany's waterways, i.e. the SUD region with the Rhine-Main-Danube Canal and the Danube up to the Austrian border and the OST region with a complex of canals connecting the Elbe with the Oder. On the waterways in these areas cases of vessels getting sucked to the waterway bottom and of the negative impact of the screw race and waves are rare – not exceeding 1% of the total number of accidents.

The number and type of failures are shown in table 1 for the WSD Südwest region and in table 2 for the WSD West region. The results are based on the statistical data posted by the particular waterway region administrations on the website: www.elwis.de. On the waterways in these regions a significant number of failures and accidents are due to the physical phenomena (suction and screw race and wave action) which occur during the movement of the vessel on restricted waters.

Accidents due to inattention and navigation errors predominate in the WSD Mitte region. 33% of the total number of accidents are collisions between vessels and 37% are collisions with a wharf or a hydro-engineering structure. Suction accidents do not exceed 3% while wave and screw race action accidents amount to less than 4%.

Table 1. Failures and accidents on waterways in WSD Südwest region.

Accident, failure	Upper and Middle Rhine				Neckar, Moselle, Lahn			
	2012		2013		2012		2013	
	No. of cases	%	No. of cases	%	No. of cases	%	No. of cases	%
Screw race, waves	13	9.0	10	7.0	15	21.0	10	15.5
Suction	25	16.5	26	19.0	12	16.5	8	12.0
Collision with structure	29	19.5	20	14.5	8	11.0	11	17.0
Collision between vessels	66	44.0	69	50.5	25	35.0	23	35.5
Other*	16	11.0	12	9.0	12	16.5	13	20.0
Total	149	100.0	137	100.0	72	100.0	65	100.0

*excluding failures connected with vessel equipment operation.

Table 2. Failures and accidents on waterways in WSD West region.

Accident, failure	Lower Rhine				Canals			
	2012		2013		2012		2013	
	No. of cases	%	No. of cases	%	No. of cases	%	No. of cases	%
Suction	50	39.0	50	35.0	0	0	2	3.5
Collision with structure	7	5.5	15	10.5	60	71.5	38	64.5
Collision between vessels	22	17.2	14	10.0	10	12.5	9	15.0
Other*	49	38.3	63	44.5	13	16.0	10	17.0
Total	128	100.0	142	100.0	83	100.0	59	100.0

*including failures connected with vessel equipment operation..

The Rhine (especially its lower stretch) is the waterway which carries the highest volume of traffic. 100 thousand vessels with cargo navigate the Lower Rhine per annum. Taking into account vessels without cargo, the total number of vessels annually navigating this stretch is estimated at 160-170 thousand. Excluding collisions between vessels, failures due to suction (table 2) predominate on the stretches of the free flowing rivers (the Lower Rhine). Suction and wave and screw race action are the factors having a bearing on the number of failures on the channelized river stretches (table 1). The predominant accidents on the channelized river sections and canals (table 2) are collisions of vessels with the elements of hydro-engineering structures.

3. SQUATTING IN VESSEL MOVEMENT ON SHALLOW WATER

Squatting is a factor contributing to failures caused by the suction of the vessel to the waterway bottom. Squatting is an apparent change in the vessel's draught. As a result, the distance between the bottom of the vessel's hull and the waterway bed becomes smaller. This is due to the lowering of the water table around the moving vessel as a result of the increasing water flow velocity relative to the vessel's hull and a change in pressure distribution along the moving vessel. The phenomena are connected with the flow continuity conservation law and the energy conservation law. The factors having a bearing on the size of squatting are:

- the sailing speed,
- the waterway restrictions – depth and width,
- the push train formation,
- the shape of the vessel's hull.

In the literature on the subject one can find several ways of roughly estimating the size of squatting [1], [4], [5]. They are based on the results of model studies or numerical computations. If squatting is not taken into account, the vessel gets sucked to the waterway bottom when:

$$T \leq h(s,t) - dT \qquad (1)$$

where:

T – the vessel's draught (constant during the voyage),

$h(s,t)$ – the waterway depth as a function of waterway stretch s in time t in which the voyage takes place,

dT – the size of squatting.

In the case of a navigable canal it can be assumed that for a given time in which the voyage takes place the waterway depth is constant. For a river (especially an unchannelized one) the waterway depth is a function of a given waterway stretch s and the hydro-meteorological conditions (the flow volume). Both the parameters are variable in time and can treated as random variables. At a fixed transit depth local shallows will occur. As a result of the action of the river current, the shallows displace along the waterway. These are the stretches of the waterway where the danger that the vessel will get sucked to the waterway bottom is the greatest.

Introducing dimensionless parameters one can assume that the size of squatting is the function:

$$dT = f\left[\frac{h(s,t)}{T}, F_{nh}, \frac{A_x}{A_0(s,t)}\right] \quad (2)$$

where:

A_x – the maximum cross-sectional area of the submersed part of the vessel's hull,

A_0 – the cross-sectional area of the waterway,

F_{nh} – the depth Froude number which defines the sailing speed/critical velocity ratio.

The Froude number has the form:

$$F_{nh} = \frac{V}{\sqrt{g \cdot h}} \quad (3)$$

V - the sailing speed [m/s].

Critical velocity $\boldsymbol{V_{cr}}$ depends on:

$$V_{cr} = \sqrt{g \cdot h} \quad (4)$$

The other parameters having a bearing on the size of squatting are: the shape of the push train formation and the shape of the vessel's hull (especially of its bow part). The qualitative effect of these parameters is presented below on the basis of the results of numerical computations and model studies [6], [9], [10].

The model studies were carried out for different push train formations (without the pusher) consisting of EUROPA II barges at a variable waterway depth and a variable draught [9]. The barge dimensions are:

length L=76.5 m,

width B=11.33 m,

investigated draughts: T= 0.74 m, 2.5 m, 3.0 m and 3.8 m,

waterway depth: h=3.5 m, h= 5 m; h=7,5 m.

Exemplary results of the studies, scaled up to the real objects, are shown in figs 1-3.

A decrease in depth at a fixed draught (fig. 1) has a similar effect as an increase in draught at a fixed depth (fig. 2). Both changes cause a decrease in the depth/draught ratio, which results in increased squatting. A change in the train configuration (fig. 3) significantly affects the size of squatting if this change leads to an increase in the train width (two barges side by side). In the case of single-row trains, an increase in the number of barges results in an increase in the total length of the train. As the train length increases so does the size of squatting, but this effect is not significant.

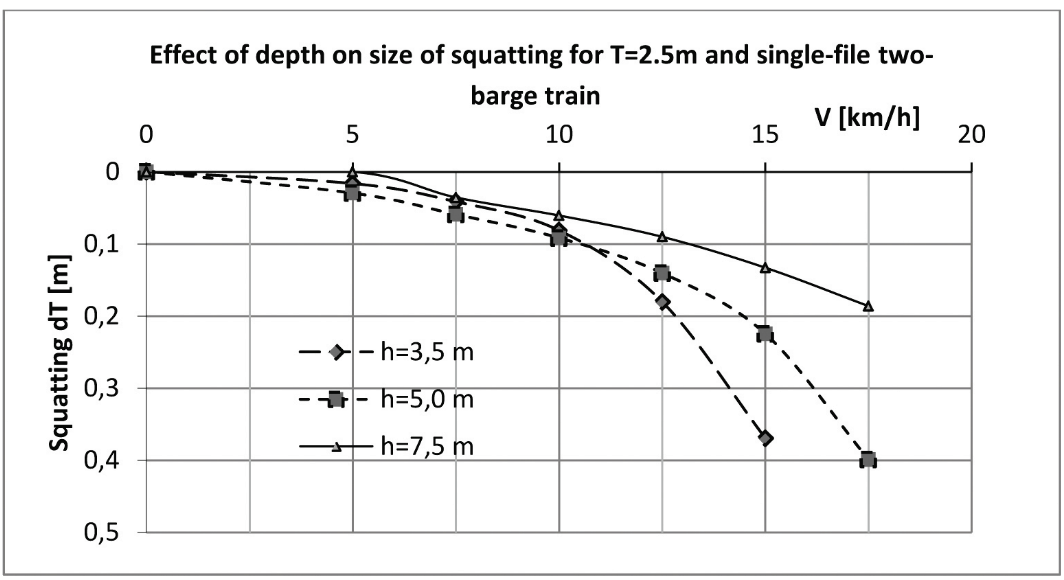

Fig. 1. Effect of depth on size of squatting.

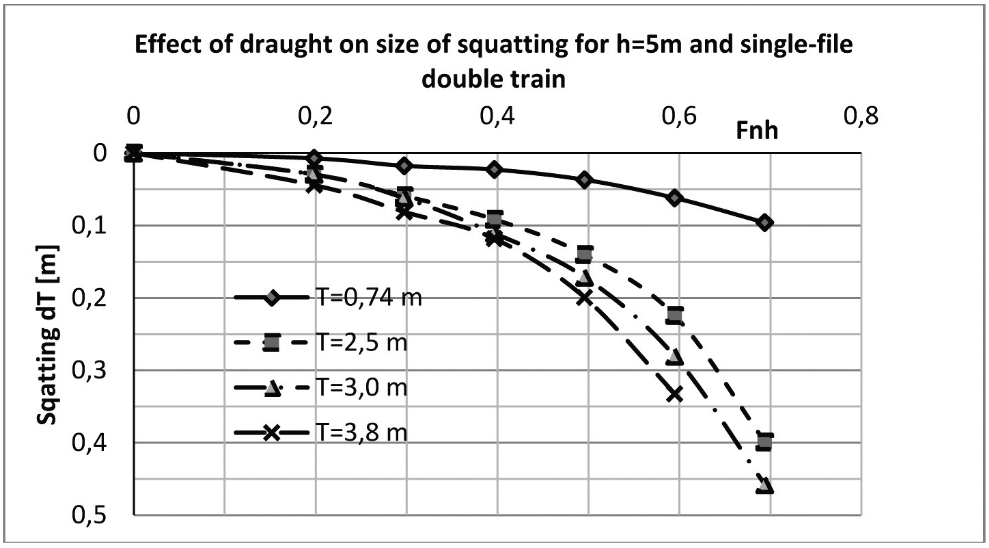

Fig. 2. Effect of barge draught on size of squatting.

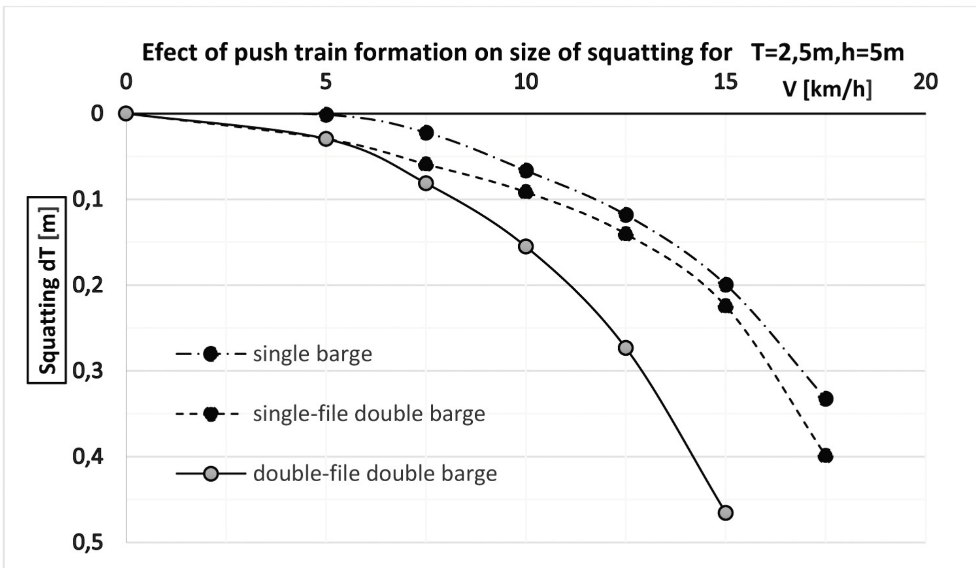

Fig. 3. Effect of push train formation.

The results of canal studies [10] are for a pusher + 2× push barge train. The draught of the push barges was constant. The canal dimensions, shown in fig. 4, were changed. Figure 5 shows the size of squatting.

Two formations differing in push barge parameters were investigated. The total length of a train consisting of EUROPA I barges and that of a train made up of EUROPA II barges amounted to respectively 160 m and 173 m. The cross-sectional area of the barges in the mid-ship section (A_x) was independent of the type of barges.

The results show that in the case of canals the mid-ship section area/canal cross-sectional area ratio has a significant effect on the size of squatting. The effect of the length of the train is considerably smaller: an increase in this length results in a slight increase in the size of squatting.

The effect of the shape of the push barge bow part was assessed through numerical computations [6]. An in-house system for computing the flow around the vessel hull on a restricted waterway was used for this purpose. The computations were carried out for a single-file two-barge push train at different waterway depths. The barge dimensions were:

length L=48.75 m,
width B=9.0 m,
draught T=1.7 m.

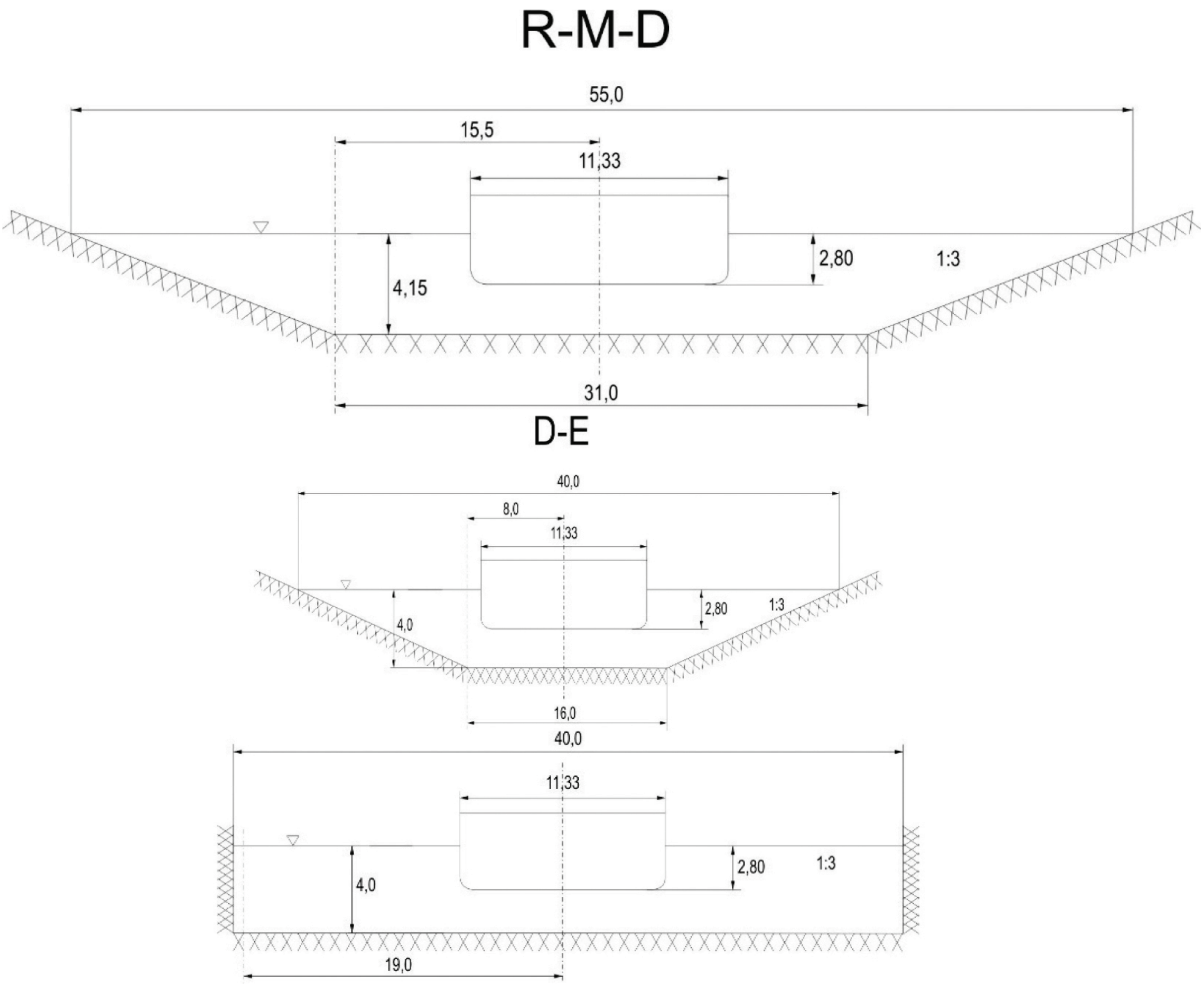

Fig. 4. Dimensions of canals: Rhine–Main–Danube Canal, Dortmund–Ems Canal.

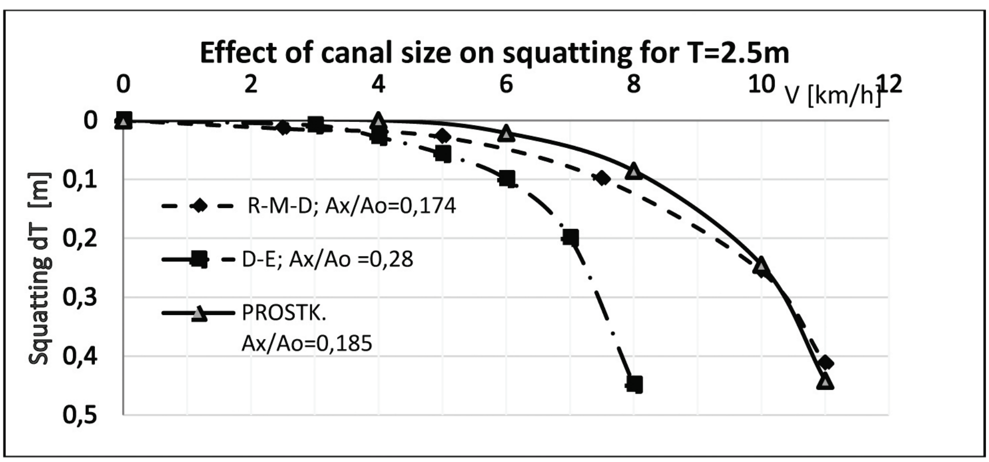

Fig. 5. Effect of canal size on squatting.

Figure 6 shows (in a dimensionless form) the studied bow shapes. At a fixed length of the bow part the bow coefficient would be changed. The bow designated as B_89 had the most full-form shape. It appears from figure 7 that for the adopted waterway and vessel draught parameters squatting can exceed the assumed depth/draught tolerance already at F_{nh} = 0.5 (i.e. at about 10 km/h).

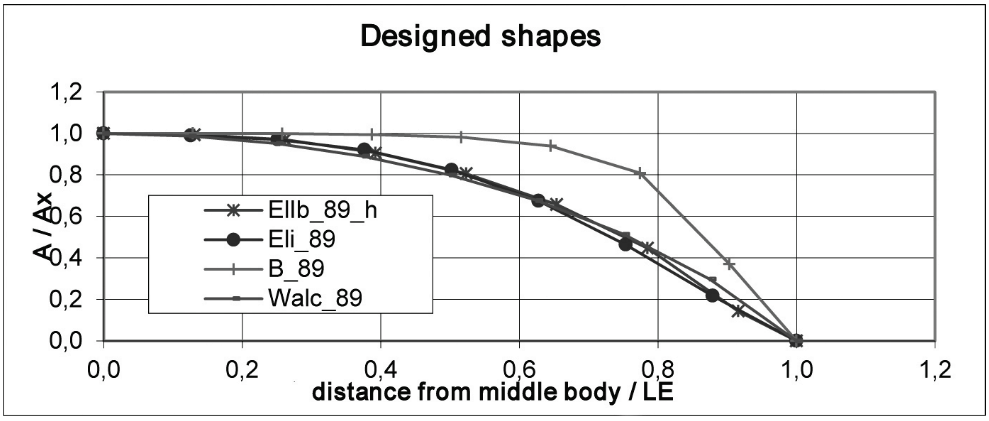

Fig. 6. Geometric characteristics of assumed bow shapes.

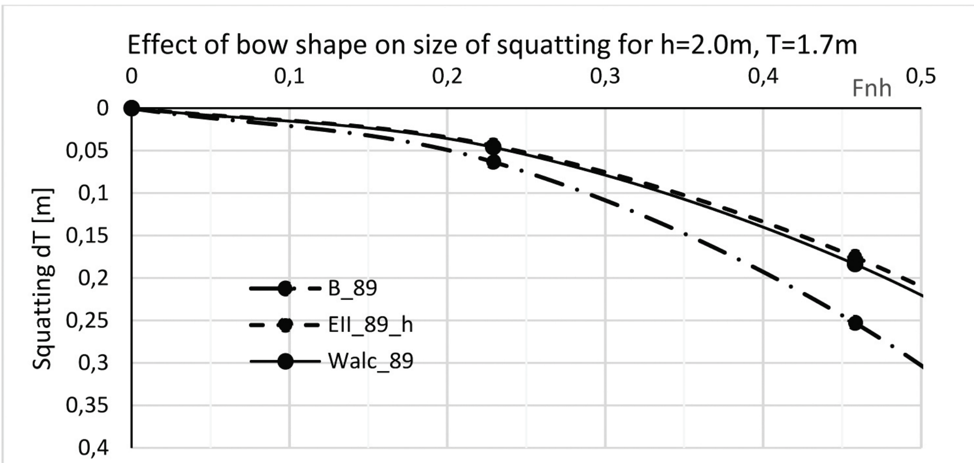

Fig. 7. Exemplary squatting computation results for different bow shapes.

4. CONCLUSION

The results indicate that the bow coefficient has the decisive effect on the size of squatting. Different shapes characterized by a similar bow coefficient have no major effect on the size of squatting. The numerical computations have confirmed that the size of squatting is mainly determined by the following parameters: vessel draught, waterway depth, canal cross section and sailing speed. In the operating conditions the only parameter which can be instrumental in preventing a vessel getting sucked to the waterway depth is sailing speed. In view of the negative impact of the system of generated waves on waterway bank protections, sailing speed limits are commonly imposed, particularly on canals and channelized stretches of rivers.

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