Influence of ship motion on waterway. Backward current velocity

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ABSTRACT

In this work was presented an influence of bow form of inland waterways ship and waterway limitations on values of backward current velocity. The analysis was performed on the basis of results of calculations with the use of numerical modeling the flow around ship hull. The applied HPSDK computation system (a computer software developed by these authors) is based on using surface distribution of vorticity to analyze the velocity field and pressure distribution around ship hull. It was proved that the generated backward current velocity exceeded its permissible non-scouring values.

Keywords : waterway, bow form, backward current.

INTRODUCTION

Traffic of inland navigation ships constitutes one of the crucial factors deteriorating the waterways. And, the ships' operators often present their reservations about some parameters of waterways which do not make it possible to fully utilize capabilities of the inland waterways ships. Correct identification of the phenomena which take place during ship motion on a limited waterway can contribute to elimination or at least moderation of the mentioned problems.

During ship motion on a limited waterway many detrimental physical phenomena occur. These are :

- ★ increase of ship resistance
- ★ ship sagging
- ★ ship trimming.

The last two make the required clearance between the waterway bed and ship's bottom plating, decreasing. Simultaneously, ship's sagging and trimming generate an additional increase of ship's resistance. The detrimental influence of ship on waterway leads to limitations of ship's service draught and speed. They are as a rule imposed by the waterways administration. They are aimed at protecting the waterways against excessive degradation as well as at preventing ships against their stopping, failure of propulsion system and/or loss of floatation - due to taking contact with waterway bed. The waterways administration recommends to lower ship draught and/or speed, that adversely influences costs of transport on inland waterways.

Moving ship narrows transverse cross-section of canal, which leads to generation of an under-pressure and increase of velocity of water flow around hull ship, the so called backward current. Both the phenomena cause degradation of canal banks and bed. The influence is manifested by :

- backward current especially intensive at an asymmetrical position of ship relative to canal sides
- behind-the-propeller stream (race) which can generate erosion (scouring) of slope and bed of canal.

There is close connection between quantity of change of ship position and that of resulting under-pressure and backward current. An increase of water speed around ship makes water level lowering, that directly causes ship sagging. As ship's hull is not symmetrical with respect to the midship plane the backward speed varies along ship's length. It means that the water level lowering is not uniform over the whole ship length, that leads to ship trimming. The trim, as demonstrated also by model tests, does not significantly influence safety of ship traffic. Large trim values occur at speeds close to critical ones. Such speeds are reached neither by cargo nor passenger ships.

An additional factor of detrimental influence of ship motion on waterway is damaging action of generated waves on waterway bank protection. Extent of the influence is tightly associated with the share of wave resistance in ship total resistance to motion.

Results of the analysis of the influence of waterway limitations (its depth and width) on backward current velocity values, are presented below on the basis of the author's model of water flow around ship hull. Ship safe speeds are additionally dependent on geological structure of waterway bed.

HPSDK COMPUTATIONAL SYSTEM

The HPSDK computational system is a computer software which has been developed for many years. Its beginnings date back to the end of the 1980s. It has been aimed mainly at elaboration of a mathematical model of hydrodynamic interactions occurring within propulsion system of inland navigation ship. On this basis, was elaborated a computer program package, which make it possible - in a numerical way - to determine such quantities as : nominal and effective wake factors (with taking into account hull interaction), propeller thrust, required torque to be delivered to propeller's cone, and propeller efficiency. Results of the calculations made it possible, if ship resistance curve is known, to elaborate prediction of ship propulsion characteristics for various values of ship service speed and waterway depth. In building the software, particular elements of ship propulsion system were assumed to be considered independently, and their mutual interactions to be taken into account in an iterative way. The choice of such approach was conditioned by available computer hardware. The elements of the propulsion system were : ship's hull, screw or ducted propeller. The limited waterway depth was associated with the data describing the form of underwater part of ship's hull. The computer software has been continuously subjected to development. In present it consists of three independent modules (Fig.1). In each of the branches are contained common segments, e.g. those intended for the calculating of propeller or nozzle-propeller unit. However main function of each of the modules is different.

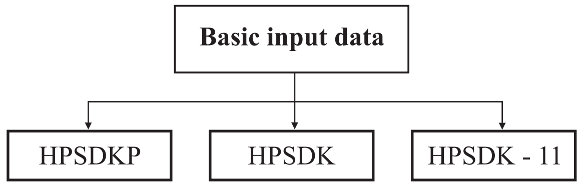

Fig. 1. *Structure of HPSDK calculation system .*

The HPSDK module is basic one. Today, it makes it possible to calculate - apart from operational parameters of propeller, nominal and effective wake factors - pressure distribution on waterway bed, quantity of ship's sag and trim [5,13]. The calculations can be carried out for conditions of limited depth of waterway and trapezoidal or rectangular cross-section of canal. It is necessary to put in coordinates of points of the mesh which models the form of the whole ship (also a push train).

HPSDKP module makes it possible to analyze influence of half-nozzles and before-propeller nozzles on operational parameters of ship propulsion system [7]. Additionally, should be introduced data which describe geometry of those elements and their position respective to the central coordinate frame connected with the propeller plane and propeller shaft axis. In the calculations, ship stern form and limited water depth can be taken into consideration.

HPSDK-11 module is intended for the analyzing of interactions within propeller - rudder blades system [8]. As compared with the basic (HPSDK) module it takes into account an influence of rudder blades. It is necessary to put in data which describe geometry of the blades and their position respective to the propeller. The module is adjusted to analyze flow around either one blade or a blade system (of three blades in one propeller stream at most). It makes it possible to perform an analysis with taking into account only the influence of behind--the-propeller stream (screw propeller, ducted propeller) or also the influence of hull and waterway bed.

All the three modules have a common block which serves for introducing basic input data which concern :

- description ship's form
- screw propeller geometry
- propeller nozzle geometry (if ducted propeller is applied)
- remaining data : waterway limitations, ship service speed, propeller rotational speed, number of propellers, and a set of control data.

The nozzle and propeller geometry input data are directly taken from working documentation of the elements. Two editors serve to this end. Making use of a catalogue of propellers and standard nozzles described in dimensionless coordinates is possible. The mesh to model the hull itself is built separately by means of the SIATKA.EXE module. The basis for data preparation is hull body plan or body form described in AutoCAD environment [9,10].

Results of calculations of wake factor and pressure distribution on waterway bed have been verified on the basis of available model test results. A proper conformity of the results of the calculations with those from model tests has been achieved [5, 6, 13]. The HPSDK computational system was comprehensively verified by applying to elaboration of ship propulsion predictions for different service conditions. The calculations have been carried out during work upon the INBAT research project realized in the frame of 5th EU Outline Program. Their results have been verified on the basis of partial results of the model tests performed in Ship Hydrodynamics Centre, Ship Design and Research Centre, Gdańsk and in a research centre at Duisburg [3,4]. The pressure distribution on waterway bed due to ship motion is presented in the form of the dimensionless coefficient c_p respective to the ship speed V_S. At a given value of the variability coefficient of pressure on the waterway bed, the local velocity V_i in any point of the waterway bed is - according to Bernoulli equation – as follows :

$$V_i = V_S \sqrt{1 - c_{pi}} \tag{1}$$

The velocity, when compared with the scouring one, can be used for the assessing of ship motion influence on waterway. The so obtained velocity determines local speed of backward current near waterway bed. The maximum value of the velocity is of a great importance from the point of view of the ship motion influence on waterway. This maximum occurs in the place where ship motion generates the largest under-pressure on waterway bed.

The HPSDK computational system makes it possible to calculate the pressure distribution in control points of the mesh modeling hull form. Making use of the relation (1), one can calculate [water flow ?] velocity in selected points of ship hull plating. Knowing its local values in ship hull control points one can calculate its mean value. The mean velocity is calculated as arithmetic one. The difference between the so determined velocity and assumed ship service speed gives the mean velocity of backward current.

The calculations in question were performed for model test conditions (in the model-scale $\alpha = 14$). The pressure distribution results are presented in the model-scale. The remaining results of the calculations (i.e. of backward current velocity) have been transformed to full-scale in compliance with the Froude modeling principle.

BACKWARD CURRENT VELOCITY

In the subject-matter literature many methods of defining the backward current can be found [4, 11]. As a rule they appear together with those for calculating quantity of sagging. Their characteristic feature is that they do not take into consideration ship hull form. Here four characteristic bow forms were assumed to take into account the shapes typical for cargo ships operating on inland waterways. They are marked as follows : EIIb_89h, ELI_89, WALC_89 i B_89. The two first forms constitute a modified EUROPA II and ellipsoidal form, respectively. The two remaining forms : WALC_89 and B_89 were proposed by these authors. The forms were elaborated under the assumption that easiness of manufacturing process and getting large cubicoidal hold are the crucial criteria in their designing. The forms are presented in Fig.2. And in Fig.3 are presented changes of areas of bow frame lines. The bow form B_89 is of the largest fullness. Its additional feature is that it is consisted of the surfaces bent in one plane only.

In this work the [backward current ?] velocities are determined on the basis of the calculation results obtained from the HPSDK computational system.

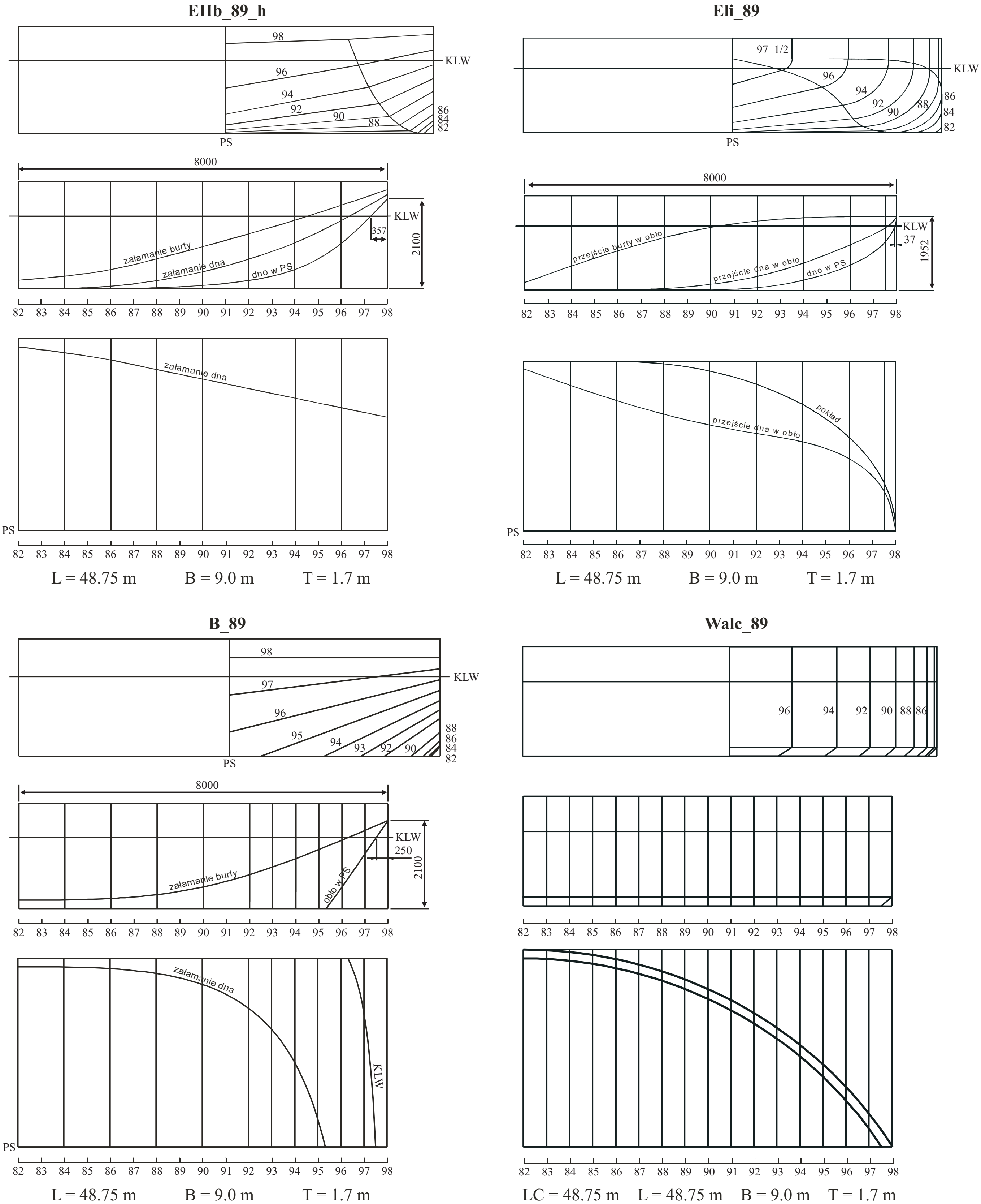

***Fig. 2.** Barge hull forms assumed for the analysis .*

By taking into account hydro-technical conditions of Polish waterways the calculations were carried out for a single-row, two-barge push train (without pusher). The following particulars of a single pushed barge were assumed :

Overall length : L_C = 48.75 m ; Breadth B = 9 m ; Draught T = 1.7 m ; Bow length L_E = 8 m.

The calculations were carried out for the limited water depth values as follows : h = 2, 2.5, 3, 4 and 5 m. Additionally, for some forms the calculations were carried out for the service conditions on Gliwice Canal which has the following particulars :

Bottom width : b_o = 20 m ; **Side slope ratio** : 1 :3.

Values of water surface width depend on assumed water depth value taken for calculations. Three water depth values were assumed : 2, 2.5 and 3.4 m. The design depth of Gliwice Canal is equal to h = 3.5 m. To assess an influence of the Canal dimensions, additional calculations were performed for the trapezoidal cross-section of the Canal assuming its bottom width b_o = 40 m, as well as for its rectangular cross-section of the width so chosen as to obtain the same cross-section area as in the case of the trapezoidal one.

Results of calculations of the maximum value of backward current velocity near waterway bed and its mean value are presented in the dimensionless form, i.e. the ratio of the velocity increment and ship service speed. The place of appearance of the maximum value of backward current velocity was determined on the basis of the calculated pressure distribution on waterway bed. Comparing the velocity value with the permissible one, preventing against scouring, one can assess whether ship motion is capable of disturbing the stability of waterway bed. The limit scouring velocity is the water velocity relative to waterway bed at which the loss of stability of waterway bed occurs (Tab. 1).

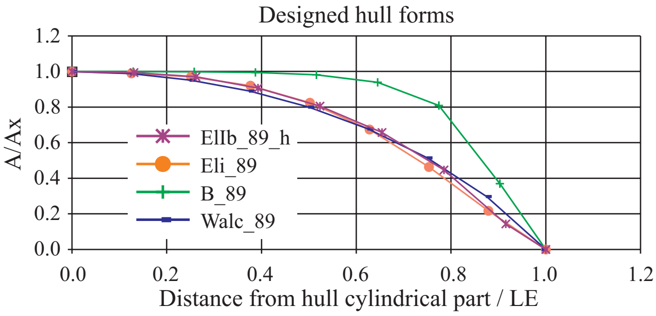

***Fig. 3.** Geometrical characteristics of the assumed barge bow forms .*

To take into account a kind of waterway is necessary when considering the backward current influence on waterway. Water velocity of the same value generates quantitatively different consequences for a canal, regulated and non-regulated river. Geological structure of waterway bed is an additional factor. On rivers where current velocity is present the influence depends on ship motion direction. If the natural phenomenon of rubble transportation occurs possible bed deformations may be leveled by the river rubble. Assessment of bed's stability consists, both in the case of river and canal, in comparing water velocities generated by ship motion with those permissible non-scouring for a given kind of bed soil. For cohesive soils it is recommended to assume the permissible velocities equal to 1,0 m/s. For loose soils this value amounts to 0,7 m/s.[1]. More accurate, but still rough values are shown in Tab. 1 [12].

***Tab. 1.** Rough values of limit scouring velocity .*

Kind of bed material	Grain size [mm]	Limit velocity V_d[m/s]
Fine sand	1-2	0.1-0.2
Coarse sand	2-7	0.2-0.3
Fine gravel	7-10	0.3-0.6
Shingle	10-20	0.6-0.7
Small stones	30	0.7-1.0
Small cobbles	100	1.5
Large cobbles	400	3.00
Boulders	700	4.00

In Fig.4 through 7 are presented example distributions of pressure exerted onto waterway bed in ship plane of symmetry. In very shallow water conditions (h/T = 1,17), a distinct influence of hull bow form can be observed. The B_89 form

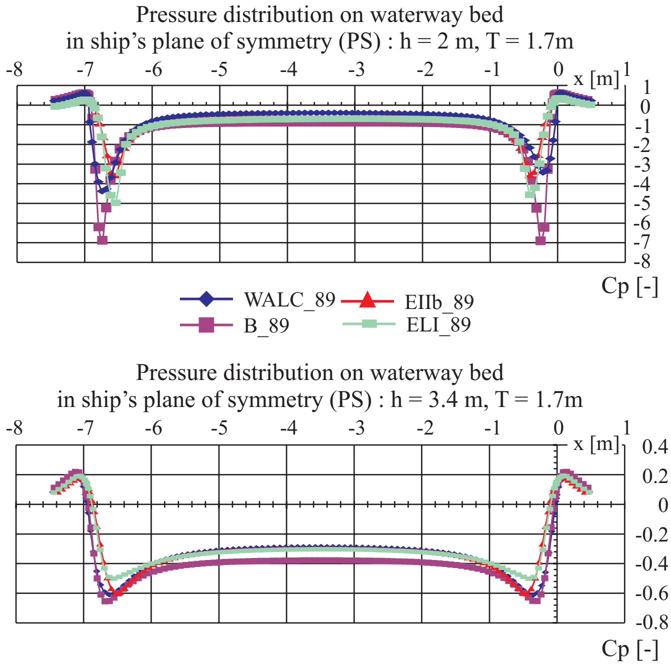

***Fig. 4.** Influence of hull form on pressure distribution on waterway bed .*

is the most unfavourable as regards quantity of the generated under-pressure on waterway bed. The form has the largest value of block coefficient of bow part of hull (Fig.3). As the water depth increases the influence of bow form distinctly decreases (Fig. 4 and 5).

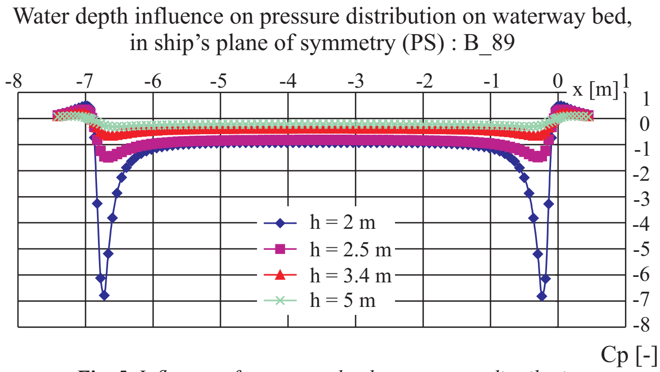

***Fig. 5.** Influence of waterway depth on pressure distribution on waterway bed .*

If a ship moves in a canal then - apart from different pressure distributions in bow and stern parts of hull- a distinct increase of under-pressure in midship area relative to the values which occur during ship motion in water of a limited depth only. Size of canal (at an assumed depth of it) in principle does not influence pressure distribution. However it can be stated that at an assumed cross-section area the rectangular canal is less favourable than that trapezoidal (Fig.6).

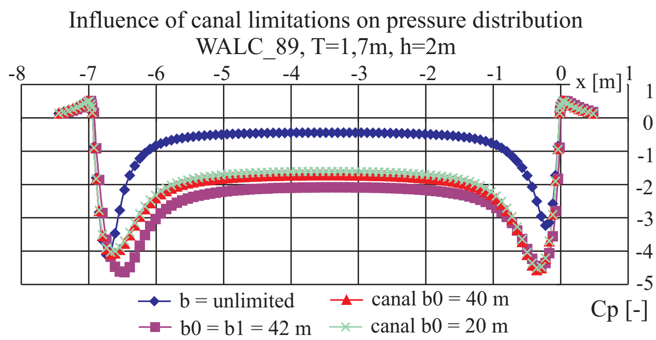

***Fig. 6.** Influence of canal limitations on pressure distribution on waterway bed, in ship's plane of symmetry .*

In Fig.7 the influence of bow part length on pressure distribution is presented for a elected bow form. The smallest under-pressure values were obtained for the shortest bow part (L_E = 4 m). In the case of the remaining analyzed lengths (L_E = 8 and 12 m) no significant differences have been observed.

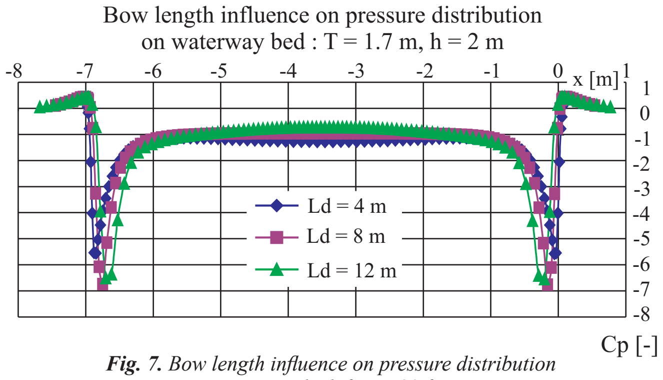

***Fig. 7.** Bow length influence on pressure distribution on waterway bed, for B_89 form .*

Fig. 8, 9, 10 and 11 presents the influence of waterway parameters and ship hull form on backward current velocity. Also, in each of the figures are presented mean values of backward current velocity as well as extreme ones determined on the basis of the maximum value of under-pressure on waterway bed. The differences can be observed especially in the case of small depths of waterway. For h/T = 1.176 the backward current velocity determined on the basis of mean velocity values, reaches from 8% to 15% of ship motion speed. The maximum backward current velocities near waterway bed, determined on the basis of pressure distribution, reach from 110% to 180% of ship motion speed. If to assume mean velocities to be a basis for analysis then the influence of hull form can be observed over the whole range of analyzed waterway depth values (Fig.8).

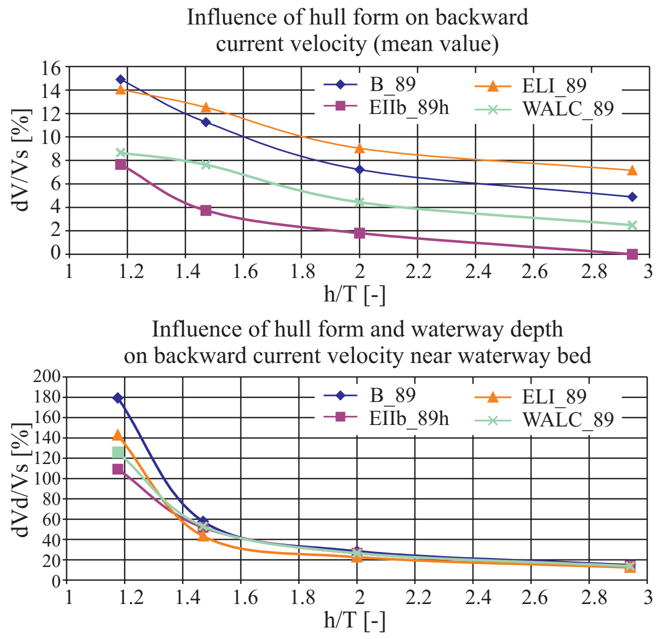

***Fig. 8.** Influence of hull form on backward current velocity .*

For water velocities near waterway bed the hull form influence is observed for the range of waterway depth from h/T = 1.176 to h/T = 2. Above the latter value the influence may be neglected. When taking into consideration the limit scouring velocities given in Tab. 1 it should be remembered that the scouring of waterway bed may occur if h/T < 2. In extreme conditions (for h/T = 1.176) the velocities near waterway bed significantly exceed their permissible values. E.g. already at ship motion speed of the order of 8 km/h (which is in principle the maximum available at that value of ship draught/water depth ratio), the backward current velocity can reach values from 2.44 m/s to 4 m/s which considerably exceed the limit ones shown in Tab.1. As results from Fig.8 for very shallow water conditions B_89 form is the least favourable, and EIIb_89 the most favourable. B_89 form is characteristic of the largest block coefficient of bow part and of a short undercut of bow in the plane of symmetry, as well as a large value of waterline entrance angle. An advantageous feature of the form in question is its simplicity and a large volume of bow part.

The bow length does not influence backward current velocity significantly. At the waterway depth h = 1.7m, (h/T = 1.176), the velocity near bed is contained in the range from 160% to 180% of ship motion speed (Fig.9). The obtained values correlate with the pressure distribution on waterway bed (Fig.7). This influence is not unambiguous. The problem should be analyzed in a greater detail. Waterway depth increasing makes backward current velocity decreasing, irrespective to bow part length. The same concerns also the backward current velocity determined by using mean velocity values. The calculation results presented in Fig.9, concern the B_89 form. In the case of the remaining forms in question similar changeability trends are observed.

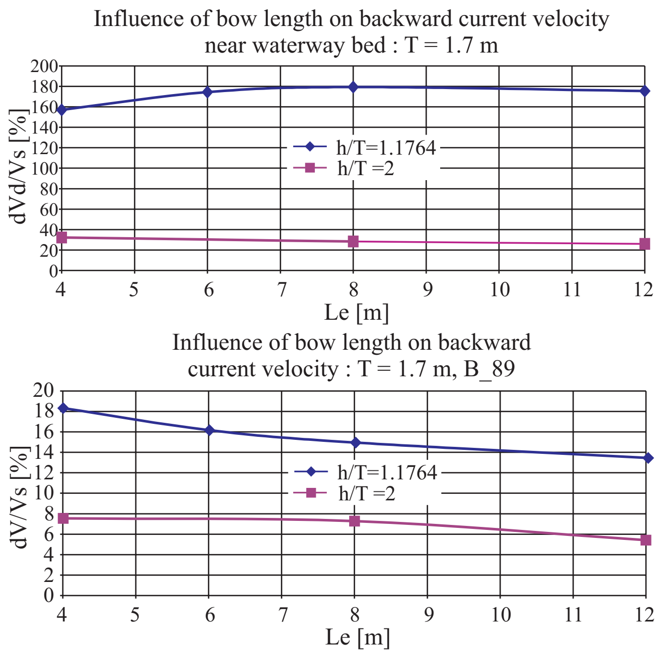

***Fig. 9.** Influence of bow length on backward current velocity, for B_89 form .*

In the case of ship motion in a canal, smaller values of backward current velocity are observed (at the same waterway depth). Its mean value for water of a limited depth only (in the whole range of analyzed depth values) is greater than that in the case of canal. A different character of changeability occurs in the case of the near-bed velocity. At the waterway depth h = 2.5 m no difference between the velocity in canal and shallow water is observed (Fig.10). The backward current velocity near waterway bed exceeds its permissible non-scouring values in a similar way as in the case of ship motion in shallow water. For the range of h/T ratio from 1.176 to 2, the velocity values varies within the range from 180% to about 30%.

In Fig.11 calculation results of backward current near waterway bed at canal slope, are presented. The results were obtained by using pressure distributions. Comparing the results with those presented in Fig.10 one can state that the velocities resulting from pressure distribution are of smaller values than those obtained on the basis of mean velocity values. Ship mo-

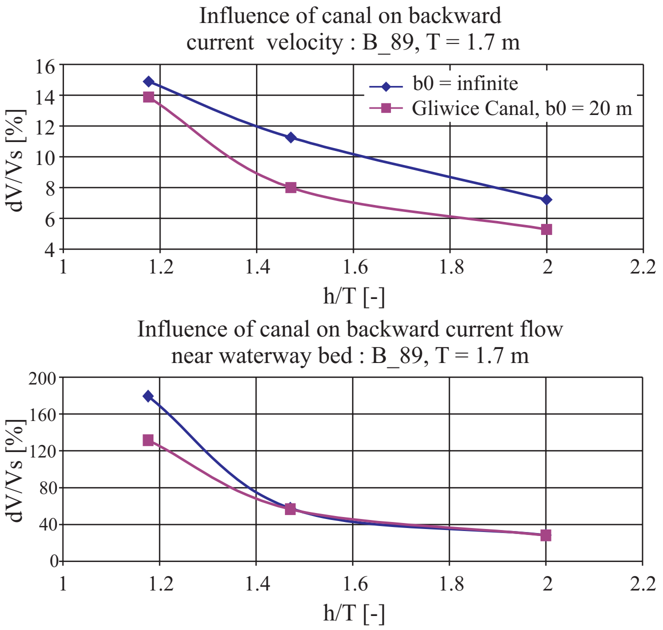

***Fig. 10.** Influence of canal on backward current velocity .*

tion influence on canal banks depends on bow form (WALC_89 bow form is more favourable than B_89 one). Also, a distinct influence of canal cross-section on backward current velocity near canal bank, appears. At the same water depth an increase of canal width leads to a significant decrease of backward current velocity. The backward current velocity itself is not a single cause of canal bank scouring. Some observations indicate that destructive action of ship motion on canal banks are mainly caused by waves generated by ship in motion.

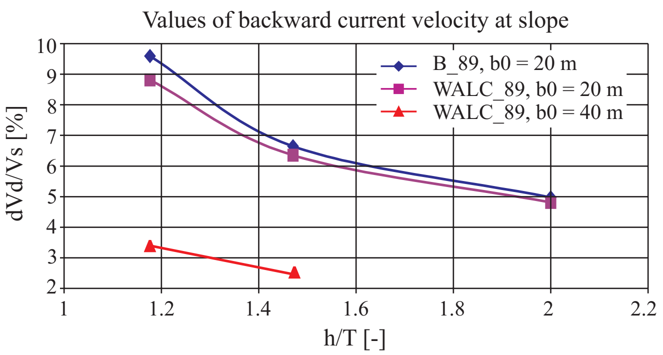

***Fig. 11.** Influence of canal cross-section on backward current velocity at canal slope .*

FINAL CONCLUSIONS

It has been shown that the HPSDK computing system can be used in preliminary analysis of influence of ship form on quantity of backward current. The bow form itself significantly contributes to the influence of ship motion on waterway. The block coefficient of bow part of hull is of a fundamental influence on values of backward current velocity. The greater value of the coefficient the greater velocity of backward current. Out of two limitations of waterway (i.e. its depth and width) the waterway depth is of significant importance. The influence of waterway depth and ship motion speed on backward current velocity is unambiguous. The decreasing of the depth and increasing of the speed constitute important factors which make backward current velocity increasing. The backward current near waterway bed may exceed the permissible non- scouring velocity values. In view of natural rubble transportation in rivers the backward current does not affect the waterway itself detrimentally. The natural rubble transportation affecting river bed is deemed to cause more significant changes in the bed than the ship motion itself. The factors which deteriorate the waterway to a larger extent are : the behind-the- propeller stream and ship-generated waves [1]. The deteriorating action of the first of them is manifested especially during ship manoeuvers when screw propellers operate under large loads. In practice, the limit ship motion speeds are determined by quantity of ship sagging and ship resistance to motion on limited waterway.

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