Influence of ship–generated waves on waterway

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ABSTRACT

Results are presented of calculations of ship – generated waves during its motion in canal. For the calculations FLUENT software was used. It was demonstrated that ship generates waves which, when approaching canal slopes, may constitute an important factor in deteriorating the banks, and that ship's wave resistance can be used as an assessment measure of influence of ship motion on waterway. The methods which are based on approximate formulae, are not reliable. The FLUENT software may be applied as a numerical towing tank.

Keywords : waterway, ship–generated waves, numerical calculations

INTRODUCTION

The wave system generated by ship in motion directly influences waterway banks. Analyzing the influence of the ship –generated waves on banks one should take into consideration the phenomenon of water level lowering which results from occurrence of backward current velocity. The two mutually interacting phenomena (i.e. ship–generated waves and water level lowering) produce alternately suction and impact pressure onto canal slope surface. The phenomena occur on the wetted zone of canal slope surface. Therefore the larger the zone the greater hazard of loss of stability of canal slope. A permissible ship speed in canal should be so determined as differences of water level in canal during ship motion not to exceed the slope strengthening zones. The differences can even reach the values of about 60 cm [1]. The deteriorating influence of ship waves on canal slope strengthened areas are observed especially where no maintenance work has been carried out. The photograph in Fig.1 shows the change of water level on Bydgoszcz Canal due to motion of an inspection ship. The observed failures of the canal slope are very distinct.

***Fig. 1.** Difference of water level on canal slope due to ship motion .*

Energy of the wave system action can be identified with the share of ship wave resistance in total ship resistance to motion. The analysis of results of model tests of inland navigation ships, presented in [4], showed that the share was contained within the range from 30 to 70% of the total ship resistance. The upper limit concerns very shallow water conditions (h/T = 1.25), the lower one concerns h/T = 3. The analysis was performed with the use of the method of splitting the total resistance into two components : friction resistance of an equivalent flat plate, and residuary(form) resistance. In doing it, was applied a form factor which takes into account an influence of ship hull form on quantity of viscosity resistance.

In this work an analysis of the share of wave resistance in total resistance was conducted by using the FLUENT software. Also, results of calculations of water level profile on canal slope are presented. The results make it possible to assess wave height on canal slope. The calculations were performed for one selected form of pushed barge only.

ASSUMPTIONS AND INPUT DATA FOR CALCULATIONS

The FLUENT software was verified by comparing the calculations of ship resistance and wave profile on ship side with model test results [4]. A suitable convergence of the calculation and model test results was obtained. An example comparison of the calculated ship-side wave profile and that obtained from model tests is presented in Fig.2.

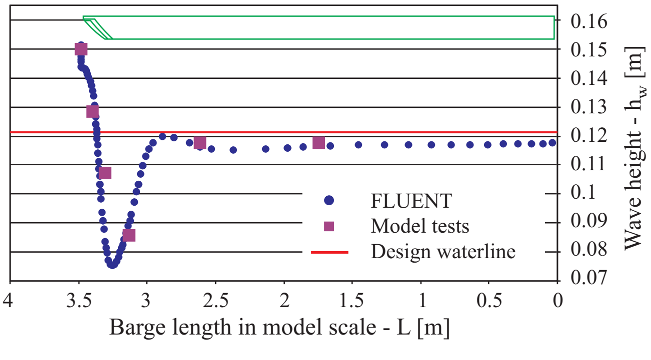


***Fig. 2.** Wave profile on side of SFKO barge,*
h = 5.0 m; T = 1.7m; Vs = 14 km/h .

The SFKO barge hull form was designed during realization of INBAT project financed within the frame of 5th EU Outline Program [3].

The calculations were performed for a two-barge one-row push-train (without pusher) satisfying hydro-technical conditions of Polish waterways. The following main particulars of a single pushed barge were assumed:

Total length : $L = 48.75$ m
Breadth : $B = 9.00$ m
Draught : $T = 1.70$ m
Bow length : $L_E = 8.00$ m.

The calculations were performed for sailing conditions in canal (limited width and depth). The following particulars of Gliwice Canal were taken into account :

Canal bed width $b_o = 20.00$ m
Canal slope ratio 1:3.

Water level width depends on water depth assumed for calculations. Two depth values were assumed : 2.0 and 3.4 m; hence the corresponding width values are : $b_1 = 32.0$ m and 40.4 m. The calculations were conducted in the model-scale $\alpha = 14$. To determine influence of limited waterway width the calculations were performed [also] for unlimited width conditions. The barge's hull form is presented in Fig.3.

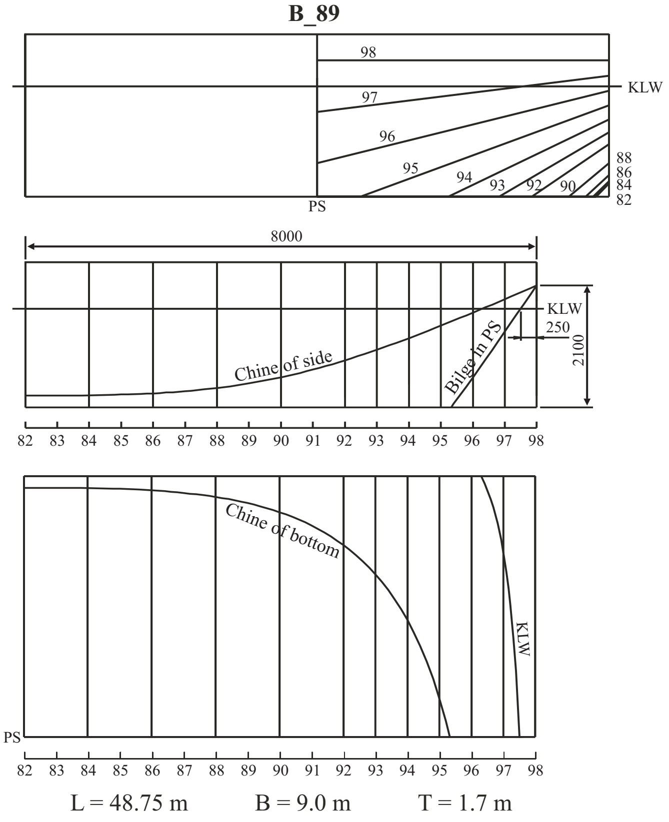


Fig. 3. *Hull bow form of the considered pushed barge .*

The mesh for modelling the flow around the hull was built by means of GAMBIT program. It was based on the barge body lines generated by SIATKA program in **igs** format. On the so prepared hull form consisted of buttock and frame lines a 3D computation domain was imposed (water plane, basin's bed and slopes, plane of symmetry). The *hexa* elements were applied in order to precisely model water boundary layer with the use of relatively small number of mesh nodes. Since the calculations were carried out either with or without taking into account free water surface the computation domain containing basic flat water surface was prepared. Such approach has two important advantages : the basic water plane is smooth which means that mesh nodes belong to it, and the computation domain for water flow without taking into account free surface can be prepared very easily (it is sufficient to remove mesh containing volumes over the basic water surface). It makes it possible to calculate water flow around the hull both with and without taking into account free water surface, by using the identical mesh, which, in the case of comparing the results of calculations, eliminates errors resulting from building the numerical mesh. The calculations were carried out both under the assumption of unlimited width of waterway and canal conditions. For example, the mesh for calculations in canal conditions comprised about 250000 elements. In Fig.4 the computation mesh of hull bow part is presented.

The calculations were conducted for a reverse flow model, i.e. the ship was not in motion but the basin was moving together with the water inside. Due to such way of modelling, values of ship motion speed were set on basin's bed and sides, and on water surface. The RNG $k - \varepsilon$ turbulence model of two equations was applied. 4% turbulence intensity was assumed. On all non-viscous partitions (ship hull, canal sides and bed), the mesh was so arranged as to maintain the parameter $y+$ which determines whether the first layer of mesh elements at a partition contains a laminar sub-layer of turbulent layer. This is Reynolds number relative to thickness of the laminar sub-layer. Value of the parameter should be contained within the range: $30 \leq y+ \leq 300$. The calculations of water flow around the hull with taking into account free water surface were conducted with the use the *Volume-Of -Fluid* multi-phase model (for non-mixing fluids, e.g. flows having free surface). The calculations were carried out with the time-step of 0.01s, and terminated when total resistance force value become stable.

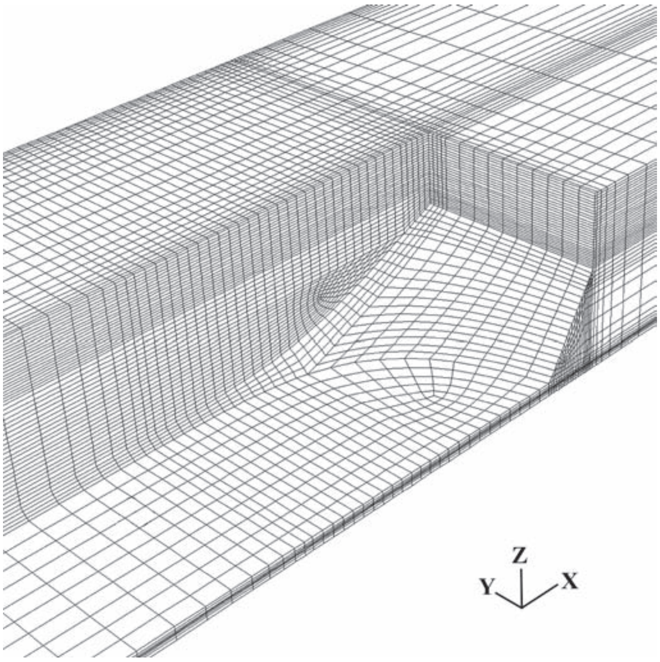


Fig. 4. *The example computation mesh of B_89 hull bow form .*

In Tab. 1 the results of the resistance calculations for the assumed barge hull form are presented for normal and tangential resistance components, separately. They were carried out with taking into account influence of free water surface. Hence, the normal resistance constitutes a sum of pressure resistance and wave resistance. The tangential resistance can be identified with viscosity resistance. The calculation results are presented in model-scale. A significant share of the normal resistance component in the total resistance can be observed. The resistance component decisively influences resistance increase due to water depth decrease in canal. In the case of shallow water of unlimited width the water depth influence on quantity of the resistance component is much less important.

It results from that inland waterways ships operate
at small Froude numbers.

Tab. 1. *Influence of waterway parameters on resistance of ship to motion.* ***For B_89 hull form*** *.*

Waterway		**Canal**		**Unlimited width**	
Water depth h [m]	Ship speed V [m/s]	Viscosity resistance [N]	Normal resistance [N]	Viscosity resistance [N]	Normal resistance [N]
0.1428	0.45	2.25	9.91	0.97	2.05
	0.6628	4.42	27.53	1.95	4.82
0.2428	0.6628	3.41	7.98	2.19	4.04

PARAMETERS OF THE WAVE AT CANAL BANK

In the literature sources [1,2] some approximate methods for determining the wave height close to canal bank, can be found. The height is dependent on ship motion speed and dimensions of canal and ship. Gucma proposed the following formula for calculation of wave height close to canal slopes:

$$h_{W\max} = CV^{3.5} \tag{1}$$

where :

$$C = 0.6\,e^{2.8\left(\frac{h}{b_r}\right)}\,k\,(0.1t{\cdot}g{\cdot}h)^{-0.75}$$

$$t = \frac{(1-a)^2}{1-(1-a^2)}$$

$$a = 0.114\,\frac{b_r}{B} + 0.715 \quad \text{for : } \; b_r/B \geq 2.5$$

$$a = 1.0 \quad \text{for : } \; b_r/B < 2.5$$

$$b_r = \frac{b_0 + b_1}{2}$$

$$k = f(F/A_M)$$

A_M – midship section area [m^2]
b_0 – canal width at bed [m]
b_1 – canal width at water level [m]
B – ship breadth[m]
F – cross-section area of canal [m^2]
g – gravity acceleration [m/s^2]
h – water depth in canal [m].
V – ship motion speed [m/s]

Basing on the data contained in [2], one can determine a value of the coefficient k from the formula :

$$k = 0.237\left(\frac{F}{A_M}\right)^{-0.9419} \tag{2}$$

Applying the formula (1) to the parameters of Gliwice Canal one obtains rather unreliable results. For the different water depths the constant C obtains its respective values as follows :

h = 2 m, C = 4.0967 ; h = 3.4 m, C = 0.52706
which yields unrealistic values
of the wave height at canal slope.

In the source [1] the wave height at canal slope is dependent on ship length and canal water-level width only. In real conditions the wave height also depends on ship motion speed.

The example results of the calculations by using FLUENT software are presented in Fig.5 (for h = 2 m) and Fig. 6 (for h = 3.4m). In the case of shallow water canal the calculations were performed for two ship motion speed : V = 0.45 m/s equivalent to 0.38V_{kr} , and V = 0.6628 m/s equivalent to 0.56 V_{kr} . At the speed V = 0.6628 m/s a contact of the ship bottom with waterway bed is highly probable. For the canal depth h = 3.4 m the speed V = 0.6628 is equivalent to 0.43 V_{kr}. Basing on the calculation results of the wave profile on canal slope, shown in Fig.5 and 6. one determined maximum differences between wave crest and trough. It was assumed that values of the wave height h_w were determined by the differences. On conversion to real-scale the values are as follows :

h = 2 m, V = 1.6837 m/s, h_w = 0.4088 m
(0.0392 m in model-scale)

V = 2.48 m/s, h_w = 1.1634 m
(0.0831 m in model-scale)

h = 3.4 m, V = 2.48 m/s, h_w = 0.35 m
(0.025 m in model-scale)

The above presented example results of the calculations indicate that the speed V = 2.48 m/s, for the ship of the draught T = 1.7 m, moving in the canal of the depth h = 2 m, is not permissible. At this speed the generated wave causes a change of water level on the slope. The difference of water levels exceeds the strengthened zone of canal slope. Energy of the ship-generated wave system is a measure of ship wave resistance. If viscosity influence and kinetic energy of motion of fluid particles are neglected the energy is proportional only to the square of wave amplitude :

$$E_c = \frac{\rho g}{2}\left(\frac{h_w}{2}\right)^2 \tag{3}$$

where :

E_c – wave system energy
h_w – wave height [m]
ρ – fluid density [kg/m^3].

Under the assumption that across the whole width of water level the wave is of the same height as that on the canal slope, the wave resistance can be determined from the relationship :

$$R_W = E_c b_1 = \frac{\rho g}{2}\left(\frac{h_w}{2}\right)^2 b_1 \tag{4}$$

The wave resistance in model-scale – after taking into account the formula (4), as well as the heights of the wave systems generated by a ship moving in canal – amounts to :

For h = 0.1428 m, and V = 0.45 m/s : $\mathbf{R_w}$ = 2.3897 N

V = 0.6628 m/s : $\mathbf{R_w}$ = 8.4680 N

For h = 0.2428 m, and V = 0.6628 m/s : $\mathbf{R_w}$ = 2.2116 N.

Normal resistance can be determined under the assumption that the free water surface is not deformed. If to compare the so calculated resistance with the results of the calculations where the free water surface has been taken into account then the difference can be considered to be the wave resistance. At the known wave resistance, and making use of the formula (4), one can preliminarily calculate the approximate wave height in canal. For B_89 hull form, the normal resistance without taking into account free water surface in canal of the depth h = 0.1428 m (in model-scale) for the ship speed V = 0.45 m/s, amounts to R_P = 7.46 N; and for the speed V = 0.6628 m/s – R_P = 15.78 N. By taking into account the pressure resistance values contained in Tab. 1. the wave resistance amounts respectively to : 2.45 N for V = 0.45 m/s, and 11.75 N for the greater speed. The values are close to those obtained by using the formula (4), and this way the wave heights on the canal slope for the values of wave resistance, are known.

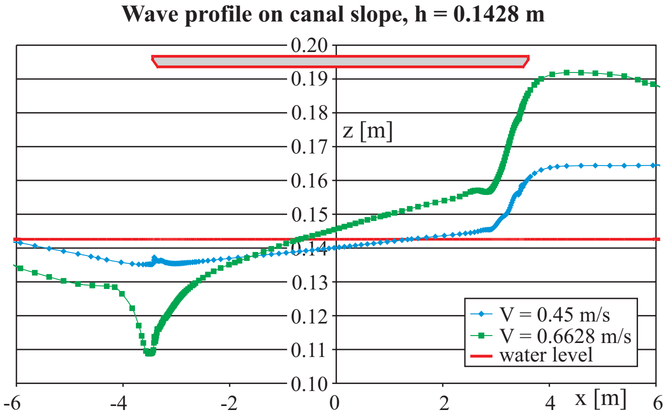


Fig. 5. *Wave profile on canal slope.*
Canal depth h = 0.1428 m. Model-scale applied .

Additionally, in Fig.7 is presented the wave profile on ship side for canal and unlimited water width conditions. The profile is different than that on canal slope (Fig.4). An influence of limited canal width can be observed, especially in the bow region. During ship motion in canal a much higher bow wave is generated. In practice it may be manifested in the form of a greater value of trim by stern.

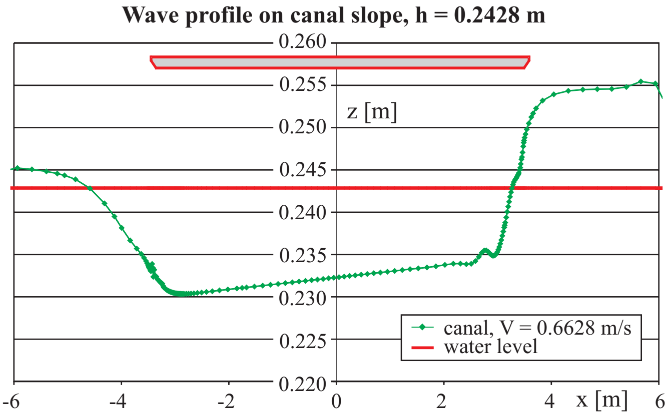
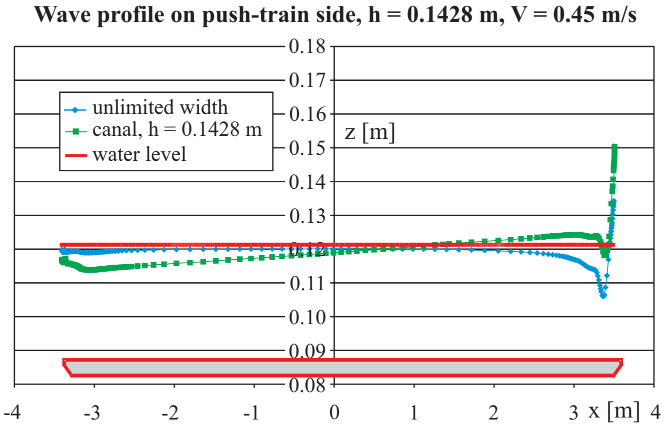


Fig. 6. *Wave profile on canal slope. For h = 0.2428m. Model-scale applied .*
Fig. 7. *Influence of canal on wave profile on ship side. Model-scale applied .*



FINAL CONCLUSIONS

The FLUENT software can be used for analyzing and describing the phenomena which occur during ship motion on limited waterway. Calculation results of shape of free water surface show a suitable quantitative conformity with those from model tests, as well as with observations in real conditions. A disadvantage of application of the FLUENT software to calculations of ship motion with free water surface taken into account is a long calculating time. It was demonstrated that ship wave resistance may be useful in preliminary analysis of wave height on waterway slope. The ship-generated waves constitute the main factor which detrimentally affects stability of waterway banks. The ship-generated under-pressure occurring on waterway bed, the influence of behind-the-propeller stream (race) in normal service conditions are of a lower importance. Natural transportation of river bed rubble is deemed to cause larger changes in the bed than those due to ship motion itself.

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NOMENCLATURE

A_M – midship section area [m^2]
B – ship breadth [m]
b_0 – canal width at its bed [m]
b_1 – canal width at water level [m]
E_c – wave system energy
F – canal cross-section area [m^2]
g – gravity acceleration [m/s^2]
h – canal depth [m]
h_w – wave height [m]
INBAT – Innovative barge trains for effective transport on shallow water
KLW – design waterline
PS – plane of symmetry
R_p – normal resistance [N]
R_w – wave resistance [N]
T – draught [m]
V – ship motion speed [m/s]
V_{kr} – critical speed [m/s]
ρ – fluid density [kg/m^3]

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Photo : Arkadiusz Łabuć