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Analysis of Squat Effect in Shallow River for Inland Ferry

J. Jachowski & M. Schoeneich
Gdynia Maritime University, Gdynia, Poland

ABSTRACT: The squat determination during ships movement on restricted water areas is one of the most important problems affecting navigational safety. Precise squat prediction is essential to minimize the risk of grounding for ships. In Poland we have about 60 operated ferry crossing, part of them are base of transport infrastructure. The Lower Vistula River in Poland is a clear example of a shallow river. Zones of active sediment transport of sandy material are big problem in navigation conditions maintenance on this river. The paper presents an analysis of squat phenomena of ferry “Flisak” by empirical method and fluid dynamic in different conditions. The results of this research could be helpful for inland transport management, risk assessment of ferry crossing the Vistula River, and analysis for a new waterway project.

1 INTRODUCTION

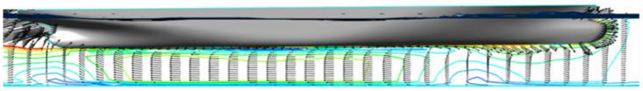
Limitations of shallow water areas relate to seaside and canal effects and refer to the vertical and horizontal plane of the waterway. The dimensions of the hydrotechnical infrastructure in the rivers and canals determine the maximum length, width, and draught of inland waterway vessels [1,2,3]. These values are implemented in local laws. A safe under-keel clearance (UKC) is required to ensure adequate manoeuvrability, sufficient stopping distance and space for sedimentation, suitable accounting of errors in bathymetry, economical fuel consumption, protection of the ship's hull and also waterway and environment, and adequate accounting of vessel pitch, roll and squat so that the vessel does not strike the waterway bottom[4].

Ferry crossing were operated from time immemorial, enabled people transport cross the rivers and lakes. One of the most important problems on restricted areas including shallow rivers is to determine hydrodynamic forces acting on moving ship’s hull on restricted water areas. The hydrodynamic behaviour of a vessel changes when sailing in shallow or confined water. The restricted space underneath and alongside a vessel has a noticeable influence on both the sinkage and trim of a vessel, also known as squat[5]. Ship squat is the reduction in UKC that happens when a vessel moves forward, caused by changes in pressure and flow of water beneath the hull. So, prediction of squat depends on the following parameters [6,5,1]:

- ship’s speed
- ship position (proximity to channel bank)
- ship geometry (length, beam, draft, shape, etc.)
- type of water area (the underwater cross-section area of ship, the cross-section area of the canal or river).

The water depth (H) and the mean draught (T) of the static ship are broadly used as the parameters to characterize shallow water. Figure 1 presents the squat phenomenon in restricted waters, caused by the acceleration of flow between the ship's hull and the bottom.

A)



B)

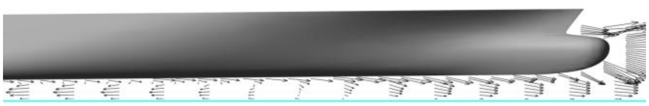


Figure 1. Squat phenomena on restricted water depending on depth and draught A) H/T=2,5; B) H/T=,5

An area of particular concern is the prediction of ship squat in shallow or restricted waters at different speeds. Squat may cause grounding of the ship which result in severe damage to the ship, and consequently higher repair bills and off hire losses. In shallow water, the effect of squat is much greater because the water has less space to move around the hull, forcing it to accelerate even more [5]. Ferry "Flisak" crossing was opened in 2023 and less than a year of operation was closed and cruises have been suspended, so research were conducted for precise determination of squat, which could be helpful for possibility of ferry operational.

2 STUDY AREA

The aim of this work is squat assessment of ferry at 763,56 km on Vistula River. "Flisak" is newly built ferry (2023) which operates between Solec Kujawski and Czarnowo, but it has problem with good functioning. About 90% of river ferries have parameters similar to length 12 m, breadth 5 m and engine power about 50-150 kW. Figure 2 presents new buildings of infrastructure and a river.

Figure 2. "Flisak" ferry during crossing Vistula river [7]

An analysed ferry is bigger than typical values. Figure 3 presented schedule of "Flisak" ferry and his main parameters.

L	24 [m]
B	11 [m]
T	0,7 [m]
D	157 [m³]
Cb	0,86
Vs	13 [km/h]
Vs	3,61 [m/s]
Engine: 89-120 kW	

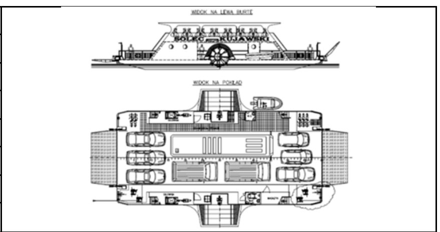


Figure 3. Main parameters and schedule of "Flisak" ferry [8]

The hydrological conditions in the Vistula basin display a high seasonal variation, with a tendency to occur in extremely high-water stages and long periods of low water levels. The breadth of the shipping lane equates to 320-420 m and has curved stretches, with the radii equating to 250-300 m. For safety navigation ferry level on gauging station should be between 175 – 375 cm but for carrying cars water level should be on 200 cm level on the other hand the big problem for navigation conditions are sandbars. In research the own data from depth measurements Vistula River in cross-sections and in the longitudinal profile of the shipping lane were used for determination of mean actual depth in given sections. Figure 4 presents cross profiles in reviewed area.

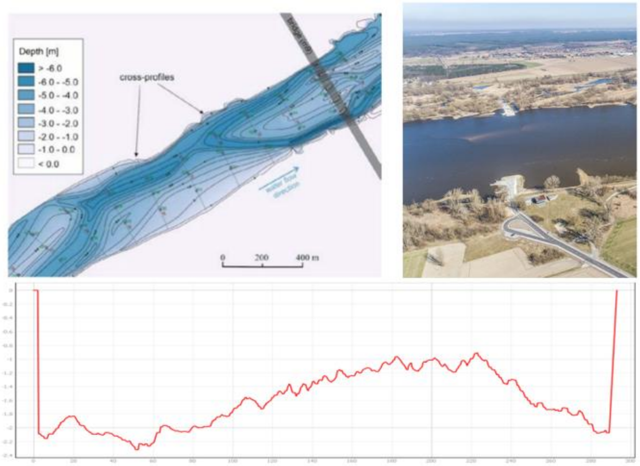


Figure 4. Example of longitudinal profile at cross section Vistula River, taking into account route of the ferry [7]

3 SQUAT ANALYSIS

In research the own data from depth measurements Vistula River in cross-sections and in the longitudinal profile of the shipping lane were used for determination of mean actual depth in given sections, next step the values for squat were calculated. Ship squat can be calculated by various strategies such as analytical method [9], numerical and experimental methods [10,11].

3.1 *Empirical methods*

Many scientific centres specializing in hydrodynamics and ship theory conduct research on ship squat. As a result of these studies, numerous methods have been developed for determining the ship's squat under way. On the other hand, each study leads to the formulation of empirical equations, the use of which allows the calculation of squat values under various conditions. Several empirical formulae have been developed for estimating maximum ship squats, most of them based on statistical analysis of experimental data. The following methods were used in the research [1,5,6]:

Tuck: $S = C_z \frac{\nabla}{L_{pp}^2} \frac{F_{nh}^2}{\sqrt{1-F_{nh}^2}}$

Huuska: $S = C_z \frac{\nabla}{L_{pp}^2} \frac{F_{nh}^2}{\sqrt{1-F_{nh}^2}} K_s$

Millward 2: $S = \left(61,7 C_b \frac{T}{L_{pp}} - 0,6\right) \frac{F_{nh}^2}{\sqrt{1-F_{nh}^2}} \frac{L_{pp}}{100}$

Turner: $S = C_b \frac{v^2}{100} \frac{T}{h}$

Barras 1: $S = 3,75 C_b S_2^{\frac{3}{4}} \left(\frac{v_s}{v_e}\right)^{\frac{1}{2}} \frac{v_s^2}{2g}$

Barras 2: $S = \frac{C_b S_2^{\frac{2}{3}} v^{2,08}}{30}$

Barras 3: $S = C_b \frac{v^2}{100}$

Simard: $S = \frac{v_s^2}{2g}\left[\left(\frac{1,01}{1-S}\right)^2 - 0,80\right]$

Eryuzlu: $S = 0,298 \frac{h^2}{T}\left(\frac{v_s}{\sqrt{gT}}\right)^{2,298}\left(\frac{h}{T}\right)^{-2,972} K_b$

Yoshimura 2: $S = \left[\left(0,7 + 1,5\frac{1}{\frac{h}{T}}\right)\left(\frac{C_B}{\frac{L_{pp}}{B}}\right) + 15\frac{1}{\frac{h}{T}}\left(\frac{C_B}{\frac{L_{pp}}{B}}\right)^3\right]\frac{V_e^2}{g}$

Norbin: $S = \frac{C_B v}{15\left(\frac{L}{B}\frac{h}{T}\right)}$

where:
S – squat,
C_z – squat factor,
∇ – displacement [m³],
L_{pp} – lenght between perpendiculars [m],
T – draught [m],
F_{nh} – Froude number: $F_{nh} = \frac{v_s}{\sqrt{gh}}$
h – depth [m],
v – vessel speed [kn],
v_s – vessel speed [m/s],
v_e – vessel speed of exploatation [m/s],
g – acceleration due to gravity [m/s²],
K_s – correction factor for channel width:

$$K_s = \begin{cases} 7,45 s_1 + 0,76 & \text{for } S_1 > 0,03 \\ 1 & S_1 \le 0,03 \end{cases}$$

S_1 – corrected blockage factor,
S_2 – velocity return factor,

$$S_1 = \frac{\frac{A_s}{A_w}}{K_1}$$

$$S_2 = \frac{A_s}{A_w - A_s}$$

A_s – ship's underwater amidships cross section [m²],
A_w – net cross section area of waterway [m²],
K_1 – correction factor on blockage (Huuska),
K_b – correction factor for channel:

$$K_b = \begin{cases} \frac{3,1}{\sqrt{\frac{D}{B}}} & \text{if } \frac{D}{B} < 9,61 \\ 1 & \frac{D}{B} \ge 9,61 \end{cases}$$

D – distance between ship hull and toe of the bank,
B – ship's beam.

The results obtained using these formulae should be regarded as approximate, as they are limited and valid only for selected conditions [1].

3.2 *Numerical approach*

Carrying out of numerical simulations requires appropriate preparation of the ship hull and water area geometry. For the simulations, the shape of the "Flisak" ferry model was used. Based on the geometry of the ship model, hydrostatic data were determined, and subsequently, the mass and coordinates of the center of gravity were calculated and implemented in the numerical simulation. The moments of inertia of the hull were estimated using the results obtained from the RhinoCeros software, assuming an exemplary distribution of cargo weight on the ferry.

The CFD technique requires the modeling of a space surrounding the ferry divided into cells. The Reynolds-averaged Navier–Stokes (RANS) equations applied give the approximate time-averaged solutions in each cell. The CFD software utilized in the presented research was Flow3D, which code is based on the finite volume method (FVM) and uses the volume of fluid (VOF) method for the free surface problems solutions [12].

The simulations were performed using the overlapping mesh technique. The assumption of this approach is that one of the meshes is stationary in the whole computational domain, related to the global reference system. The high accuracy of computation is achieved by solving the governing equations in the 'free surface' cells (the cells partly filled with liquid). The simulations of turbulent flows were based on the Large Eddy Simulation (LES) turbulence model was applied. The practical application of the Flow3D software is based on the consecutive steps performance (creation 3D geometry, importing geometry and numerical mesh creation, setting Solver options, calculations and results).

The assumptions accepted in CFD modelling of the ferry movement are as follows:
– 3-dimensional flow simulations are used,
– simulations are performed in full scale,

– calculations are based on model 6DOf for ferry over variable bottom profile,
– simulations are performed using overlapping meshes, enabling ferry pitch and roll motions, draught,
– simulations are performed using overlapping meshes, enabling ferry roll, pitch and vertical (Z) motions – three degrees of freedom,
– the LES (Large Eddy Simulation) turbulence model was applied,
– the VOF method was applied for the free surface problems.

The CFD technique was verified in [13], which showed that the CFD method could be used in the future for squat determination and practical applications. Figure 5 shows the computational domain and the applied boundary conditions for "Flisak" squat simulation.

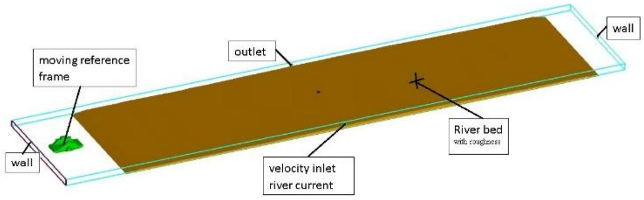


Figure 5. The computational domain of ferry crossing Vistula river

The computational mesh used in Flow3D consisted of approximately 5 million finite volume cells (FV). A high-resolution 3D block with refined cell size was placed around the ferry hull to accurately capture flow gradients and free surface effects, while it was surrounded by a coarser shallow-water block to optimize computational efficiency – Fig.6.

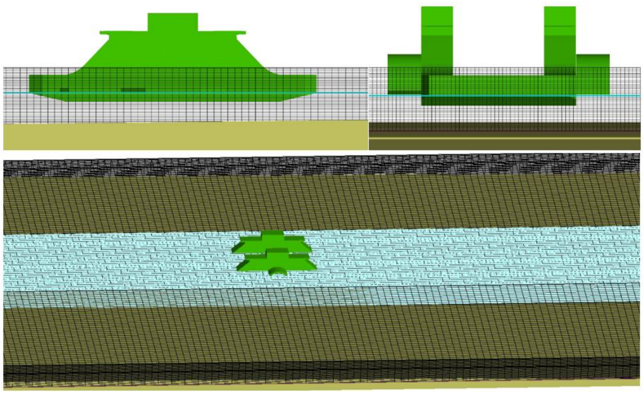


Figure 6. Structural mesh applied for ferry squat simulation

4 RESULTS

The analysed case concerns the squat phenomenon at a small under-keel clearance, with a depth-to-draught ratio (h/T) of 1,26. At such a small clearance, the boundary layer effects from both the riverbed and the ship's hull significantly influence the squat results. Figure 6 presents the results of bow and stern squat, as well as the port and starboard side sinkage at midship for the "Flisak" ferry. On the other hand non typical is navigation crossed the river so simulations checked the influence of river current additionally.

The simulations were carried out both without river current and with a river current of 1 m/s. For the case including the river current, the ferry was assumed to move at an angle to the ground track, resulting from the combination of the vessel's velocity vector and the transverse current vector. Based on the simulations, a heel of the ferry due to the river current is clearly visible. In addition, simulations were conducted to assess the influence of the river current on the squat behaviour. The results are shown in Figure 7.

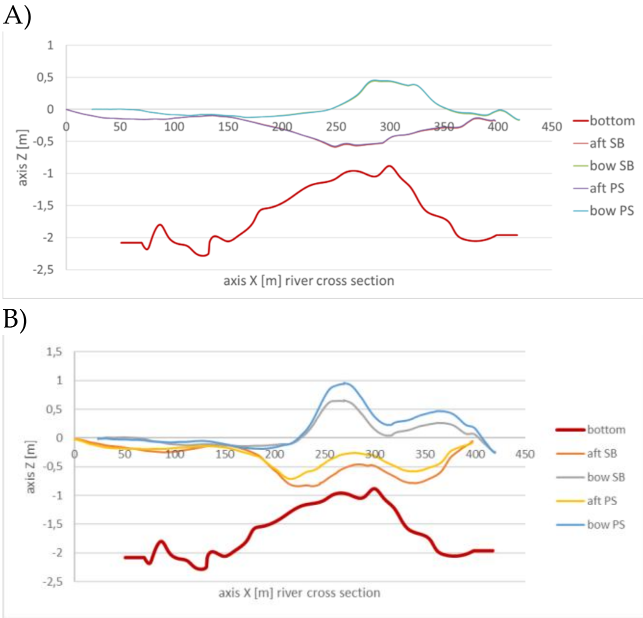


Figure 7. Results of the squat changes for the Flisak ferry during river crossing at a speed of 3 m/s – CFD simulation results. A) without current B) with 1 m/s river current (SB-starboard PS-port side)

The wave pattern generated during the squat phenomenon can be visualized with Flow 3D. The red area indicates the elevation of the bow wave, whereas the blue area shows the water surface depression at the stern. Figure 8 shows an example of the wave pattern generated by the ferry moving at a speed of 3 m/s on the river surface.

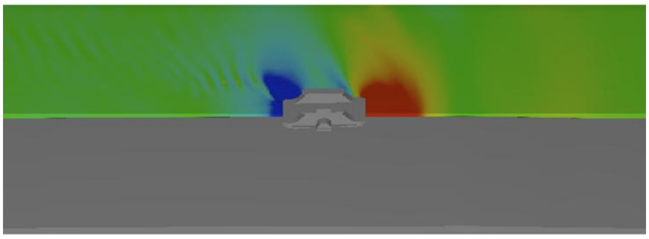


Figure 8. Example of the wave pattern generated by the ferry moving at 3 m/s on the river surface

The results of the numerical and empirical analyses are presented and next compared the squat values obtained from CFD simulations with those calculated using selected empirical methods (Figure 9). The comparison allows for the evaluation of the accuracy and applicability of these methods under shallow water conditions of the Vistula River.

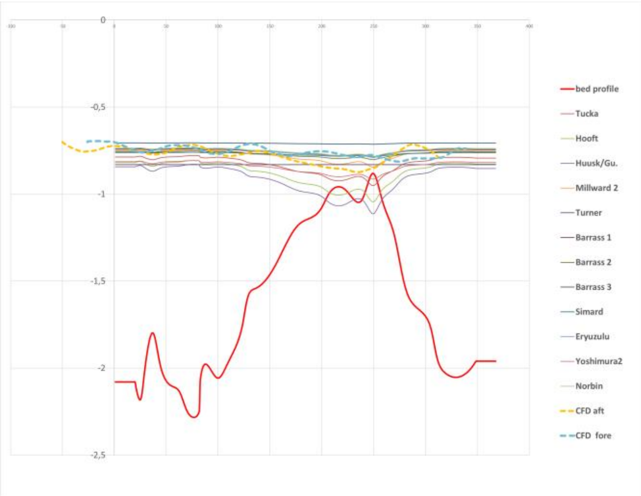
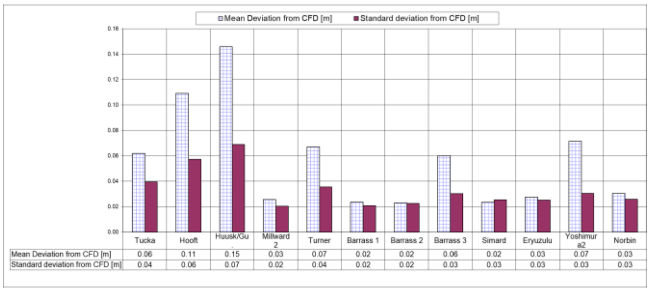


Figure 9. Comparison of squat values for the Flisak ferry over an irregular riverbed calculated using CFD and 12 approximate empirical methods for a ferry speed of 3 m/s.

It should be noted that most empirical squat prediction methods show variability of results, as they are generally formulated for larger under-keel clearances and do not account for river currents. Selected methods indicate a probability of grounding, however the CFD simulation results do not confirm this.

Based on the data comparison (Fig. 9), the mean deviation and standard deviation of squat values relative to CFD results are presented in Figure 10.



	Tucka	Hooft	Huusk/Gu.	Millward 2	Turner	Barrass 1	Barrass 2	Barrass 3	Simard	Eryuzulu	Yoshimura2	Norbin
Mean Deviation from CFD [m]	0.06	0.11	0.15	0.03	0.07	0.02	0.02	0.06	0.02	0.03	0.07	0.03
Standard deviation from CFD [m]	0.04	0.06	0.07	0.02	0.04	0.02	0.02	0.03	0.03	0.03	0.03	0.03

Figure 10. Comparison of mean deviation and standard deviation of squat values obtained from 12 approximate empirical methods relative to CFD results.

Analysing the results presented in Figures 9 and 10, it can be concluded that at small under-keel clearances (UKC) — for example, when h/T ≈ 1,3 — the difference in squat estimation as a component of the safe under-keel clearance becomes more significant. Differences of results between empirical methods become significant when navigation takes place in shallow waters with irregular bottom geometry, such as the Vistula River.

5 CONCLUSIONS

Newly built ferry "Flisak" which operates on Vistula river from the last year can't operate in navigational season due to hydrologic situation and sandbars. The study aimed to compare empirical methods with CFD results. The CFD technique shows higher value of squat with river current. The results indicate that the squat accounting for the river current increased by nearly 30% in the section with the minimum depth. The study showed that the lowest coefficient of variation was obtained using the Yoshimura 2 method, while the highest was observed for the Barras 2 method. The wave pattern formed during the ferry's movement is responsible for the squat effect, which is more significant at the stern. This comparison allows for an evaluation of the methods' accuracy and applicability in the shallow water of the Vistula River. Results of this analysis can be used for further research connected with minimal safety depth determination and risk analysis in reviewed area. The research results provide the foundation for further potential analysis of Lower Vistula transport possibilities.

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