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PRESENTATION OF THE SHIP SQUAT EFFECT AS A FUNCTION

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ABSTRACT

In this article the authors propose a change in approach when providing information included in maneuvering documents on the squat effect of a ship. The development of ships which is aimed at increasing the loading capacity contributes to the increase of their draft and construction dimensions. This fact renders it necessary to develop ports and to interfere in the bathymetric layer of the basin, i.e. its deepening. However, the under keel clearance along the ship's route and during the port towing maneuvers is often significantly limited. This makes it crucial to adapt the speed to the sailing conditions. Knowledge of the draft change with a low water level under the keel is important for the safety of navigation. Hence, the authors proposed expanding the maneuvering information contained in the ship's documentation with the additional curve of squat effect presented in the form of polynomial functions.

Keywords - under keel clearance, squat, shallow water

1. INTRODUCTION

Each vessel in motion causes disruption of the balance of the body of water causing wave movement around itself and the creation of a pressure field along the ship's hull. A noticeable effect of generating pressure along the ship's hull in motion is the increased water level at the bow and stern area and reduced in the midship area. The effect of the created pressure field is the creation of phenomena that are particularly visible in restricted waters. The most important phenomena occurring in restricted waters are the deterioration of maneuvering properties, decrease in speed and vessel squat. Vessel squat is a dynamic phenomenon that causes changes in draught and trim of the ship in motion. This is caused by a change in the water pressure distribution around the submerged part of the hull by increasing the speed of liquid flowing around the hull in its more complete part [1-3]. This causes a real change in the ship's draught (suction to the bottom). During the ship's movement, the hull's position changes in the vertical axis y (sinkage) and x (running trim) [4]. Knowing the amount of the squat and other corrections of static nature, we can calculate the actual water supply under the keel. There are two main types of shallow water bodies: shallow water and channel. Shallow water is an area unlimited in width and limited in depth. A clear effect on the change in the ship's draught and maneuverability can be observed when the ratio of the depth of the water (h) to the draught (T) is h / T = 1.5. [5]. The channel is a body of water limited in width and depth. The behavior of vessels in a body of water limited in depth and width significantly differs from the behavior of a ship in shallow water [6].

As required by the STCW Convention, every navigator must know and understand the concept of vessel squat. One of the elements of the handing over watch duties is to provide information on the extent of the squat [7]. Therefore, assessing the amount of squat of a ship in motion and predicting the amount of water under the keel is one of the main activities when navigating in coastal waters. In this article, the authors propose changes in the ship's maneuvering documentation by implementing a squat curve sheet and a set of squat features of the ship thanks to which the navigator can determine its value for a given amount of water under the keel and, within certain limits, interpolate intermediate values for the UKC sought. This chart is invaluable help in navigation conditions in restricted waters. This is especially true of shallow waters, where the water supply under the keel is on the border of navigation safety. These charts can also be made for unusual operating conditions of the ship (for a given loading condition).

2. THEORETICAL BASIS FOR DETERMINING THE SQUAT OF SHIP'S HULL

2.1. IMO REQUIREMENTS REGARDING DOCUMENTATION INFORMING ABOUT THE EFFECT OF HULL SQUAT

Pursuant to IMO Resolution A.601, the officer on the watch must have access to the vessel's detailed maneuvering data. There are three types of convention maneuvering documents:

a. Pilot card - is an abridged maneuvering document of the ship which does not contain any data on the effect of the hull squat down despite the fact that the vessel entering the port moves at speeds oscillating within 5-6 knots. For these speeds there is the effect of squat of the vessel, which can be very important for maneuvers with a very low water supply under the keel.

b. Wheelhouse poster - contains tabular information on vessel squat due to speed at full load. As can be seen in Figure 1 in the table, it is possible to enter only two values of water supply under the keel. Entering data for shallow and deep water does not show detailed data differences between the considered values.

Table 1. Obligatory element of wheelhouse poster IMO Res. A. 601(15).

DRAUGHT INCREASE (LOADED)				
Estimated Squat Effect			**Heel Effect**	
Under Keel Clearance	Ship's speed (knots)	Max. bow squat estimated (m)	Heel angle (degrees)	Draft increase (m)
(m)			2	
			4	
			8	
(m)			12	
			16	

Assuming, for shallow water, the ratio of submersion to depth factor at 1.2 will determine the squat of the hull for a water supply under the keel 2 m at a draught of 10 m. This supply may be much smaller during port maneuvers, or e.g. towing a ship in port canals, on rivers etc. In the case of transportation of dangerous goods, detailed information on the effect of the hull squat should be available on the bridge and handed over to the pilot during maneuvers. This will allow proper selection of the ship's speed during standard maneuvers or towing.

c. Maneuvering booklet - According to IMO guidelines, the maneuvering book should contain data on the effect of the ship's hull squat, but it was not specified what data it should be. Hence, in the absence of the need to specify detailed data for varying water supply under the keel and ship speed, this information often coincides with that available at the wheelhouse poster.

2.2. ANALYTICAL METHODS FOR CALCULATING THE SQUAT EFFECT OF A SHIP'S HULL

Analytical methods for determining ship squat parameters use empirical models which are created based on the synthesis of real test results and practical knowledge. The results obtained by analytical methods are approximate to real values. These methods are simple but not very accurate. In 1997, the PIANC WG30 report (Permanent International Association of Navigation Congress - Working Group, 30) was published, in which the equations for determining ship settlement parameters were presented. They were developed based on tests in various conditions (ballasted / loaded ships, various combinations of waters). The PIANC report contains the methods listed below [8-9]:

a. ICORELS

The ICORELS method is approved and published in the PIANC WG30 report. ICORELS is used to determine the increase in draught in the bow under shallow water and deepened fairway.

$$S_B = C_S \times \frac{\nabla}{L_{PP}^2} \times \frac{F_{nh}^2}{\sqrt{1 - F_{nh}^2}} \tag{1}$$

where:
∇ - volume of the immersed part of the hull $[m^3]$,
LPP – length between perpendiculars $[m]$,
C_S is the coefficient which depends on the hull fullness coefficient C_B.

$$C_S \begin{cases} 1{,}70 & C_B < 0{,}70 \\ 2{,}00 & 0{,}70 \le C_B < 0{,}80 \\ 2{,}40 & C_B \ge 0{,}80 \end{cases} \tag{2}$$

$$F_{nh} = \frac{V}{\sqrt{g \cdot h}} \tag{3}$$

where:
Fnh- ratio of ship speed to gravitational wave speed,
V- ship speed $\left[\frac{m}{s}\right]$,
h- body of water depth $[m]$,
g- gravitational acceleration $\left[\frac{m}{s^2}\right]$.

$$F_{nh} = \frac{V_S}{\sqrt{gh}} \tag{4}$$

where:
V_S- speed of the ship for which squat is determined $\left[\frac{m}{s}\right]$,
g – gravitational acceleration $\left[\frac{m}{s^2}\right]$,
h – body of water depth $[m]$,

b. Barras

The Barras method is one of the simplest methods and can be used for any type of body of water. With this method we can determine the maximum squat of the ship. The method does not specify the value
of squat on the bow or stern. The conditions limiting the use of the method are:

- Hull fullness coefficientC_B,
- The ratio of depth of water to the average draught of a ship h/T.

$$S_{MAX} = \frac{K \times C_B \times V^2}{100} \tag{5}$$

where:
C_B- Hull fullness coefficient,
V- ship speed $[m/s]$,
Coefficient K is related to the factor:

$$K = 5{,}74 \times S^{0{,}76} \tag{6}$$

$$0{,}10 \le S \le 0{,}25 \begin{cases} S = 0{,}10 - shalow\ water \\ S = 0{,}25 - fairway, canal \end{cases} \tag{7}$$

c. Eryuzlu

The Eryuzlu method was developed based on a series of tests on real models of cargo ships, including bulk cargo units equipped with a bulbous bow. Many of the methods published in the

ICORELS report did not take into account the impact of the bulbous bow on the squat effect of the ship. The tests of the effect of the vessel squat were carried out in shallow water and deepened waterways, which is also the limit of the method's application. The value of vessel squat at bow S_B is presented with the equation:

$$S_B = 0{,}298 \times \frac{h^2}{T} \times (\frac{V_S}{\sqrt{gT}})^{2{,}289} \times (\frac{h}{T})^{-2{,}972} \times K_B \tag{8}$$

KB is the correction factor for the width of the measured body of water.

$$K_B \begin{cases} \frac{3{,}1}{\sqrt{W/B}} & \frac{W}{B} < 9{,}61 - dredged\ fairway \\ 1 & \frac{W}{B} \geq 9{,}61 - shalow\ water \end{cases} \tag{9}$$

where:
W - body of water width $[m]$,
B- ship width $[m]$

The KB correction for the specific body of water tested varies as a function of the ship's width. The Canadian Coast Guard uses only the Eryzulu method to assess the squat value of a ship.

d. Huuska

The Husska / Guliev method was created by developing the Hooft method for vessel squat in shallow water. The modification consists of the implementation of the correction factor K_S taking into account the width of the body of water. Spanish ROM Recommendations for Designing Maritime Configurations of Ports, Approach Channels and Floatation areas uses the Husska method as the main one for designing approach tracks.

The value of vessel squat is given by the formula:

$$S_B = C_S \times \frac{\nabla}{L_{PP}^2} \times \frac{F_{nh}^2}{\sqrt{1 - F_{nh}^2}} \times K_S \tag{10}$$

Value $C_S = 2.40$ is used as average for all variants.

$$K_S = \begin{cases} 7{,}45 s_1 + 0{,}76 & s_1 > 0{,}03 \\ 1{,}0 & s_1 \leq 0{,}03 \end{cases} \tag{11}$$

where s_1 is the water cross-sectional factor.

$$s_1 = \frac{S}{K_1} \tag{12}$$

Cross-sectional factor is determined on the basis of diagram.

e. Yoshimura

The method was developed by the Japanese scientific institute. Designed to determine the change in draught at the bow as an aid in the design of fairways and canals. It is also used to determine the squat on the bow in shallow water. The speed of the ship should be improved by a factor S as in the Barras method.

$$V_e = \begin{cases} V_S - \ Shalow\ waters \\ \frac{V_S}{(1-S)} - \ Fairway, canal \end{cases} \tag{13}$$

V_e- the speed of the ship corrected $[\frac{m}{s}]$

$$0{,}10 \leq S \leq 0{,}25 \begin{cases} S = 0{,}10 - Shalow\ waters \\ S = 0{,}25 - Fairway, canal \end{cases} \tag{14}$$

The value of squat at the bow was specified by the equation:

$$S_B = [\left(0{,}7 + \frac{1{,}5}{h/T}\right) \times \left(\frac{C_B}{L_{PP}/B}\right) + \frac{15}{h/T} \times \left(\frac{C_B}{L_{PP}/B}\right)^3] \frac{V_e^2}{g} \tag{15}$$

where:
C_B- hull fullness factor;
g – gravitational acceleration $\left[\frac{m}{s^2}\right]$,
h – body of water depth $[m]$,
LPP - length between ship's perpendiculars $[m]$,
V_e- ship speed corrected $\left[\frac{m}{s}\right]$,
B – ship width $[m]$.

f. Rommish

Römmisch based on the tests carried out on the restricted water basin, the deepened fairway and the channel set the formula for determining the squat of the bow and stern. The presented method is one of the most complex but gives results closest to real measurements.

$$S_b = C_V C_F K_{\Delta T} T \tag{16}$$

$$S_s = C_V K_{\Delta T} T \tag{17}$$

where:
C_V – correction factor for the speed of the ship,
C_F – correction factor for the shape of the ship's hull,
$K_{\Delta T}$ – correction factor for the squat of the ship at critical speed.
Each of the aforementioned coefficients are determined by the formula:

$$C_V = 8\left(\frac{V}{V_{cr}}\right)^2\left[\left(\frac{V}{V_{cr}} - 0{,}5\right)^4 + 0{,}0625\right] \tag{16}$$

$$C_F = \left(\frac{10C_B}{L_{PP}/B}\right)^2 \tag{17}$$

$$K_{\Delta T} = 0{,}155\sqrt{h/T} \tag{18}$$

Critical speed V_{cr} changes in the function of a given body of water.

$$V_{cr} = \begin{cases} CK_U & Shallow\ waters \\ C_m K_C & Channel \\ C_{mT} K_R & Dredged\ fairway \end{cases} \tag{15}$$

3. SIMULATION RESEARCH

In order to verify the proposal to change the approach to the presentation of hull squat data in the ship's maneuvering documents, a number of simulation tests were carried out. For this purpose, the Transas navigation and maneuvering simulator software Navi Trainer Professional 5000 was used. The purpose of the simulation tests was to compare the results obtained with analytical methods and to develop functions that allow determining the value of hull squat for a given ship speed and water supply under the keel.

Simulation tests were carried out for 10 types of ships, however, due to the extensive research material, the article presents 3 types of ships:

Table 2. General Particulars of the Ships.

Ship type	LOA [m]	LPP [m]	Breadth [m]	Draught [m]	Block Coeff. [-]
Container Ship	393	377	56	13,7	0,66
Gas Carrier	294,6	281,6	46,5	11,1	0,75
Bulk Carrier (Panamax)	230	218	32	12	0,83

3.1. CONTAINER SHIP

Figures 1 and 2 present graphs of the ship's bow and stern squat function based on simulation tests. The graphs show the phenomenon of squating for three values of water supply under the keel and speeds in the range of 3.9 - 8.9 m/s. Colored markers specify registered values for which a non-linear function has been developed, thanks to which it is possible to interpolate the searched intermediate values.

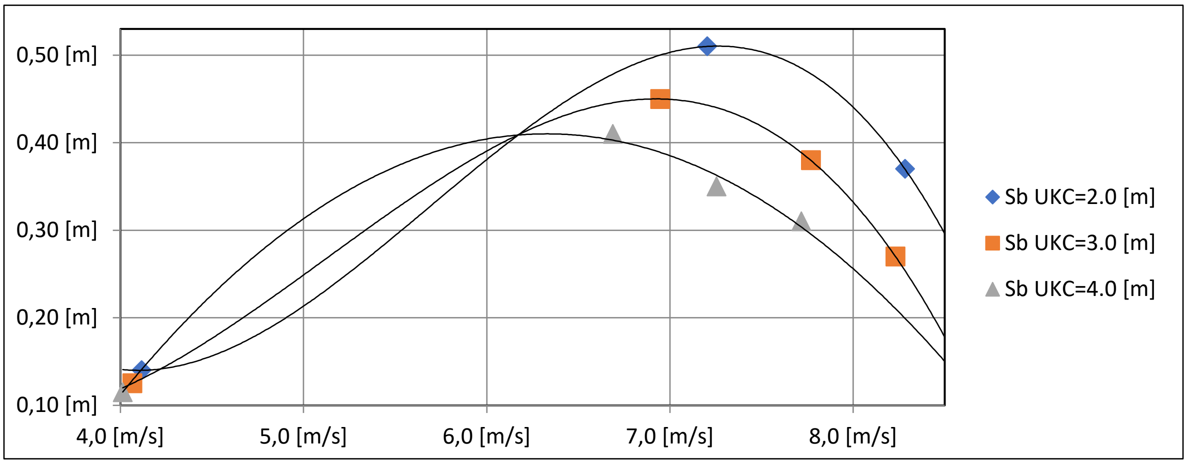


Figure 1. Bow squat – Container ship.

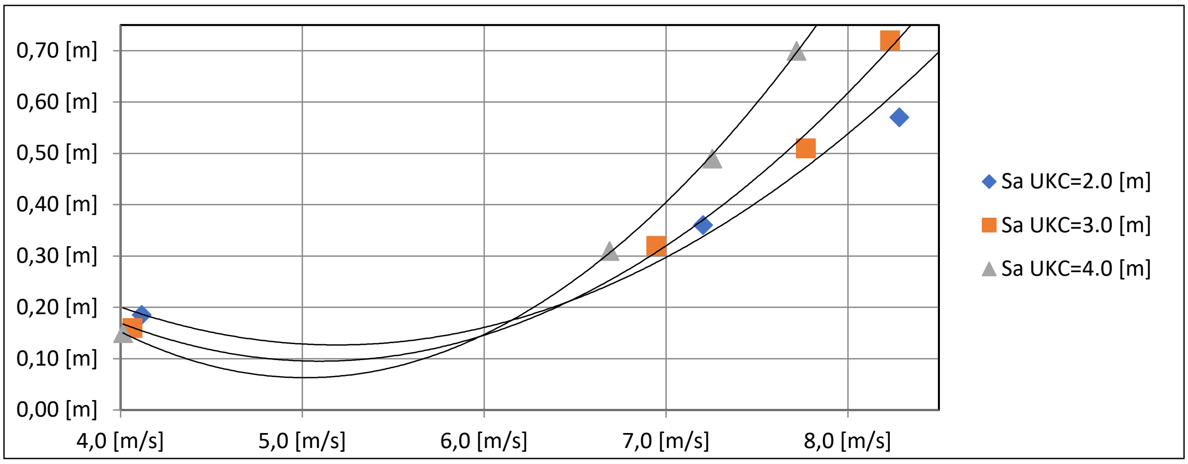


Figure 2. Stern Squat - Container ship.

The presented functions can be shown in tabular form (Table 2) and used to create an application which allows you to get detailed data on the squat of the ship for the manoeuvering parameters sought.

Table 3. Container vessel squat functions.

DRAUGHT INCREASE – Container Ship			
ESTIMATED SQUAT EFFECT			
UKC[m]	**V_S [m/s]**	**Bow squat estimated S_B [m]**	**Stern squat estimated S_A [m]**
2.0	<3.9-8.9>	$S_B = -0.0233\ V_S^3 + 0.3976\ V_S^2 - 2.0824\ V_S + 3.6025$	$S_A = 0.0521\ V_S^2 - 0.5407\ V_S + 1.5299$
3.0		$S_B = -0.0156\ V_S^3 + 0.2403\ V_S^2 - 1.0785\ V_S + 1.5888$	$S_A = 0.0619\ V_S^2 - 0.6307\ V_S + 1.7017$
4.0		$S_B = -0.0551\ V_S^2 + 0.6966\ V_S - 1.7935$	$S_A = 0.0868\ V_S^2 - 0.8703\ V_S + 2.2454$

The ship's manoeuvering documentation can be enriched with the implementation of the ship's squat table, which is shown in Figure 3.

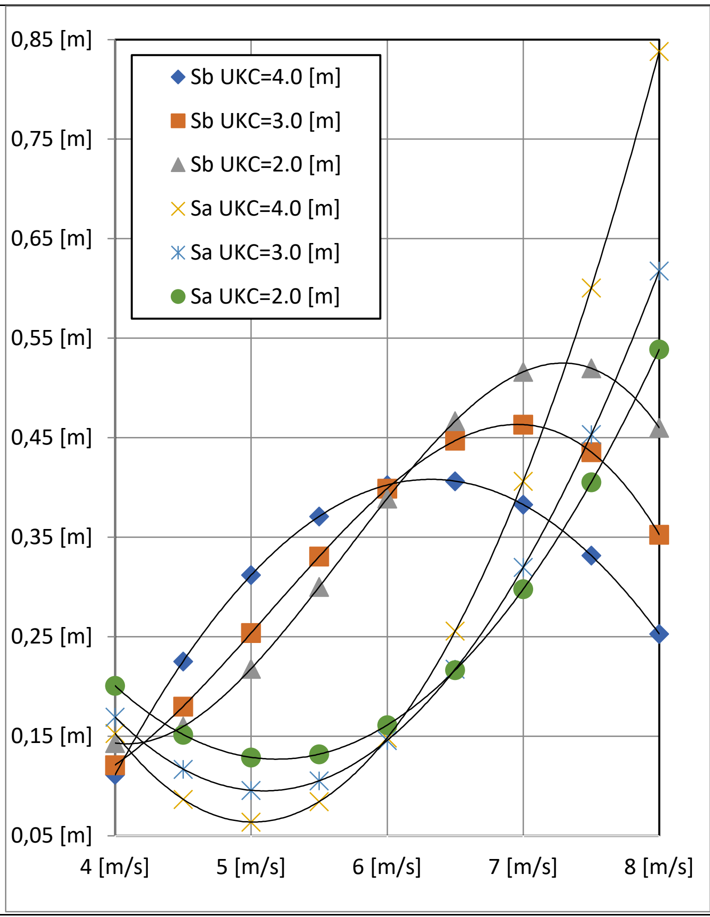
Proposition of enriched manoeuvering documentation					
UKC	Vs [m/s]	Vs [knt.]	Sb [m]	Sa [m]	Approximated values of vessel squat – Container Ship
4.00	4	7.78	0.11	0.15	
	4.5	8.75	0.23	0.09	
	5	9.72	0.31	0.06	
	5.5	10.69	0.37	0.08	
	6	11.66	0.40	0.15	
	6.5	12.63	0.41	0.26	
	7	13.61	0.38	0.41	
	8	15.55	0.25	0.84	
3.00	4	7.78	0.12	0.17	
	4.5	8.75	0.18	0.12	
	5	9.72	0.25	0.10	
	5.5	10.69	0.33	0.11	
	6	11.66	0.40	0.15	
	6.5	12.63	0.45	0.22	
	7	13.61	0.46	0.32	
	8	15.55	0.35	0.62	
2.00	4	7.78	0.14	0.20	
	4.5	8.75	0.16	0.15	
	5	9.72	0.22	0.13	
	5.5	10.69	0.30	0.13	
	6	11.66	0.39	0.16	
	6.5	12.63	0.47	0.22	
	7	13.61	0.52	0.30	
	8	15.55	0.46	0.54	

Figure 3. Container vessel, bow and stern squat functions.

3.2. GAS CARRIER

Figures 4 and 5 present graphs of the ship's bow and stern squat function based on simulation tests. The graphs show the phenomenon of squatting for four values of water supply under the keel and speeds in the range of 3.0 - 8.3 m/s. Colored markers specify registered values for which a nonlinear function has been developed, thanks to which it is possible to interpolate the searched intermediate values.

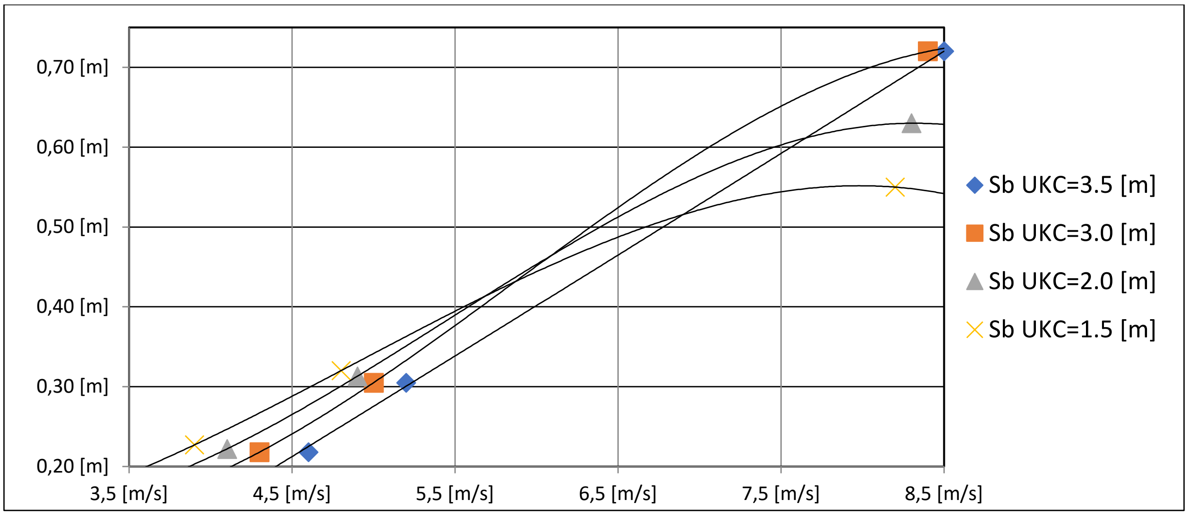


Figure 4. Bow Squat - Gas Carrier.

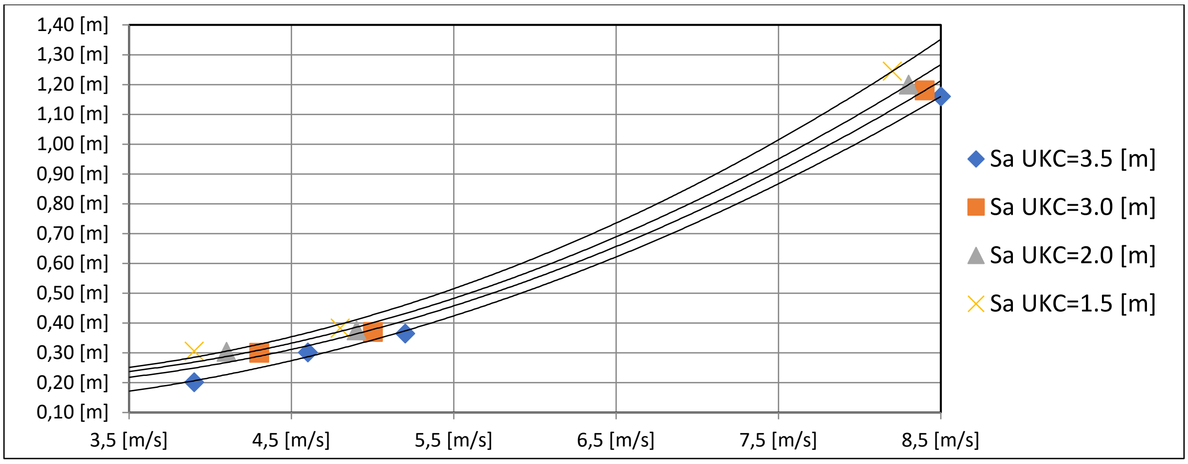


Figure 5. Stern Squat - Gas Carrier.

The nonlinear functions presented in the form of formulas are presented in Table 4.

Table 4. Gas Carrier squat functions.

DRAUGHT INCREASE – Container Ship			
ESTIMATED SQUAT EFFECT			
UKC[m]	**V_S [m/s]**	**Bow squat estimated S_B [m]**	**Stern squat estimated S_A [m]**
3.5	< 3.0-8.3 >	$S_B = 0.00034\ V_S^2 + 0.12249\ V_S - 0.34565$	$S_A = 0.0237\ V_S^2 - 0.0872\ V_S + 0.1856$
3.0		$S_B = -0.0056\ V_S^3 + 0.0979\ V_S^2 - 0.4246\ V_S + 0.6761$	$S_A = 0.0264\ V_S^2 - 0.1174\ V_S + 0.3061$
2.0		$S_B = -0.0053\ V_S^3 + 0.0862\ V_S^2 - 0.3415\ V_S + 0.5356$	$S_A = 0.0278\ V_S^2 - 0.1272\ V_S + 0.3428$

3.3. BULK CARRIER(PANAMAX)

Hull squat charts for a Panamax type ship are presented in Figures 6 and 7. The charts show the phenomenon of squatting for three values of water supply under the keel and speeds in the range 2.2 - 5.6 m/s.

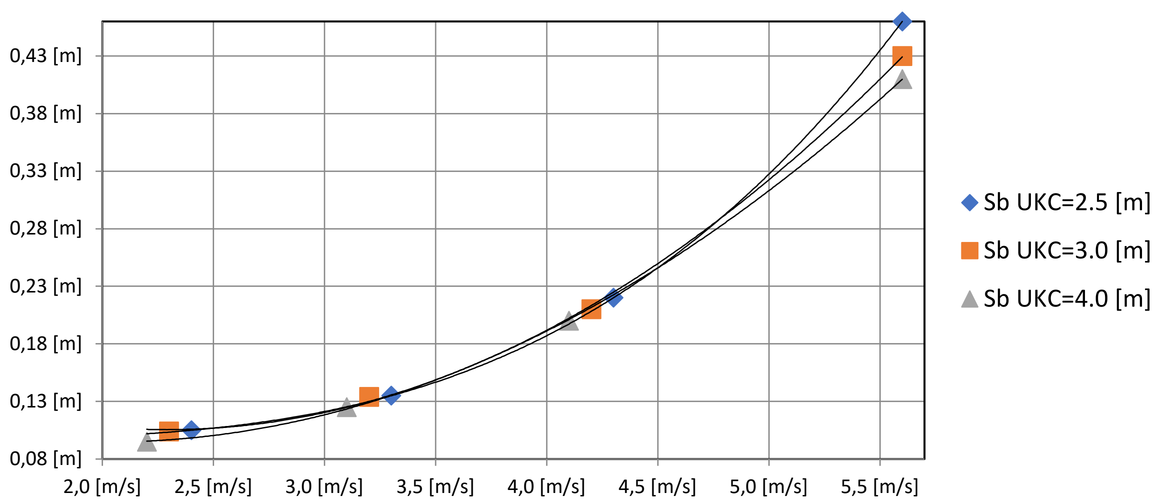


Figure 6. Bow Squat - Bulk Carrier.

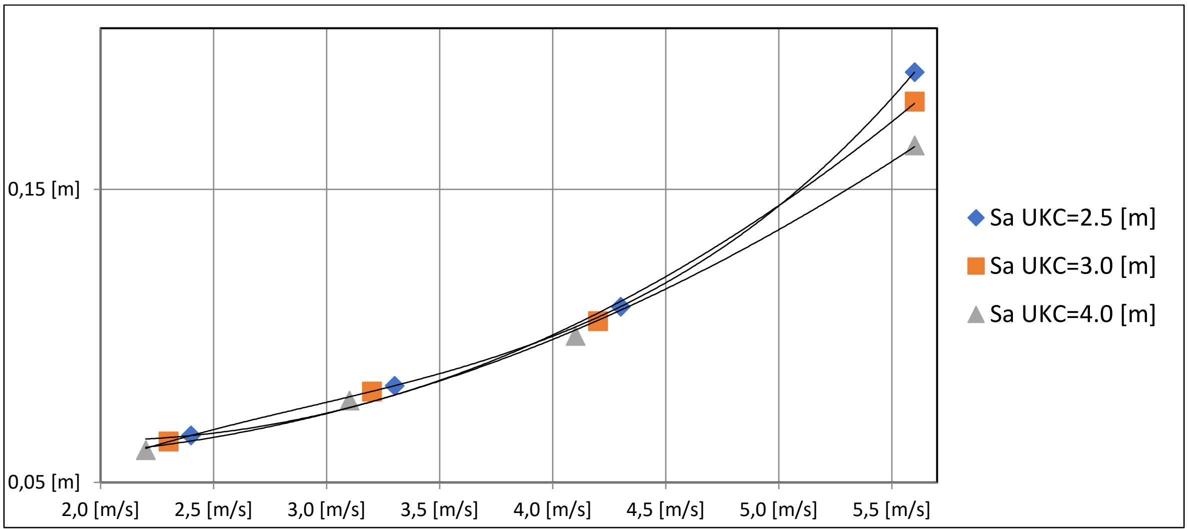


Figure 7. Stern Squat - Bulk Carrier.

Table 5 presents nonlinear functions in the form of formulas.

Table 5. Bulk Carrier squat functions.

DRAUGHT INCREASE – Container Ship			
ESTIMATED SQUAT EFFECT			
UKC[m]	**V_S [m/s]**	**Bow squat estimated S_B [m]**	**Stern squat estimated S_A [m]**
4.0	< 2.2–5.6 >	$S_B = 0.0245\ V_S^2 - 0.0991\ V_S + 0.1947$	$S_A = 0.0061\ V_S^2 - 0.0172\ V_S + 0.0654$
3.0		$S_B = 0.0296\ V_S^2 - 0.1354\ V_S + 0.2607$	$S_A = 0.0087\ V_S^2 - 0.0343\ V_S + 0.0931$
2.5		$S_B = 0.005\ V_S^3 - 0.0232\ V_S^2 + 0.0417\ V_S + 0.0688$	$S_A = 0.0034\ V_S^3 - 0.0293\ V_S^2 + 0.1035\ V_S - 0.0649$

3.4. COMPARISON OF SIMULATION RESEARCH RESULTS WITH ANALYTICAL METHODS

In order to verify the accuracy of determining the squat of the ship's hull by analytical methods, a comparative analysis was performed with the results of simulation tests. For this purpose, settlement values were calculated using the methods presented in the first part of the article. Figures 8-10 show comparative charts for the Container Ship.

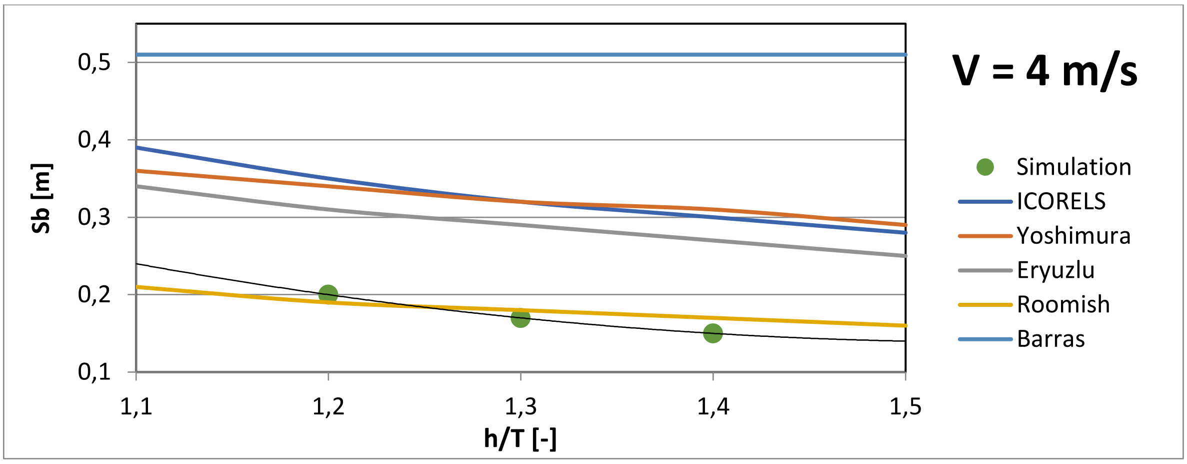


Figure 8. Bow squat of Container ship by the use of selected methods V= 4 m/s.

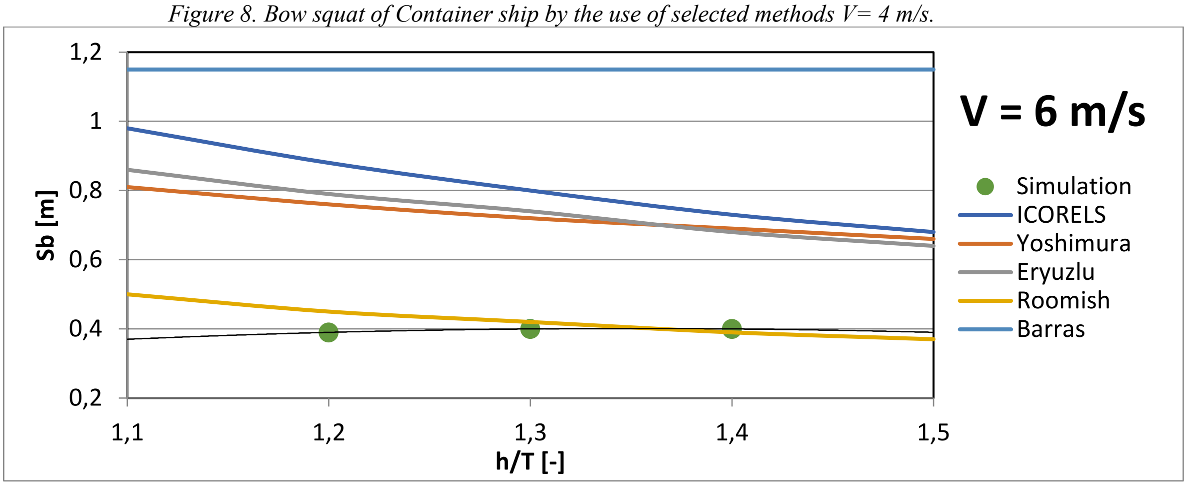


Figure 9. Bow squat of Container ship by the use of selected methods V= 6 m/s.

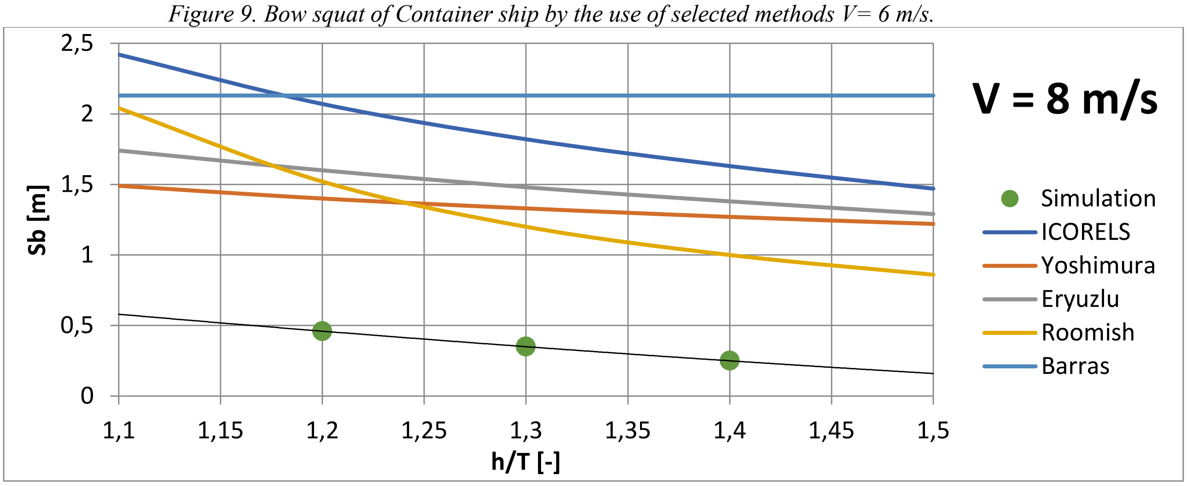


Figure 10. Bow squat of Container ship by the use of selected methods V= 8 m/s.

An analysis of the above graphics shows a certain correlation of the proposed function with the Roomish model in the low speed range. However, it can be seen that the differences for the other models are significant and their use for estimating hull squat for small values under the keel is dangerous.

4. DISCUSSION

Based on the analysis presented, it can be seen that the hull squat data are nonlinear. Therefore, it is difficult to estimate the value of this effect for the sought data for water supply under the keel and the speed of the ship. Information on the ship's hull squat value for two parameters of water supply under the keel available in the ship's maneuvering documentation may be insufficient. This applies especially to the situation when maneuvering the vessel in shallow water reservoirs with less water under the keel than the data available in the documentation. It can therefore be concluded that it is necessary to enrich the ship's maneuvering documentation with more detailed information on the ship's squat. The proposed functions enable presentation in a legible, graphic and tabular form of the document. In addition, based on the relationships provided, it is possible to develop a computer application to which we can enter the assumed water supply under the keel and the speed of the ship to obtain the exact value of the hull's squat.

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