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COMPARISON BETWEEN FORMULAS OF MAXIMUM SHIP SQUAT

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Abstract: *Ship squat is a combined effect of ship’s draft and trim increase due to ship motion in limited navigation conditions. Over time, researchers conducted tests on models and ships to find a mathematical formula that can define squat. Various forms of calculating squat can be found in the literature. Among those most commonly used are of Barrass, Millward, Eryuzlu or ICORELS. This paper presents a comparison between the squat formulas to see the differences between them and which one provides the most satisfactory results. In this respect a cargo ship at different speeds was considered as a model for maximum squat calculations in canal navigation conditions.*

Keywords: *ship squat, formula, channel configuration, cargo ship.*

INTRODUCTION

A phenomenon that occurs on vessels in channels, rivers, canals and harbors is **ship squat**, which may be defined as the sinkage and/or trimming of the ship due to pressure changes along the ship length in shallow waters. The trim change can be explained by hydrodynamic interactions between the ship and the bottom due to speed and pressure distribution change. The squat effect is directly related to ship dimensions, its speed and water depth; therefore, it interests port and waterway designers as much as masters and naval architects [1].

Ship squat phenomenon has been the subject of studies in many ways for a long time. In general, most researches rely on empirical formulas, experimental tools or numerical (Computational Fluid Dynamics) techniques, among which the first two types are more widely used [2].

Squat formulas have been developed for estimating maximum squat for vessels operating in restricted and open water conditions with satisfactory results. Some have been measured on real ships and some on models [3].

Scientific research on ship squat was started by *Constantine* (1960), which studied the phenomenon for subcritical, critical and supercritical speeds. In subcritical domain, *Tuck* (1966) demonstrated that in open water conditions of constant depth, the sinkage and trimming of the vessel varies linearly with depth Froude number. This theory was developed by others, such as *Beck* (1975) for dredged channels, *Naghdi and Rubin* (1984), *Cong and Hsiung* (1991), *Jiang and Henn* (2003) or *Gourlay* (2008) [4].

Current researches on this phenomenon are limited to experiments on scale models for an accurate mathematical expression of ship squat. The literature presents various formulas of squat, the most commonly used being those of *Barrass* (2004), *Millward* (1992), *Norrbin* (1986), *Hooft* (1974) and *Romisch* (1989) [5].

FORMULAS FOR CALCULATING SHIP SQUAT

PIANC[1] (1997) classifies restricted navigation areas in unrestricted channels, restricted channels and canals. Figure 1 is a schematic of these three types of entrance channels for ocean-going or deep draft ships. The main channel considerations are proximity of the channel sides and bottom, as represented by the channel depth *h* and cross-sectional configuration [6].

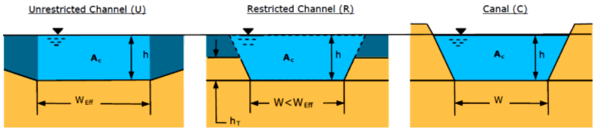

Figure 1. Schematic channel types [6]

Unrestricted channels can be classified as relatively large areas without side restrictions, but with shallow waters. The second type of channel is the restricted channel with an underwater trench that is typical of dredged channels. The restricted channel is a cross between the canal and unrestricted channel type. The trench acts as a canal by containing and influencing the flow around the ship and the water column above the h_T allows the flow to act as if the ship is in an unrestricted channel. The last type of channel is the canal. This kind of channel is representative of channels in rivers with emergent banks [6].

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PIANC (1997) lists three empirical equations for predicting ship squat that apply to canals. This includes equations of *Huuska* (1976), *Barrass* (1979, 1981) and *Romisch* (1989). *Eryuzlu et al*. equation (1994) is also applicable for unrestricted shallow water, but requires values for block coefficient C_B greater than 0.8.

In PIANC equations were used the following assumptions:

a. For ships with difference in bow and stern drafts it was used the medium draft when calculating ship squat and area of mid-ship cross-section.

b. In *Barrass*'s equation, unrestricted channel conditions exist when the channel width (*W*) is greater than 8 times the ship's breadth (*B*). Although not stated in PIANC (1997), the cross-sectional area of the unrestricted channel was considered to be equal to *8*B*h*.

c. If the length between perpendiculars and block coefficient are not known for the ship whose squat is calculated, there can be used typical values given in PIANC (1997) [7].

The report of PIANC Working Group 30 included 11 empirical formulas and a graphical method from 9 different authors to predict ship squat. These were based on physical models experiments and on site measurements for various vessels, channels and load conditions. Formulas included pioneering work of *Tuck*, *Tuck and Taylor*, *Beck et al.*, and more recent researches of *Hooft*, *Dand*, *Eryuzlu* and *Hausser*, *Romisch* or *Millward* [8].

PIANC recommends two stages for waterways and channels design. The first phase is the "concept" design where a quick response is needed. Working Group 30 report recommended at this stage to use *ICORELS* formula. The second step is the "detail" design phase where it is necessary for more accurate predictions and comparisons. For this step, Working Group 30 recommended *ICORELS*, *Huusk*a, *Barrass* and *Eryuzlu et al.* formulas.

All these formulas give squat predictions at bow S_b, except *Romisch*'s formula, which gives the squat prediction also at stern S_s for all channel types. *Barrass*'s formula calculates squat at stern for unrestricted channels and for restricted channels and canals depending on the block coefficient C_B. Each formula has some constraints that should be satisfied before being applied. If these formulas are used in conditions other than those for which they were developed, there should be given special attention [8].

In 2005, PIANC MarCom formed Working Group 49, who was in the process of review these formulas to achieve an updated design for channels. It has several changes from the previous report. *Barrass* continued to develop and improve its formula, which can calculate bow and stern squat. *Ankudinov et al.* proposed a formula developed for Maritime Simulation and Ship Maneuverability (MARSIM 2000), which calculates the maximum squat based on an average sinkage point and vessel trim in shallow water. It is one of the most detailed and intricate formulas for predicting ship squat. The tests carried out in St. Lawrence channel on VLCC led to the creation of a formula based on measurements performed by *Stocks et al. Briggs* developed a program using FORTRAN to calculate squat using most of these formulas.

The most representative formulas are shown below. Some of these trusted formulas are often validated; others are based on more recent research. Table 1 summarizes the channel configurations and parameter constraints for these formulas according to the individual testing conditions. The user should always be mindful for the original constraints. Some of these constraints are very restrictive (especially for the newer vessels coming on line) as they are based on the limited set of conditions tested in physical models by the individual researchers. This does not mean that the particular formula would not be applicable if the constraints are exceeded by a reasonable amount [6].

Table 1. Channel configurations and parameter constraints for squat formulas

	Channel configuration			**Constraint type**					
Formulas	**U**	**R**	**C**	C_B	***B/T***	***h/T***	h_T/h	L_{pp}/B	L_{pp}/T
Barrass	X	X	X	0.5-0.85		1.1-1.4			
Eryuzlu et al.	X	X		≥ 0.8	2.4-2.9	1.1-2.5		6.7-6.8	
Huuska/Guliev	X	X	X	0.6-0.8	2.19-3.5	1.1-2.0	0.22-0.81	5.5-8.5	16.1-20.2
ICORELS	X			0.6-0.8	2.19-3.5	1.1-2.0	0.22-0.81	5.5-8.5	16.1-20.2
Hooft	X								
Yoshimura	X	X	X	0.55-0.8	2.5-5.5	≥ 1,2		3.7-6.0	
Romisch	X	X	X		2.6	1.19-2.25		8.7	22.9
Soukhomel	X							3,5-9	

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Millward	X			0.44-0.83		1.25-6.0			14.9-23.2

ICORELS[2]

ICORELS formula for bow squat is one of the formulas outlined in the PIANC Working Group 30 report. It was developed only for open or unrestricted channel, which is why it should be used with caution for restricted channels or canals. Similar to equations of *Hooft* and *Huuska*, is defined as:

$$S_b = C_S \frac{\nabla}{L_{pp}^2} \frac{Fn_h^2}{\sqrt{1-Fn_h^2}}, \quad (1),$$

where C_S = 2.4, ∇ is ship's displacement volume, Fn_h is Froude number calculated with depth h, L_{pp} is ship length between perpendiculars.

The Finnish Maritime Administration (FMA) uses this formula with different values of C_S, based on the block coefficient, C_B:

- C_S = 1.7, for C_B < 0.7;
- C_S = 2.0, for 0.7 ≤ C_B < 0.8;
- C_S = 2.4, for C_B ≥ 0.8.

It is recommended to use the value of C_S = 2.0 for large container ships which today can have C_B < 0.7 [6].

Barrass

Barrass's formula is one of the simplest and easy to use and can be applied to all channel configurations. Being based on his research from 1979, 1981 and 2004, the maximum bow or stern squat S_{max} is determined by the ship's block coefficient and speed.

$$S_{max} = \frac{K C_B V_K^2}{100}. \quad (2)$$

According to *Barrass*, the block coefficient C_B determines where the squat is produced, at bow or stern. Full-form ships with C_B > 0.7 tend to squat by the bow, whereas fine-form ships with C_B < 0.7 tend to squat by the stern. The C_B = 0.7 is a situation of "even keel" when squat occurs equally at fore and aft. This formula is based on regression analysis of more than 600 laboratory and prototype measurements.

The coefficient K is defined by blockage factor S, as follows:

$$K = 5.74 S^{0.76}. \quad (3)$$

A value of S = 0.10 is equivalent to a wide river (or unrestricted channel). For the value of K = 1, the denominator of the fraction in S_{max} equation remains 100. If S < 0.10 K's value should be set to 1. For restricted channels, values of S = 0.25 and K = 2 are obtained and the denominator is 50. Thus, the effect of K is to constantly change the denominator with values between 50 and 100. The constraints of this equation are 1.10 ≤ h/T ≤ 1.4 and 0.10 ≤ S ≤ 0.25.

In unrestricted channels, for even keel vessels when in static conditions, the squat can be estimated at the other end of the ship (either bow or stern) using S_{max} equation. Thus, if the C_B indicates a bow squat, this formula will give stern squat and vice versa:

$$[1-40(0.7-C_B)^2]S_{max} = \begin{Bmatrix} S_B, C_B \le 0.7 \\ S_S, C_B > 0.7 \end{Bmatrix}. \quad (4)$$

Yoshimura

Ohtsu et al. proposed the following formula to calculate squat S_B. This formula is derived from *Yoshimura*'s equation for unrestricted channels typical in Japan. The ranges of parameters when this formula can be applied are listed in Table 1. In 2007, *Ohtsu* proposed a small change on ship speed V_S (now is V_e) to include the term S for squat prediction in restricted channels and canals:

- $V_e = V_s$ – unrestricted
- $V_e = \frac{V_s}{(1-S)}$ – restricted, canal.

This prediction of squat S_B is generally close to the average of most PIANC formulas for predicting bow squat, regardless the type of the vessel:

$$S_B = \left[\left(0.7 + 1.5\frac{1}{h/T}\right)\left(\frac{C_B}{L_{pp}/B}\right) + 15\frac{1}{h/T}\left(\frac{C_B}{L_{pp}/B}\right)^3\right]\frac{V_e^2}{g}.$$

(5)

Eryuzlu

One of the most recent series of tests on physical models and field measurements was led by *Eryuzlu et al.* for cargo ships and bulk carriers with bulbous bows, in restricted and unrestricted channels. The tests were carried out on the self-propelled models with bulbous bows. *Eryuzlu* formula for bow squat S_B is defined as:

$$S_B = 0.298\frac{h^2}{T}\left(\frac{V_s}{\sqrt{gT}}\right)^{2.289}\left(\frac{h}{T}\right)^{-2.972} K_b. \quad (6)$$

K_b is a correction factor for channel width W relative to ship's breadth B, as follows:

$$K_b = \frac{3.1}{\sqrt{W/B}}, if\ \frac{W}{B} < 9.61 \quad (7)$$

$$K_b = 1, \quad if\ \frac{W}{B} \ge 9.61.$$

For unrestricted channels it should be used K_b = 1, regardless of the effective width W_{eff} because the channel has no limiting effects on the flow and pressures on the vessel hull [8].

Huuska/Guliev

Finnish professor *Huuska* expanded *Hooft*'s research for unrestricted channels to include

[2] International Commission for the Reception of Large Ships

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restricted channels and canals by adding a correction factor for channel width K_S, developed by *Guliev*. In general, this formula should not be used for $Fn_h > 0.7$.

Huuska/Guliev formula is defined as:

$$S_b = C_S \frac{\nabla}{L_{pp}^2} \frac{Fn_h^2}{\sqrt{1-Fn_h^2}} K_s. \quad (8)$$

where $\nabla = C_B{*}L_{pp}{*}B{*}T$.

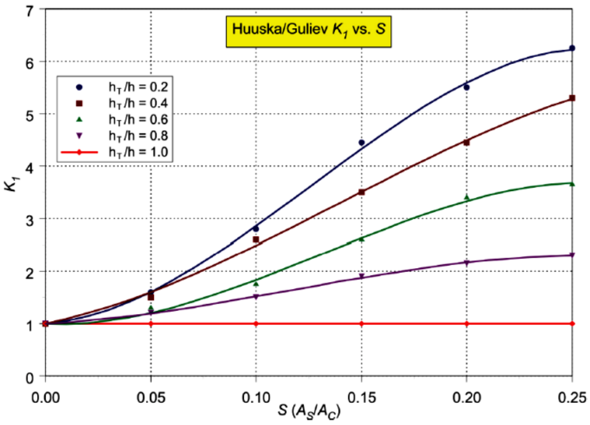

Figure 2. *Huuska/Guliev* K_1 versus S [6]

The squat constant $C_S = 2.4$ is usually used as a mean value in this formula. The value of K_S for restricted channels and canals is determined from:

$$K_s = 7.45 s_1 + 0.76, \; s_1 > 0.03 \quad (9)$$
$$K_s = 1, \qquad s_1 \le 0.03,$$

with a corrected blockage factor s_1 defined as $s_1 = (A_s/A_c){*}K_1$, A_s is mid-ship cross-section area equal to $0.98{*}B{*}T$ and A_c is canal's cross section area. Additional information about the calculation of K_1 coefficient is found in PIANC (1997).

The correction factor K_1 is given by the *Huuska* diagram of K_1 versus S in Figure 2 for various ratios h_T/h. For unrestricted channels there should be used $h_T = 0$ and for canals $h_T = h$.

Romisch

Romisch developed squat formulas for both bow and stern based on experiments on ship models in all three channel configurations. Its empirical formulas are the most difficult to use, but offers better predictions of bow squat S_B and stern squat S_S as follows:

$$S_B = C_V C_F K_{\Delta T} T, \quad (10)$$
$$S_S = C_V K_{\Delta T} T, \quad (11)$$

where C_V is a correction factor of ship speed, C_F is a correction factor of body shape and $K_{\Delta T}$ is a correction factor for squat at critical speed of the ship. C_F value is equal to 1 for stern squat.

These coefficients values are:

$$C_V = 8\left(\frac{V}{V_{cr}}\right)\left[\left(\frac{V}{V_{cr}} - 0.5\right)^4 + 0.0625\right], \quad (12)$$

$$C_F = \left(\frac{10 C_B}{L_{pp}/B}\right)^2, \quad (13)$$

$$K_{\Delta T} = 0.155\sqrt{\frac{h}{T}}. \quad (14)$$

Ship's critical speed V_{cr} is the speed which cannot be exceeded due to the equality between the continuity equation and Bernoulli's law. For unrestricted channels, ship's critical speed V_{cr} is defined as:

$$V_{cr} = 0.58\left(\frac{hL}{TB}\right)^{0.125}\sqrt{gh}. \quad (15)$$

For economic reasons, the maximum speed of vessels is typically 80% of the critical velocity V_{cr} (m/s). This varies depending on channel configuration as follows:

$$V_{cr} = \begin{cases} C K_U, & unrestricted \\ C_m K_C, & canal \\ C_{mT} K_R, & restricted \end{cases} \quad (16)$$

The three parameters for wave celerity C, C_m and C_{mT} (m/s) are defined as:

$$C = \sqrt{gh};\; C_m = \sqrt{gh_m};\; C_{mT} = \sqrt{gh_{mT}}. \quad (17)$$

The average water depth h_m (m) is a standard hydraulic parameter that is used in canals and restricted channels, which is defined as:

$$h_m = \frac{A_C}{W_{top}}, \quad (18)$$

where W_{top} (m) is the projection of channel width on the surface of the channel equal to:

$$W_{top} = W + 2nh. \quad (19)$$

The relevant water depth h_{mT} (m) is used for restricted channels and is defined as:

$$h_{mT} = h - \frac{h_T}{h}(h - h_m). \quad (20)$$

The correction factors K_U, K_C and K_R for unrestricted channels, restricted channels and canals are defined as follows:

$$K_U = 0.58\left[\left(\frac{h}{T}\right)\left(\frac{L_{pp}}{B}\right)\right]^{0.125} \quad (21)$$

$$K_C = \left[2 sin\left(\frac{\arcsin(1-S)}{3}\right)\right]^{1.5} \quad (22)$$

$$K_R = K_U\left(1 - \frac{h_T}{h}\right) + K_C\left(\frac{h_T}{h}\right) \quad (23)$$

It has to be noted that K_R for restricted channels is a function of K_U and K_C coefficients. Table 2 presents a list of K_C coefficient values as a function of $1/S$ [6].

Table 2. *Romisch*'s K_C coefficient versus $1/S$ [6]

1/S	1	6	10	20	30	∞
K_C	0.0	0.52	0.62	0.73	0.78	1.0

Soukhomel and *Zass*

Under conditions of limited depth, squat phenomenon is widening, especially when the ratio h/T = 1.2 ... 1.5 is satisfied, where h is water

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depth and T is ship's draft. Current design practice uses a series of empirical formulas for determining the medium sinkage (s_m), stern sinkage (s_{AP}), bow sinkage (s_{FP}) and ship's trim t.
Soukhomel and *Zass* proposed the following relationship:

$$\text{for } h/T \geq 1.4,\ s_m = 12.96k\sqrt{\frac{T}{h}}U^2; \tag{24}$$

$$\text{for } h/T < 1.4,\ s_m = 12.96kU^2; \tag{25}$$

where, $k = 0.0143\left(\frac{L_{pp}}{B}\right)^{-1.11}$ for $3.5 \leq \frac{L_{pp}}{B} \leq 9$, U is ship speed in m/s and T is medium draft [9].
For ships with reduced breadth is assumed that $s_{AP} > s_{FP}$ and stern sinkage is calculated with the following relationships:

$$\text{for } 3.5 \leq \frac{L_{pp}}{B} < 5,\ s_{AP} = 1.5s_m; \tag{26}$$

$$\text{for } 5.0 \leq \frac{L_{pp}}{B} < 7,\ s_{AP} = 1.25s_m; \tag{27}$$

$$\text{for } 7.0 \leq \frac{L_{pp}}{B} < 9,\ s_{AP} = 1.1s_m. \tag{28}$$

Hooft

Hooft used the form proposed by *Tuck and Taylor*:

$$s_m = C_z\frac{\nabla}{L_{pp}^2}\cdot\frac{Fn_h^2}{\sqrt{1-Fn_h^2}} \tag{29}$$

$$t = C_\theta\frac{\nabla}{L_{pp}^2}\cdot\frac{Fn_h^2}{\sqrt{1-Fn_h^2}} \tag{30}$$

where C_z = 1.4 ... 1.53 and C_θ = 1 for various forms of vessels [9].

Millward

Millward developed an expression for bow sinkage calculation, in shallow but unrestricted waters, valid for $0.44 \leq C_B \leq 0.83$ and for ratios L_{pp}/h = 6 ... 12,

$$s_{FP} = \left(15C_B\frac{B}{L_{pp}} - 0.55\right)\frac{Fn_h^2}{1-0.9Fn_h}\cdot\frac{L_{pp}}{100} \tag{31}$$

and another one based on *Tuck*'s interpretation:

$$s_{FP} = \left(61.7C_B\frac{T}{L_{pp}} - 0.6\right)\frac{L_{pp}}{100}\cdot\frac{Fn_h^2}{\sqrt{1-Fn_h^2}}. \tag{32}[9]$$

All formulas give reasonable predictions of ship squat and can be used with confidence in waterways and channel design.

SQUAT CALCULATION FOR CARGO SHIP

To see which formula gives satisfactory results and what are the differences between them there was considered a cargo ship with dimensions specified in Table 3 for which maximum squat was calculated when sailing with 8 knots in a canal with vertical sides.

Table 3. Main dimensions of cargo ship

Ship type	*Δ* [tdw]	*L_pp* [m]	*B* [m]	*T* [m]	C_B
Cargo ship	7800	118	17.1	7.76	0.667

For this study it was chosen a rectangular cross-section canal having dimensions close to a real one. It has a width W = 123 m and a depth h = 10 m (Figure 3) therefore, the value h/T = 1.289 is in the limits for this ratio.
From all squat formulas presented in Table 1 and taking into consideration the constraints of each one, only those of *Barrass*, *Huuska/Guliev, ICORELS*, *Soukhomel* and *Zass* and *Millward* can be applied for maximum squat calculation on this kind of ship, but only the first two can be used for canal conditions.

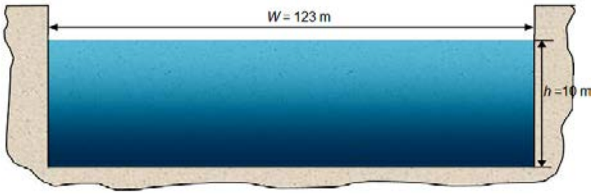

Figure 3. Rectangular cross-section canal [3]

The depth Froude number is needed and for the considered speed is given by:

$$\mathrm{Fn_h} = \frac{\mathrm{V_s}}{\sqrt{\mathrm{gh}}} = 0.415606 \tag{33}$$

where V_s is ship's speed in m/s, g = 9.806 m/s^2 is the gravitational acceleration and h is water depth.
Since $Fn_h \leq 0.70$, it is acceptable for all methods.
For k coefficient from *Soukhomel* and *Zass* formula it was calculated a value of 0.001676.
After calculations were made the results presented in Table 4 came up.

Table 4. Squat results

Formula	S_{max} @ 8 knots
Barrass	0.40842 m
Huuska/Guliev	0.52909 m
ICORELS	0.34186 m
Soukhomel and *Zass*	0.32401 m
Millward	0.29301 m

One can notice the different values of maximum squat determined with most commonly used formulas.
The *Barrass* formula is relatively easy to apply and gives reasonable estimates. In order to determine the blockage factor S, mid-ship cross-sectional area A_S and canal's cross-section area A_C must be calculated. Therefore,

$$A_S = 0.98 \times B \times T = 130.0421 \text{ m}^2 \tag{34}$$

$$A_C = W \times h = 1230 \text{ m}^2 \tag{35}$$

and the blockage factor is given by

$$S = A_S/A_C = 0.105725. \tag{36}$$

For this type of canal, the maximum squat obtained using *Barrass*'s formula is 1.4 times

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higher than the one calculated using *Millward*'s, about 0.8 times lower than *Huuska/Guliev* and almost 1.2 times bigger than *ICORELS* and *Soukhomel* and *Zass*. Therefore, we conclude that *Barrass*'s formula takes very much into consideration canal configuration and ship speed.
The *Huuska/Guliev* formula is more complicated to use than others, but not as difficult as the *Romisch*. It is very similar to the *ICORELS* formula, but includes a correction factor for restricted channels and canals.
The first step is to calculate the correction factor K_1 that is used in the corrected blockage factor s_1. Since $h_T = h$ for this case, which is similar to a canal, one can use the graph from Figure 2 to get the value of K_1 = 1.0. The second step is to calculate the corrected blockage factor s_1 = 0.105725. The third step is to calculate the correction factor for channel width K_s, which depends on the value of s_1. The first equation for K_s is used since s_1 > 0.03 and results K_s = 1.547653. The fourth step is to calculate the ship's displacement volume ∇ = 10443.97 m^3.
Huuska/Guliev formula varies with Froude depth number, thus with speed. Also ship's displacement volume and blockage factor S are significant parameters. *Barrass* and *Huuska/Guliev* formulas consider as variables ship's dimensions, canal configuration and speed but such a difference in ship squat values could result from the fact that in *Huuska/Guliev* formula the constraint of L_{pp}/T ratio couldn't be satisfied.
ICORELS squat value cannot be reliable for the described conditions because it was developed only for open or unrestricted channel, which is why it should be used with caution for canals.
Similar result with *ICORELS* are obtained using *Soukhomel* and *Zass* formula because both take into account ship dimensions (L_{pp}, B, T), speed and water depth but neither this was designed for canals.
On the other hand, *Millward* disregards any blockage factor and considers as variables ship dimensions (L_{pp}, B, C_B) and speed by using depth Froude number. The result is different from the others because the expression for bow squat calculation was also developed for shallow and unrestricted waters.

For a better observation of the difference between formulas, ship squat was calculated for other speeds: 6, 10 and 12 knots. The speed wasn't further increased because at 14 knots, depth Froude number already exceeds the limit of 0.70. The results were compiled in Figure 4 were it can be seen that all formulas give an increasing trend for squat because it varies with speed.

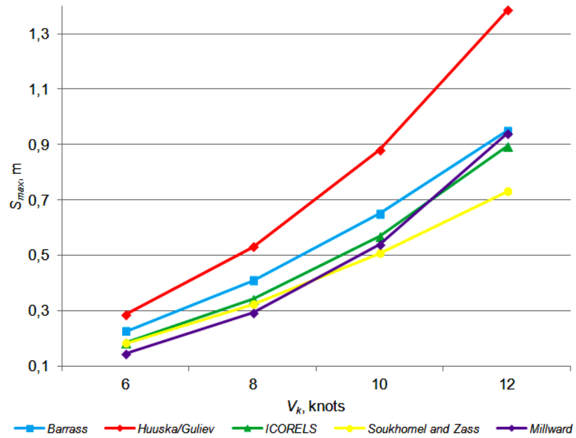

Figure 4. Comparison of empirical squat formulas

Generally, *Soukhomel* and *Zass* squat has the smallest values because the formula was designed for unrestricted channels and this is not the case. It has similar values with *ICORELS* and *Millward* until 10 knots. Then the differences between them are obvious and at 12 knots *Millward*'s formula give the biggest value of the three. These formulas are used in conditions other than those for which they were developed, so they should be given special attention.
Huuska/Guliev formula has the highest values of all and one could take them for granted because it was designed for canal conditions, but in this case L_{pp}/T ratio constraint wasn't fulfilled, so the values cannot be reliable.
Barrass formula overestimates ship squat and due to its simplicity is better to use it for the "concept" phase of waterways design. Moreover, using bigger squat values than real ones can be considered a precautionary measure in terms of navigation safety in shallow waters.

CONCLUSIONS

Restricted waters impose significant effects on ship navigation. Ship squat is a phenomenon that occurs every time vessels are underway but is visible when navigation conditions are restricted, like shallow and narrow waters.
This paper has focused on some of the advances in predicting ship squat and its effect on under keel clearance. Several of the more popular PIANC empiric formulas were presented. All empiric formulas have

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certain constraints based on the field and laboratory data used in their development. It is up to the user to chose when applying these formulas as they give a range of squat values.

Squat calculations were made for an underway cargo ship with various speeds in canal conditions to see the differences between formulas. Some of these didn’t offer reliable results because they weren’t designed for canal conditions, but those who were, gave good results. *Huuska/Guliev* formula gives the highest values compared to real squat, while *Barrass* values are close to reality but still overestimated.

Under keel clearance for the cargo vessel exceeds 1 m for all considered formulas and speeds, except the *Huuska/Guliev* at 12 knots whose values cannot be reliable. For shallower depths *Barrass*’s formula should be considered for squat calculation, since bigger values of squat are obtained. Thus, it is taken a precautionary measure for navigation in shallow and narrow waters. In reality ship squat is smaller, but for safety of navigation it is necessary to calculate and take into account its maximum possible value.

Maximum squat determination for shallow and/or narrow waters remains an important issue for safety of navigation. Masters should know before entering such areas, where and how much the draft will increase to take actions for countering this phenomenon.

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