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SQUAT ASSESSMENT FOR SAFE NAVIGATION OF RIVER NILE CRUISERS

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Review paper

Summary

In recent years a great deal of research efforts in ship hydromechanics have been devoted to practical navigation problems in moving larger ships safely into existing harbors and inland waterways. 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.

River Nile cruisers are encountering squat every movement due to lacking water depth and stand up to grounding risk day after day. In this paper a series of simple but practical useful theoretical models concerning ship squat problems in shallow waterways are discussed. Luxor-Aswan is a selected waterway for the present study. In the course of this study, characteristics of Luxor-Aswan waterway and main feature of existing Nile cruisers are outlined.

Finally, theoretical squat analysis of a candidate Nile cruiser has been presented. The results show the position and magnitude of maximum squat, grounding speed has been also identified. It has been found that masters awareness of squat phenomenon and its prediction for each specific vessel is of great concern for vessel safety. This work can be useful for ship designers, naval architects and naval officers, who have to be aware of squat effects, with a specific end goal to avoid any squat related accidents.

Key words: *Ship squat; River Nile Cruisers; Luxor-Aswan Waterway.*

1. Introduction

Most maritime professionals may genuinely say that they know about “squat” - the sinkage and trim that a vessel experiences when operating in shallow water or in a channel. There is developing evidence, however, that most masters do not fully appreciate the serious potential magnitude of squat effects. For example, recent analyses, highly publicized maritime accidents have revealed that squat was a contributing factor. It also comes as a surprise to many that both the U.S. Coast Guard (USCG) and the International Maritime Organization (IMO) require a prediction of squat effect, and that squat effect calculations are a recommended part of the ISM Code, STCW training and the International Chamber of

Shipping (ICS) Bridge Procedures Guide. This deficiency in understanding such a critical design topic is quite surprising given the extensive research and publications on squat. However, it seems to be that the design community has deemed squat be relatively unimportant [1]. When the problem of ship squat belongs to a passenger or cruise vessels the consequences became worthy; when a ship grounds due to excessive squat ship owners may be faced with the following costs:

1. A large repair bill,
2. Loss of passenger bookings in the weeks following a grounding,
3. Compensation for passengers already booked,
4. Compensation claims for oil spillage, if applied,
5. Compensation claims for loss of life, if applied.

The presence of locks through Luxor -Aswan waterway and shallow water nature of River Nile represent several constraints on the dimensions of River Nile cruisers [2], where, this ship type has tended to be shorter in length and wider in breadth. Also, River Nile cruisers are characterized by great values of the hull block coefficient (C_B) in order to achieve a larger displacement at small draught moreover, to gain maximum capacity and revenue. This has prompt reporting grounding accidents due squat. Therefore, this paper presents a useful guideline to assess every specific case with its specific operation conditions by a quick and simple strategy in order to determine the degree of grounding risk stemmed by squat in shallow water.

2. Underkeel clearance

Fig. 1 shows the additive components in calculating underkeel clearance (UKC) of a ship in shallow water [3]. In order for the navigation to be considered safe, the "Nett UKC" must always remain greater than a predetermined safety margin. The Nett UKC is calculated as follows:

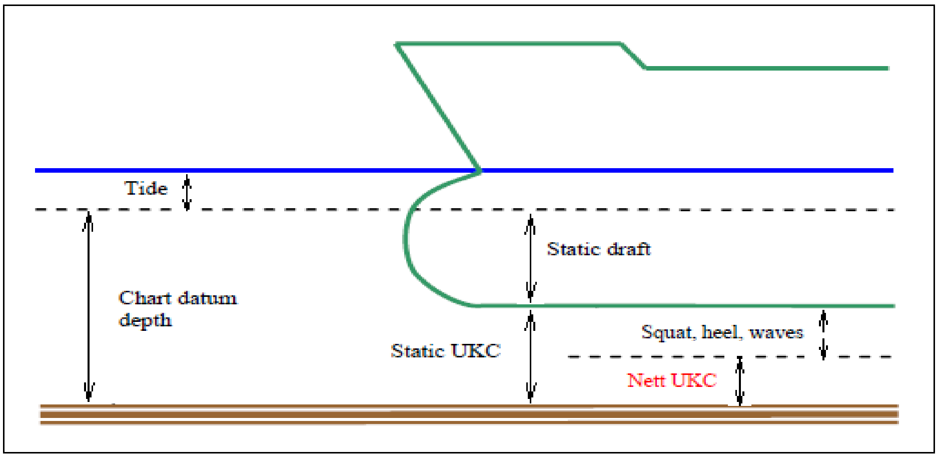

Fig. 1 Components of underkeel clearance [3]

$$[\text{Nett UKC}] = [\text{Chart datum depth}] + [\text{Tide}] - [\text{Static draft}] - [\text{Squat, and other allowances}] \quad (1)$$

3. Shallow water theory

The hydrodynamic behavior of a vessel changes when sailing in shallow and/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. The water depth (H) and the mean draught (T) of the static ship are broadly used as the parameters to characterize shallow water. If the ratio H/T drops below 1.5, one will, in general, experience a measurable change in the draught of the ship (sinkage). As H/T approaches 1.0 (grounding), the effect of shallow water increases significantly. Tuck [4] presented an analytical solution for squat of slender hull vessel traveling in open water. In the subcritical domain, he proved for laterally open water conditions of constant water depth (H) that the sinkage and trim of a vessel sailing at a steady speed (V) is proportional to depth Froude number (F_{nh}).

Tuck's theory was extended to dredged channels by Beck [5] with a matching of solutions between the deep and shallow regions of the cross section. Naghdi and Rubin [6] solved Tuck's problem using a nonlinear steady state solution of the differential equations of the theory of a thin ship. Shallow water theory of Tuck predicts ship squat for the critical speed value corresponding to F_{nh} =1. On the other hand, based on the Bernoulli principle and conservation of mass, Dand and Ferguson [7] and Gourlay [8] give a blockage dependent critical speed range instead of one particular critical speed value. Also, they depended upon experimental research to extend their theoretical developments towards different bottom conditions and very wide waterways. Dand [9] proposed a correction for the effect of the propeller and applied the effective width parameter (W) to cope with large or even infinite canal widths.

As the ship is generally not symmetrical about its half-length and because of the viscous effects of water, the changes in pressure are not identical for the fore and aft parts of the hull. This causes the ship to trim forward or astern depending on the hull shape. Thus, the magnitude of squat depends on the hull shape, the side and under-keel clearance and the speed through the water. Briggs [10] presented an comprehensive overview of publications and calculation methods related to bow squat based on physical model tests and field measurements for different channel configurations, ship types, and loading characteristics. These formulae can be used easily to calculate bow squat by masters navigating in shallow water to overcome grounding.

4. Slender versus fuller ships

When a ship proceeds through water, she pushes water ahead of bow. In order not to leave a hole in the water, this volume of water must return down the sides and under the bottom of the ship. The streamlines of return flow are accelerated under the ship. This causes a drop in pressure, resulting in the ship dropping vertically in the water. As well as dropping vertically, the ship generally trims forward or aft depending on the vessel's block coefficient (C_B). The overall decrease in the static underkeel clearance "UKC", forward or aft, is called ship squat. Thus, ship squat is made up of two components, namely mean bodily sinkage plus a trimming effect.

Experimental measurements have shown that bow squat is greater in magnitude than trim; thus it has more effect on grounding. It has been observed that the variation of squat follows the same trend for various ship types although the magnitude differs from slender to full forms. The results portray that full form ships such as tankers trim more by the bow than the slender hull forms. If a ship moves forward with a very high speed in shallow water, then grounding due to excessive squat could occur at the bow or at the stern. Therefore, location of maximum squat can be explained as follows [11]:

1. If $C_B > 0.70$, then maximum squat will occur at the bow,
2. If $C_B < 0.70$, then maximum squat will occur at the stern,
3. If C_B is very near to 0.70, then, squat will consist only of mean bodily sinkage with no trimming effects.

Some ships have a static trim when they are stationary. This static trim will decide the position of maximum squat while the ship is underway. For example, if a ship has static trim by stern, then she will have dynamic trim in the same direction as the static trim. In other words, she will have increased trim and could possibly run aground at her stern.

5. Factors affecting ship squat

All recent research indicates that ship squat relies on upon ship characteristics and channel configurations. The most important factors influencing the size of ship squat are as follows [11]:

1. Ship speed (V) is the most important factor influencing ship squat. Detailed analysis has shown that squat varies as speed to the power of 2.08. However, squat can be said to vary approximately with the speed squared.
2. The block coefficient (C_B) is another factor which directly influences squat. Full-form ships such as oil tankers undergo more squat than passenger ships which have fine hull form.
3. The blockage factor (S) is another important factor affecting ship squat. This factor can be defined as the ratio of the underwater cross-section area of ship at amidships (A_S) to the cross-section area of the canal or river (A_C). Blockage factor (S) can be calculated as follows:

$$S = \frac{A_S}{A_C} = \frac{B \cdot T}{W \cdot H} \tag{2}$$

Since an open water channel has no channel width (W), an effective channel width (W_{eff}) can be used as follows [12]:

$$W_{eff} = \left[7.7 + 45 \left(1 - C_{WL} \right)^2 \right] B \tag{3}$$

4. Water depth (H)/ship draft (T) also affects ship squat. At a specified ship speed, ship squat increases as depth to draft (H/T) ratio decreases.
5. As to the nearness of river or canal banks, the closer banks are to the sides of a moving vessel, the greater will be the squat.
6. The nearness of another ship in a narrow river will also affect squat of the considered ship, so much so, that squats can double in value as she passes/crosses the other vessel.

Information of ship squat is necessary when navigating through shallow water areas, such as rivers and channels. Precise squat prediction is therefore essential to minimize the risk of grounding for ships.

6. Empirical squat equations

Ship squat can be calculated by various strategies such as analytical method [13], numerical and experimental methods [14, 15]. Due to the existence of complicated three-dimensional flow around the ship in shallow water, experimental methods are the most viable option and the most accurate method. Several empirical formulae have been developed for estimating maximum ships squats most of them are derived statistically from experimental data. Some of these formulae are presented as follows:

- Barrass (1981)

  Based on validation with full-scale measurements, Barras [16] proposed the following formula for bow squat (δ_b):

$$\delta_b = \frac{C_B \cdot S_2^{2/3} \cdot V_k^{2.08}}{30} \tag{4}$$

$$S_2 = \frac{S}{1-S} \tag{5}$$

- Eryuzlu and Hausser (1978)

  Eryuzlu and Hausser [17] conducted physical model tests for large fully loaded self-propelled oil tankers in open water channels. Their formula for bow squat (δ_b) is defined as follows:

$$\delta_b = 0.113\, B \left[\frac{1}{H/T}\right]^{0.27} F_{nh}^{1.8} \tag{6}$$

- Eryuzlu et al. (1994)

  Eryuzlu [18] conducted series of physical model tests and field measurements for cargo ships and bulk carriers with bulbous bows in confined and open water channels. Their formula for bow squat (δ_b) is defined as follows:

$$\delta_b = \frac{0.298\, H^2}{T} \left(\frac{V_k}{\sqrt{g\ T}}\right)^{0.289} \left(\frac{H}{T}\right)^{-2.972} K_b \tag{7}$$

$$K_b = \begin{cases} \dfrac{3.1}{\sqrt{W/B}} & for \quad W/B < 9.61 \\ 1 & for \quad W/B \geq 9.61 \end{cases} \tag{8}$$

- Hooft (1974)

  Based on Tuck's (1966) formulations for squat from sinkage and trim in open water channels, Hooft [19] proposed the following formula for bow squat (δ_b):

$$\delta_b = \frac{1.96\, \nabla\, F_{nh}^2}{L^2 \sqrt{1-F_{nh}^2}} \tag{9}$$

  The constant "1.96" is used as an average value, but values from 1.9 to 2.03 are also sometimes used.

- Huuska (1976)

  Huuska [20] extended Hooft's work to include confined channels and canals by adding a correction factor for channel width K_s. He proposed the following formulae for bow squat (δ_b):

$$\delta_b = \frac{2.4 \ \nabla \ F_{nh}^2}{L^2 \sqrt{1 - F_{nh}^2}} \cdot K_s \tag{10}$$

$$K_s = \begin{cases} 7.45\, S' + 0.76 & for \quad S' > 0.03 \\ 1 & for \quad S' \le 0.03 \end{cases} \quad where, \; S' = S / K \tag{11}$$

The correction factor K_s is given by Huuska's plot of K_s versus S for different trench height ratios.

- ICORELS (1980)

The International Commission for the Reception of Large Ships (ICORELS) formula for bow squat is defined as follows [21]:

$$\delta_b = \frac{2.4 \nabla F_{nh}^2}{L^2 \sqrt{1 - F_{nh}^2}} \tag{12}$$

It is noted that the "2.4" constant is sometimes replaced with a smaller value of "1.75" for full form ships with larger C_B.

- Millward (1990)

Millward [22] conducted physical model tests for different ship types in open water channels. His formula for bow squat (δ_b) is defined as follows:

$$\delta_b = 0.01\, L \left(\frac{15 C_B}{L / B} - 0.55 \right) \frac{F_{nh}^2}{1 - 0.9 F_{nh}} \tag{13}$$

- Millward (1992)

Millward [23] rearranged his test results and presented them in a format similar to Tuck (1966). His formula for bow squat (δ_b) is defined as follows:

$$\delta_b = 0.01\, L \left(\frac{61.7 C_B}{L / T} - 0.6 \right) \frac{F_{nh}^2}{\sqrt{1 - F_{nh}^2}} \tag{14}$$

- Norrbin (1986)

Norrbin [24] developed a formula for bow squat (δ_b) for a ship in an open water channel. This formula must satisfy the constraint $Fn_h < 0.4$. Thus, it is somewhat limited in its application. Norrbin formula for bow squat (δ_b) is defined as follows:

$$\delta_b = \frac{C_B \cdot V_k^{\,2}}{15 (L / B)(H / T)} \tag{15}$$

- Romisch (1989)

Romisch [25] developed formulae for both bow and stern squat from physical model experiments for all three channel configurations (open water channels, confined channels and canals). His predicted values for bow (δ_b) and stern squat (δ_s) are defined as follows:

$$\delta_b = 8 \left(\frac{V}{V_{cr}} \right)^2 \left[\left(\frac{V}{V_{cr}} - 0.5 \right)^4 + 0.0625 \right] \left(\frac{10\, C_B}{L / B} \right)^2 \left(0.155\, T \sqrt{H / T} \right) \tag{16}$$

$$\delta_S = 8\left(\frac{V}{V_{cr}}\right)^2\left[\left(\frac{V}{V_{cr}}-0.5\right)^4 + 0.0625\right]\left(0.155\ T\sqrt{H/T}\right) \tag{17}$$

These formulae are based on physical model tests and field measurements for different channel configurations, ship types, and loading characteristics. Therefore, each formula has certain constraints and conditions that it should satisfy before being applied, usually based on the conditions under which it was developed. Table 1 is a summary of the applicable channel configurations and parameter constraints according to the individual testing conditions [10].

Table 1 Parameter constraints for squat formulae [10]

Squat Formulae	Constraints			Configuration		
	C_B	H/T	L/H	Open Water	Confined	Canal
Barrass (1981)	0.5 to 0.9	1.1 to 1.5		Y	Y	Y
Eryuzlu and Hausser (1978)	≥ 0.8	1.08 to 2.75		Y		
Eryuzlu et al. (1994)	≥ 0.8	1.1 to 2.5		Y	Y	
Hooft (1974)				Y		
Huuska/Guliev (1976)		1.1 to 2.0			Y	Y
ICORELS (1980)				Y		
Millward (1990)	0.44 to 0.83		6 to 12	Y		
Millward (1992)			6 to 12	Y		
Norrbin (1986)				Y		
Romisch (1989)		1.19 to 2.25		Y	Y	Y

Barras's formula is among the most simple and easy to use for all channel configurations [26]. Based upon his research from 1979, 1981 and 2004, δ_{max} is determined as follows [11]:

$$\delta_{\max} = \frac{C_B \cdot S^{0.81} \cdot V_k^{2.08}}{20} \tag{18}$$

In this context, (V_k) is the ship's speed relative to water; therefore the effect of current/tide must be taken into account. Two simplified formulae relative to Eq. 3 are [11]:

$$\delta_{\max} = \frac{C_B \cdot V_k^2}{100} \tag{19}$$

Eq. 19 is valid for open water conditions only, with the ratio H/T between water depth and ship draft ranging from 1.1 to 1.4 [11], and

$$\delta_{\max} = \frac{C_B \cdot V_k^2}{50} \tag{20}$$

Eq. 20 is valid for confined channels where the blockage factor (S) has values between 0.100 and 0.265 [11]. An S value of 0.100 appertains to a very wide channel, almost in open water conditions, while a blockage factor (S) of 0.265 appertains to a narrow channel [11].

7. Luxor-Aswan waterway

Luxor-Aswan waterway is 216 km long and mainly utilized by tourist Nile cruisers with heavy traffic density of more than 5 units per hour [27], while the traffic density of other navigation types can be neglected as it is limited to less than 2 units per hour [27]. Luxor-Aswan waterway is classified as a first class waterway according to the classification of the General River Transport Authority in Egypt. Table 2 shows characteristics of river Nile waterways in Egypt [28].

Table 2 Characteristics of river Nile waterways in Egypt

Criterion	1st class	2nd class	3rd class
Min. bridge height (above water surface)	13 m	3.5 m	2.5 m
Min. water depth	2.5 m	1.8 m	1.25 m
Max. ship draft	1.8 m	1.5 m	1.0 m
Total length	2191 km	121 km	813 km

It is obvious that each class of the Egyptian waterways has specific characteristics and consequently the design criterion and traffic considerations of Nile cruisers will be varied from one waterway to other. River Nile cruises route map is shown in Fig. 2.

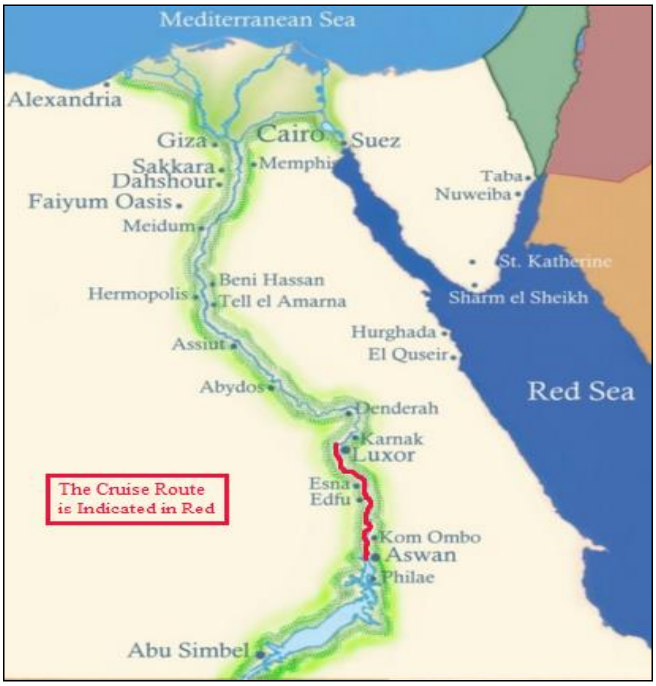

Fig. 2 River Nile cruises route

One of the obstacles that threaten the navigation through Luxor-Aswan waterway is the lack of enough water depth for navigation throughout the year. Since most of Nile water is used for irrigation (about 85%), the water level in Luxor-Aswan waterway is affected by the irrigation requirements [29]. During December and January the irrigation water requirements are low. Therefore, water level in Luxor-Aswan waterway during this period is the lowest;] throughout the year and consequently, Nile cruisers which have draft higher than 1.5 meter face real problems such as grounding accidents owing to enormous squat and other reasons [29]. Unfortunately, the peak season for Nile cruisers and tourism is during the period from

November to February. This period matches the low discharge period, which is considered a real threat to the tourism industry.

8. Case study

In the following section, squat analysis is carried out for a specific Nile cruiser ("M/S Davinci") that runs from Luxor to Aswan. It carries approximately 136 guests and its particulars are shown in Table 3. M/S Davinci has a block coefficient (C_B) greater than 0.7, hence maximum squat (δ_{max}) will occur at bow.

Table 3 Main particulars of M/S Davinci (full load condition)

L_{OA}	72.0 m	T	1.75 m
L_{WL}	70.5 m	C_B	0.83
B	13.6 m	C_{WL}	0.92
D	3.60 m	Sun deck height	11.9 m

Up to now there is no exact evaluation method for ship squat. It is recommended to use a reliable evaluation method which will deliver results on the so called "safe side". Briggs [10] presented a worked example to calculate ship squat of bulk carrier in open water channel using the aforesaid squat formulae. The results of this study show that, Barras's formula gives the highest estimation of ship squat. Thus, in the present analysis squat analysis will be carried out using Barras's formula considering "safe side" concept.

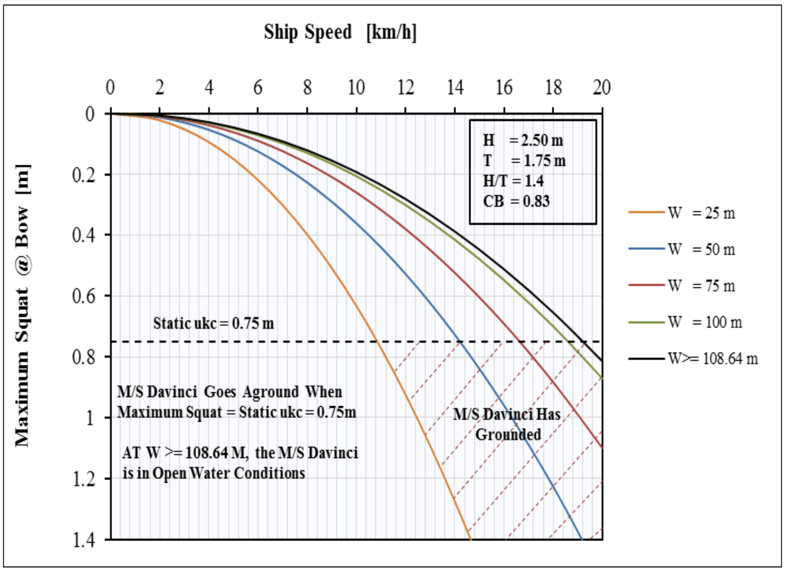

Fig. 3 Maximum ship squats for M/S Davinci, plotted against various ship speed.

According to the Egyptian River Transport Authority (RTA), the minimum water depth (H) of Luxor-Aswan waterway is 2.5m and it has a water width (at river bed) greater than 120 m throughout its length. In this case, according to Eq. 3, effective width (W_{eff}) equals 108.64 m. Hence, M/S Davinci is operating in open water condition and any width of water greater than 108.64 m will give similar maximum squat (δ_{max}) value as shown in Figs. 3 and 4.

Fig. 3 shows maximum squats for M/S Davinci when she is in open water condition, without the presence of adjacent river banks. Ship squat varies parabolically with ship speed. At a speed of 8 km/h, it will have a maximum squat of approximately 0.12 m at bow, while at a speed of 16 km/h, it will have a maximum squat of around 0.51 m at bow. Fig. 3 shows that maximum squat increases as river width decreases from 108.64 m down to 25 m.

When M/S Davinci has a forward speed of 10.85 km/h in river width of 25 m, it will have a maximum squat of 0.75 m. grounding at bow will be occurred.

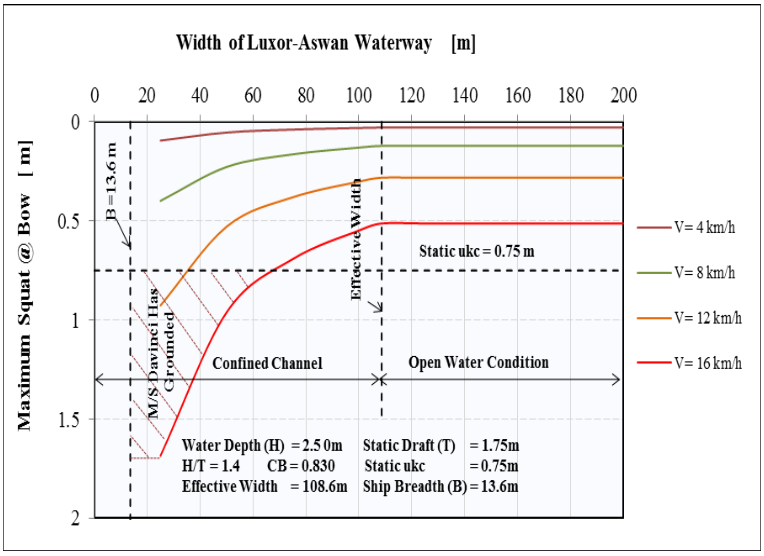

Fig. 4 Maximum ship squats for M/S Davinci, plotted against various river widths.

Fig. 4 is a diagram of cross-curves produced from Fig. 3. At a speed of 4 km/h, a perpendicular line was drawn on Fig. 3. The intersection with each river width (W) curve was lifted and re-plotted into Fig. 4. These plotted points were then drawn as shown. This process was repeated for M/S Davinci speeds of 8, 12, and 16 km/h.

At river width of 108.64m, a series of asymptotic lines appeared. This verifies earlier comments about the effective width of this waterway. At river width greater than 108.64m, the maximum squats did not decrease. They are a constant value. This means that when M/S Davinci is navigating through Luxor-Aswan waterway, the width of water to be used in the calculation for ship squat is about 8 ship breadths. At river width less than 108.64m, the squats increase. They increase sharply as the width of river approached the limiting value of 13.6 m (the moulded breadth of M/S Davinci).

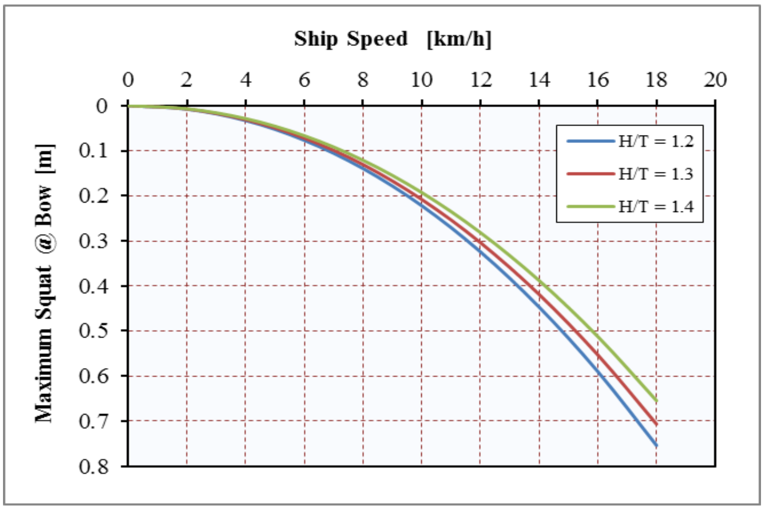

Fig. 5 Squats for M/S Davinci at different values of depth to draft ratio.

Ship squats for M/S Davinci are calculated as a function of vessel speed at different values of depth to draft (H/T) ratio, to justify the effect of the water depth (H) on squat. The results are plotted as shown in Fig. 5. Obviously, at a specified ship speed, ship squat increases as depth to draft (H/T) ratio decreases.

Masters and naval officers clearly need to identify the maximum speed in order to avoid grounding accidents. Indeed, they need also to predict the maximum squat value: from which they can predict a reasonable minimum dynamic under-keel clearance at the bow or stern. Dynamic underkeel clearance is calculated as follows [26]:

$$UKC = H - T - \delta_{\max} \tag{21}$$

In this case, the authors suggest that the remaining under-keel clearance, at a requested forward speed, should be at least 0.50 m. Fig. 6 shows the dynamic underkeel clearance at different ship speeds.

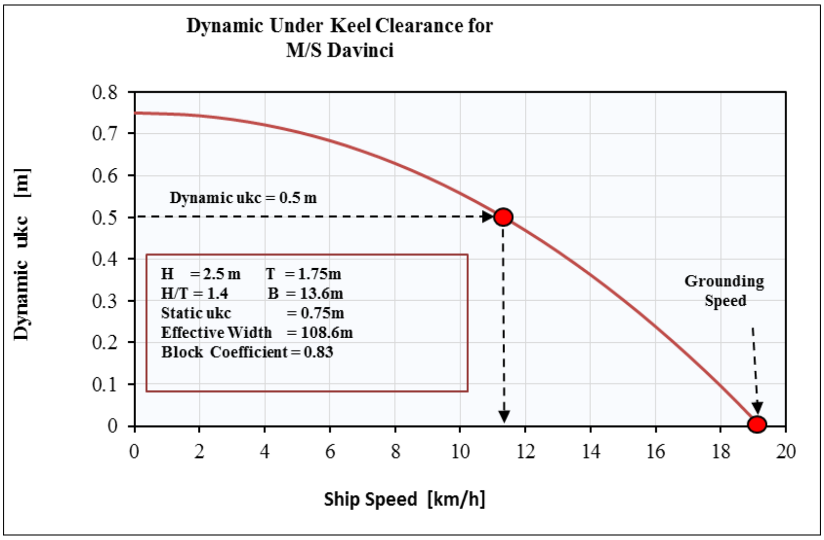

Fig. 6 Dynamic underkeel clearance for M/S Davinci, plotted against various ship speed.

It is self-evident that, while M/S Davinci navigates with a forward speed of 19.22 km/h through Luxour-Aswan waterway, it will have a maximum squat of 0.75 m (dynamic UKC = 0). At this speed, it will ground at bow. Also, M/S Davinci can safely navigate through Luxor-Aswan waterway with a speed less than or equal 11.35 km/h. At this speed, it will have a maximum squat of 0.25 m (dynamic UKC = 0.5m).

9. Conclusions

Ship squat and the accurate prediction ability of its magnitude is an essential issue that strongly influences maritime transportation efficiency, safety and pollution prevention.

The aforesaid analysis is an attempt to assess the squat for a test case runs through Luxor-Aswan waterway with a reliable simplified and understandable procedure. This analysis is applicable for other Nile cruisers at any waterway. The results of this analysis showed that M/S Davinci will have grounding at bow if her speed exceeds 19.22 km/h through Luxor-Aswan waterway, while, she can sail safely through the same waterway with a speed less than or equals 11.35 km/h (with dynamic underkeel clearance of 0.5m).

The most effective measure to minimize or avoid any commencing squat is the immediate reduction of speed. Therefore, the authors would encourage all ship operators to utilize the existing Eco sounding systems that they have on-board to begin recording vertical measurements of UKC when running in shallow water ways which also may be useful for navigational charts updates. Moreover, specific Eco sounder alarming setting with automatic speed control/reduction considering each vessel specific safe UKC would be useful for safe navigation without grounding fear.

NOMENCLATURES

A_S	Mid-ship cross-section area, m^2
A_C	Canal /river cross-section area, m^2
B	Vessel Breadth, m
C_B	Block Coefficient
C_{WL}	Water line coefficient
F_{nh}	Depth Froude number
H	Water depth, m
K, K_b, K_s	Equation constants
L	Ship length, m
S	Blockage factor
T	Vessel draft, m
UKC	Under keel clearance, m
V	Vessel Speed, knots
V_k	Ship speed relative to the water in knots
V_{cr}	Critical ship speed, knots
W	Channel width, m
W_{eff}	Effective canal/river width, m
δ_b	Squat, m
δ_s	Stern squat, m
δ_{max}	Maximum squat, m
∇	Ship volume of displacement, m^3

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