Mathematical & Computational Applications, Vol. 6, No. 1, pp. 1-11, 2001

BEHAVIOR OF SHIPS IN SHALLOW AND RESTRICTED WATERS

Metin Taylan
I.T.U. Naval Architecture and Ocean Engineering Faculty,
80626 Maslak Istanbul, Turkey

Abstract-Ship motions in open waters and waves are always dynamic and most of the time are nonlinear. Even though behavior of ships in shallow and restricted waters does not sound as violent at first thought, it is equally important in terms of capsizing. There has been so many casualties reported that claimed so many lives. In this study, squat phenomenon is dealt with especially addressing its determination in the preliminary design stage. For this purpose, approximate formulae have been proposed to predict bow squat of ships and compared with the other methods and experimental data found in the literature to come up with a pragmatic method to guide naval architects and masters towards avoiding excessive squat in shallow water. It is known that forward speed plays an important role in squat, hence there exist a Froude number, called critical speed, for a particular ship at which squat characteristics start changing drastically. This fact is also taken into account in the regressional analysis. Some of the results are then compared with that of the similar studies and a real life incident. It has been found that the method compared fairly well with other methods and experiments.

1. INTRODUCTION

Ship motions in shallow water somewhat differs from the motions in deep water. This fact attracted many researchers since there occurred so many accident because of it. Squat may be defined as the sinkage and/or trimming of the ship due to pressure changes along the ship length in shallow water. Ship to ship and ship to bank interactions are also associated with the same phenomenon. The cause of this trim can be better explained by the hydrodynamic interaction between the ship and the sea floor due to the speed and pressure and the change in pressure distribution because of the waveform. Especially, large and fuller ships such as tankers and bulk carriers should pay extra attention when navigating in restricted waters. Squat, which is directly related to the ship dimensions, speed and depth of water, interests port designers and operators as much as it does masters and naval architects. The undesired hydrodynamic trim ensued from speed in shallow water along with the hydrostatic trim due to ship form and cargo may result in grounding or worst yet in capsizing. In 1987, a Ro-Ro passenger ferry 'Herald of Free Enterprise' capsized and 163 people perished while leaving Zeebrugge harbor. It is strongly believed that the capsize happened as a result of hydrodynamic trim and bow waveform. Upon forgetting the bow door open, water entered the car deck through already trimmed bow door causing ship to lose its stability and capsize.

The only parameters that can be changed in order to evade squat are speed and direction while sailing in shallow water, since ship particulars and water depth are constant. Hydrodynamic model tests have shown that sinkage and dynamic trim increase significantly with increasing speed. In general, model test results are presented as empirical expressions based on the nondimensional ratios such as Froude number, water depth/draft and ship length/water depth rendered from forward speed, depth and ship characteristics. These empirical or semi-empirical formulaė and curves may help masters determine their critical speeds depending on the water depth in that particular region in order to navigate safely.

2. THEORETICAL ASSESSMENT OF SQUAT

The first hydrodynamic theory on squat has been developed by Tuck [5]. Using one-dimensional theory, let the cross section of a ship be A(x) which is advancing in a rectangular canal having sectional area of A_0. If the water velocity is U, the continuity requires that;

$$UA_0 = U_1(x)\left[A_0 + w\zeta(x) - A(x)\right] \tag{2.1}$$

Here, the perturbations in y and z directions are neglected. In equation (2.1),

$$U_1(x) = U + u(x)$$

where;

- w : width of canal.
- ζ (x) : water surface elevation near the ship.
- u(x) : longitudinal perturbation velocity.

Having utilized Bernoulli equation at the free surface, one may obtain;

$$\frac{1}{2}U^2 = \frac{1}{2}U_1(x)^2 + g\zeta(x) \tag{2.2}$$

After necessary mathematical manipulations, equations (2.1) and (2.2) yield;

$$\frac{F_{nh}{}^2}{2}\left[\frac{U_1(x)}{U}\right]^3 - \left[1 - m(x) + \frac{F_{nh}{}^2}{2}\right]\frac{U_1(x)}{U} + 1 = 0 \tag{2.3}$$

where m(x) is the local blockage ratio defined as $\left[m(x) = \dfrac{A(x)}{A_0}\right]$ and F_{nh} is the Froude number based on the undisturbed water depth defined as $F_{nh} = \dfrac{V}{\sqrt{gh}}$.

Following Bernoulli's equation, for the nondimensional water surface elevation $\zeta^*(x)$;

$$\zeta^*(x) = \frac{\zeta(x)}{h} = -F_{nh}{}^2 u^*(x)\left[1 + \frac{u^*(x)}{2}\right] \tag{2.4}$$

where; $$u^*(x) = \frac{u(x)}{U}$$

According to the theory, from equation (2.4) average sinkage and trim coefficients can be found as follows respectively;

$$C_S = \frac{100.S_m}{L_{BP}} = 100\frac{h}{T}\cdot\frac{T}{L_{BP}}\cdot\frac{\int \zeta^*(x)B(x)dx}{\int B(x)dx} \tag{2.5}$$

$$C_T = 100T = 100\frac{h}{T}\cdot\frac{T}{L_{BP}}\cdot\frac{\int \zeta^*(x)B(x)x dx}{\int B(x)x^2 dx} \tag{2.6}$$

In equations (2.5) and (2.6), all moments are taken about the center of floatation of the ship and all B(x) and x are nondimensionalized by dividing them by ship length, L_{BP}.

One-dimensional theory assumes that the longitudinal perturbation is constant at a given fluid section. However, this assumption is not quite valid if the canal width is infinite. One-dimensional theory have developed the concept of "effective canal width" in order to surmount this dilemma [5]. The effective canal width is then defined as below;

$$\overline{w} = \frac{w}{L_{BP}}\sqrt{1 - F_{nh}{}^2} \tag{2.7}$$

Following the results of model experiments, The mean sinkage and trim coefficients are defined as follows respectively;

$$C_{Sn} = \alpha(\overline{w})C_{S1} \tag{2.8}$$

$$C_{Tn} = \beta(\overline{w})C_{T1} \tag{2.9}$$

where;

$$\alpha(\overline{w}) = \frac{1}{1 + \delta C_s}$$

$$\beta(\overline{w}) = \frac{1}{1 + \delta C_T}$$

The coefficients δC_S and δC_T can be determined based on the effective canal width. If the width of the canal is chosen large enough or an effective canal width is defined, one will be able to investigate the behavior of the ship in open water.

3. MODEL EXPERIMENTS

The model experiments have been performed by Millward [3] in the No.2 tank of British Maritime Technology Ltd. The dimensions of the tank is 195x6.1 m. with the depth of 2.7 m. more than halfway and the remainder is shallow water which can be set within the range of 0 to 0.6 meters.

Originally 6 ship model were used covering wide range of ship types in order to examine variation of squat with ship particulars (see Table 1). Some models were fitted with bulb and other appendages such as bossing and brackets and towed via a universal joint attached to a strain gauge to measure resistance. During the experiments, resistance, trim and squat were recorded at various speed values for four shallow water depths. The ship length/water depth ratios were chosen to be 6, 8, 10 and 12.

Although Millward carried out experiments for all six models, in this work only two models are selected (model A and model D) being the representatives of two extreme cases: light displacement ship and tanker with no appendages respectively. The squat data about the capsized ro-ro ferry is adopted from Dand [4].

Table 1. Particulars of the models.

Model type	L_{BP}(m)	L_{BP}/T	L_{BP}/B	C_B
A	3.167	20.70	6.463	0.444
B	3.715	24.28	7.887	0.502
C	3.115	23.25	6.242	0.735
D	3.344	18.27	7.831	0.763
E	3.387	18.02	6.464	0.820
F	3.536	14.92	6.128	0.828

Hydrodynamic trim may be measured at the midship and the bow of a ship. It is believed that bow squat is greater in magnitude thus has more effect on grounding or capsizing. It has been observed that the variation of squat follows the same trend for various ships although the magnitude differs from slender to fuller forms. There exists a critical value of speed, which is so-called the critical Froude number (F_{nh}=1) that shape of the squat curve changes bluntly. Therefore the speed values above the critical speed called supercritical speeds whereas the ones below the critical speed are called subcritical speeds. The main interest is focused on the range values up to and around the critical speed namely in the subcritical regime. At supercritical speeds squat may even become negative for some vessel types. That means the ship rises with compare to its original static draft line. The results depict that full form vessels such as tankers trims more by the bow than the slender forms. Barrass [9] and Fuhrer and Romisch [10] concluded that slender ships trim by stern however full form vessel trim by the bow. This conclusion was also confirmed by Dand and Ferguson [1] and Eryuzlu and Hausser [11] who both stated that their fuller models trimmed by the bow more. Millward [3] found that for full ships the trim was always bow down although this value got very small for slender ships. Some of the existing methods available in the literature are supplied in the Appendix.

Baker [7] has concluded in his earlier work that there is a critical speed at which no wave resistance was encountered and the increase was only due to skin friction, form and eddy making. He further stated that eddy making would grow rapidly and all wave making was increased in shallow water.

4. THE '*HERALD OF FREE ENTERPRISE*' CASE

The ro-ro passenger and freight ferry has been lost on March 6, 1987 right off the Zeebrugge harbor which was concluded to be due to both squat and bow waveform resulting in heavy loss of 163 lives. When she left the harbor, the bow door where large amount of water entered the main deck was forgotten to be shut. Thus, due to the combination of human error and squat the vessel lost its stability and unfortunately went down. British Maritime Technology Ltd. carried out an investigation to find out the causes of capsize, Dand [4]. For this purpose a series of model tests and full-scale trial were performed to simulate the events at the time of the incident. The data used in this work has been adopted from the above-mentioned study. The characteristics of the ferry is as follows:

Length between perpendiculars	L	= 126.1 m.
Breadth	B	= 22.7 m.

Draft	$T = 5.7$ m.
Block coefficient	$C_B = 0.525$
Deadweight tonnage	DWT = 2000

The data about the ferry will be used later in this work to verify the validity of the proposed expressions to estimate the bow squat.

5. PRESENTATION OF RESULTS

As was stated in the foregoing argument, the experimental results of highly slender and full hull forms were treated by a curve fitting method and formulated by powers or exponential of the Froude number to be used practically by masters. The expressions found by this analysis quantify the bow squat as a percentage of the ship length or ship draft for various water depths. First, the bow squat as a percentage of ship length with respect to depth Froude number is approximated including all four water depth values for model A and model D separately. The regression analysis revealed the best fit with exponential law with the following expression and coefficients, Figures 1-2;

$$S_{bow}(\%L_{BP}) = K1\, e^{K2 F_{nh}} \quad (5.1)$$

where the coefficients K1 and K2 are;

$$K1 = \frac{T}{10B} \cdot 1.12 \qquad \text{and} \qquad K2 = \frac{10T}{B} \cdot 7.9 \quad (5.2)$$

This time, the same data were used to calculate the bow squat as a percentage of the draft with respect to $(T/h)V^2$ by the same technique regardless of water depth for both models. As before, the exponential law gave the best result linking two variables together, Figures 3-4;

$$S_{bow}(\%T) = K1\, e^{K2 (T/h) V^2} \quad (5.3)$$

where the coefficients K1 and K2 are;

$$K1 = 3.06\, CB + 2T \qquad \text{and} \qquad K2 = 5.4\, B \quad (5.4)$$

The preceding formulae is valid irrespective of ship type or dimensions, water depth and canal width.

The comparison with other approximations are shown in the Figures 1-4. Eryuzlu and Hausser [11] underestimates the bow squat whereas Fuhrer and Romisch [10] overestimates for model A both having water depth limitations. For model D however, both researchers predict bow squat over the experimental values. Millward [3], which has canal width limitation on the other hand, gives good approximation for both models akin the present method. Evidently, the theoretical estimations are always above the experimental values due to the slender body assumption.

Moreover, the percentage of bow squat is plotted against the Froude number for each water depth just to observe the effect of depth on squat. These conditions are depicted schematically for model A and Model D in Figures 5-6 respectively. Finally for two water depth values 12.2 m. and 16.5 m. the absolute bow squat values of the Herald of Free Enterprise is plotted with respect to ship speed in Figures 7-8 comparatively with other methods.

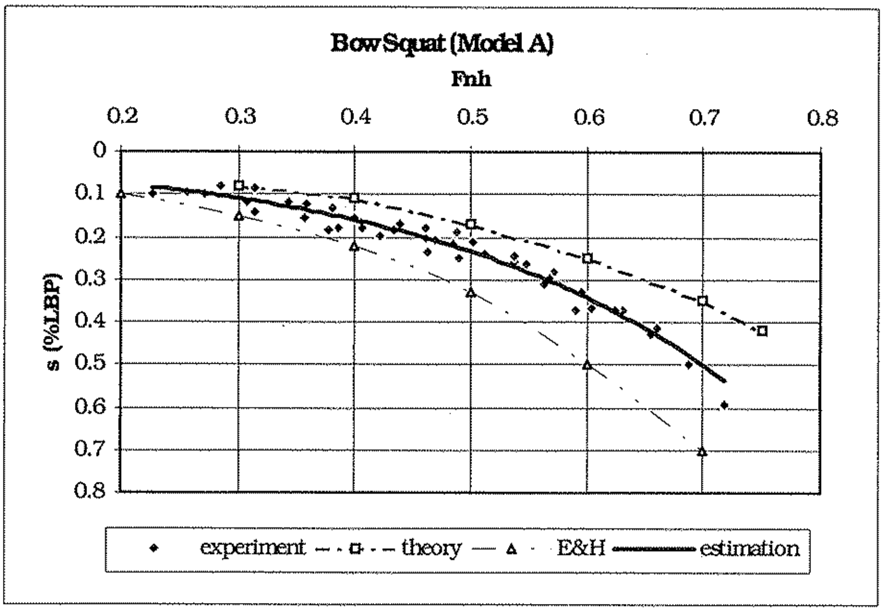

Fig.1 Bow squat comparison for model A (%L_{BP}).

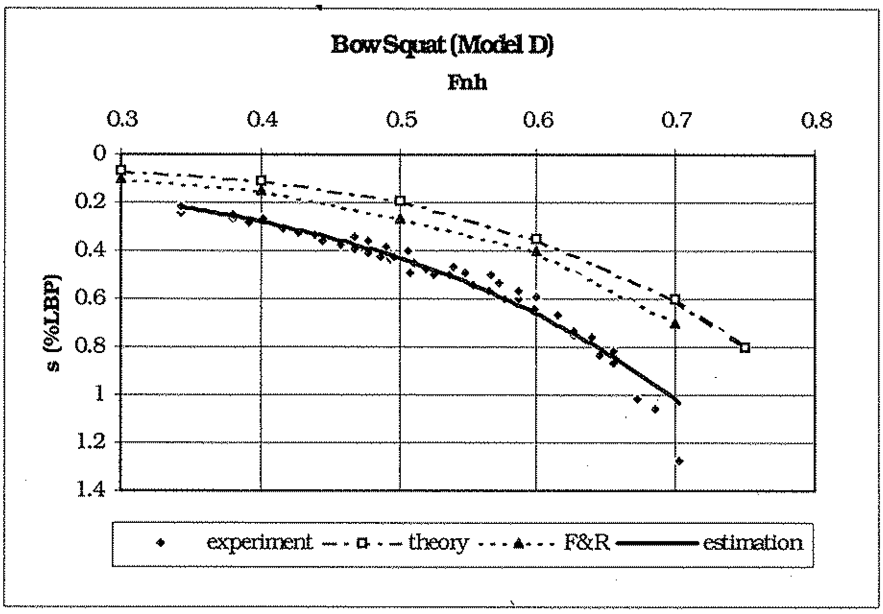

Fig. 2 Bow squat comparison for model D (%L_{BP}).

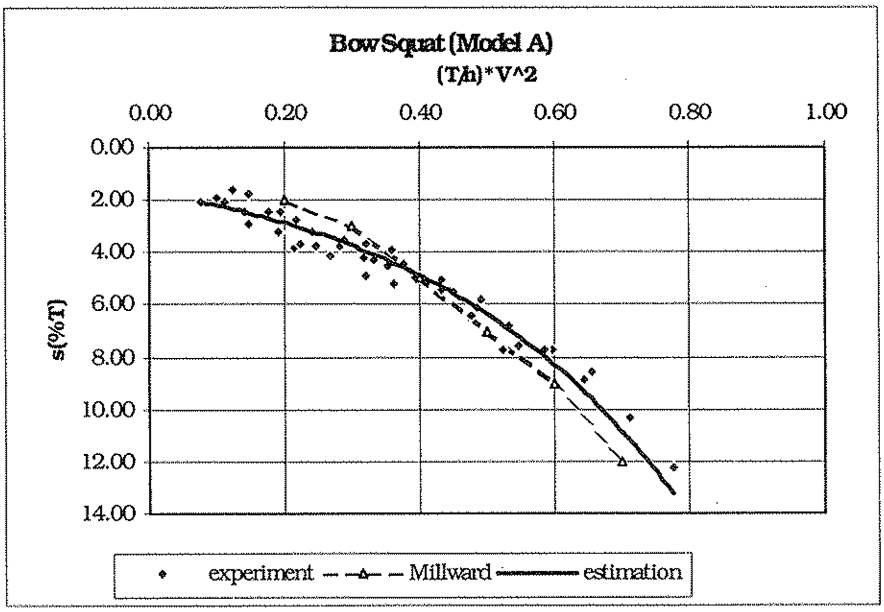

Fig. 3 Bow squat comparison for model A (%T).

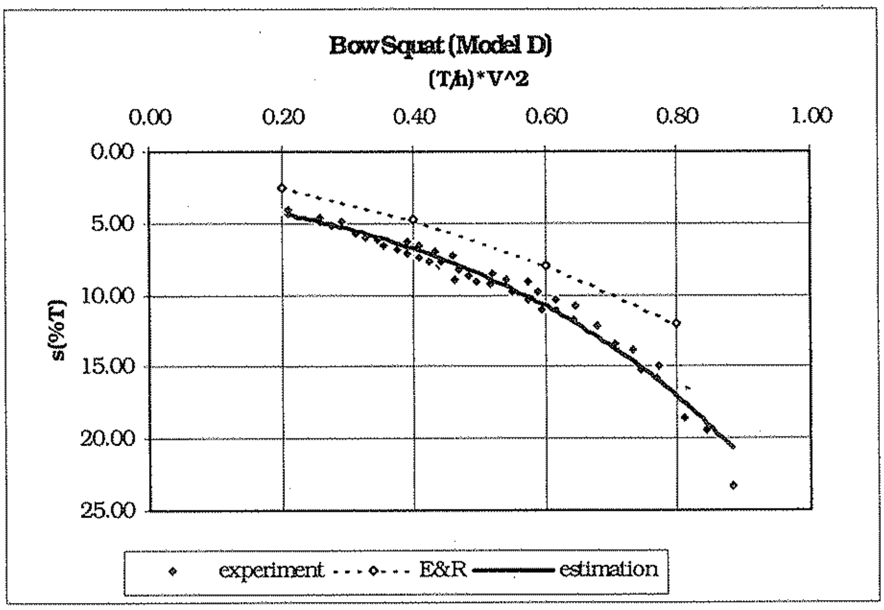

Fig. 4 Bow squat comparison for model D (%T).

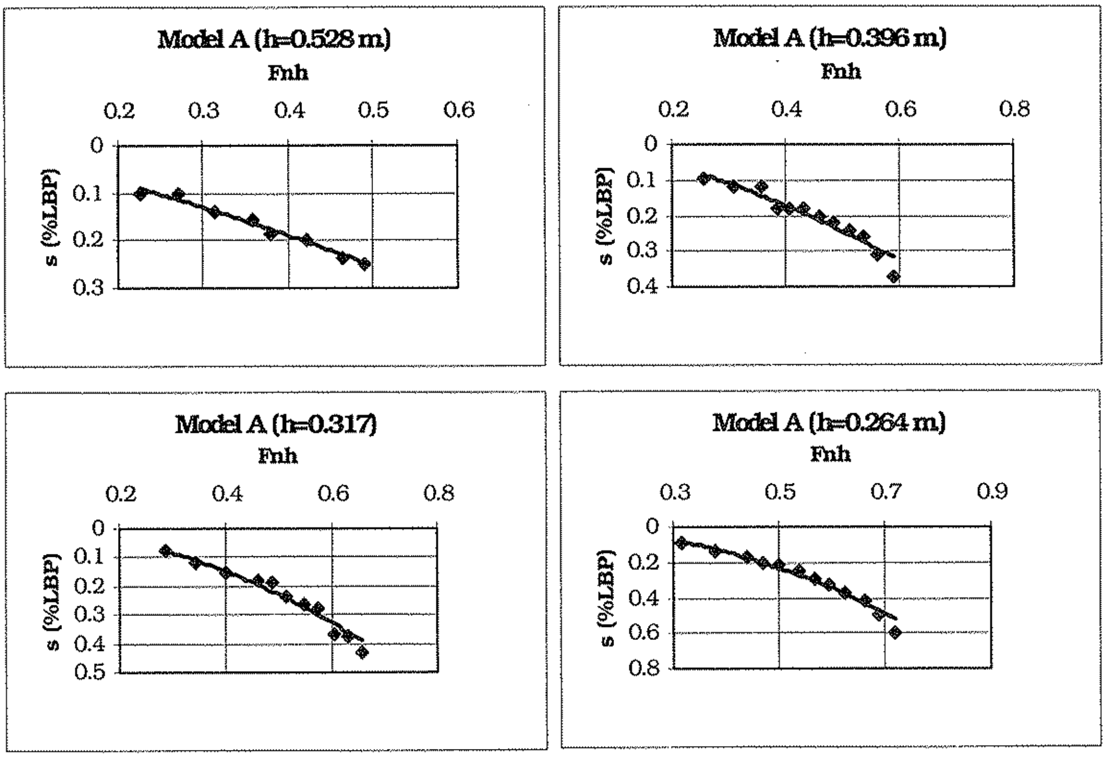

Fig. 5 Effect of water depth on bow squat for model A.

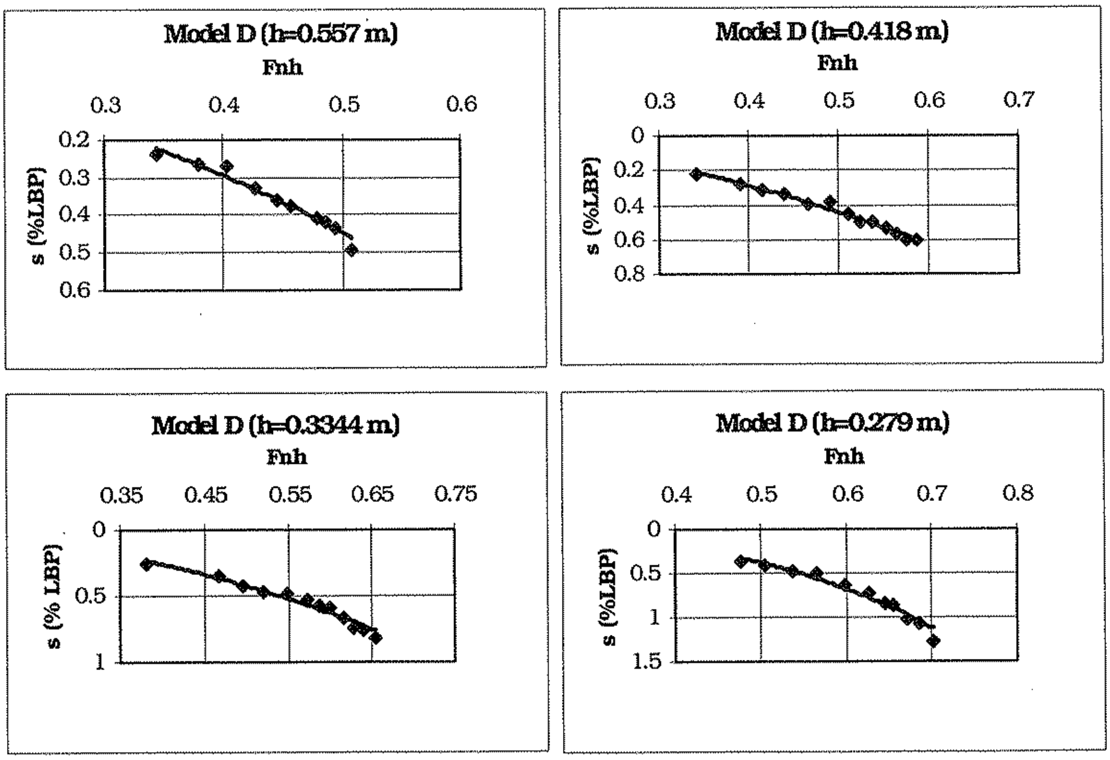

Fig. 6 Effect of water depth on bow squat for model D.

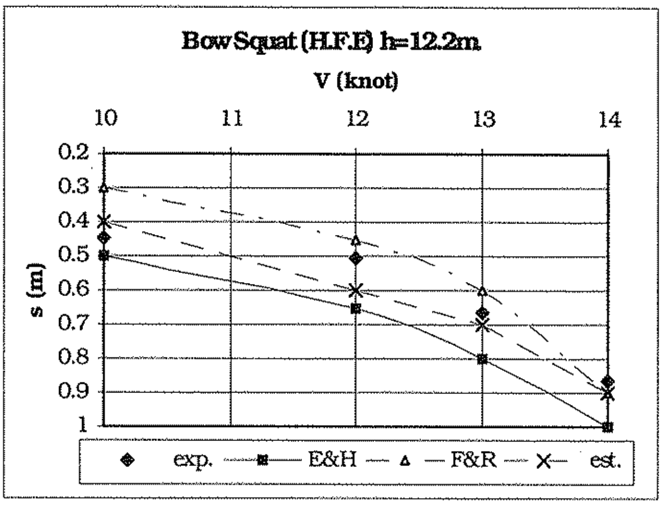

Fig. 7 Bow squat comparison for HFE at 12.2 m. depth.

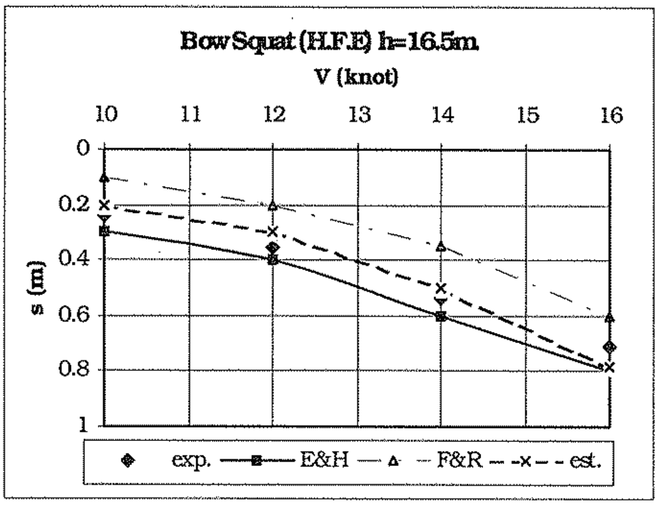

Fig.8 Bow squat comparison for HFE at 16.5 m. depth.

6. CONCLUSIONS

At present, there does not exist an effective theoretical model to predict squat of a ship in shallow water other than the one presented by Tuck [5] which utilizes slender ship assumption. Hence experimental and empirical estimations must be relied on until any better method becomes available. There are parameters such as initial trim, speed, and water depth/draft ratio that affect the squat to a great deal. Especially trim by head or stern dictates whether the head or the stern will ground first. An attempt was made to express the empirical estimation of bow squat and it was shown that they correlate very well with the experimental data without imposing any limitations in application. Most of the existing methods have limited application area and predict squat poorly with compared to the proposed formulae. Therefore they can be used easily to calculate bow squat by masters navigating in shallow and restricted waters to avoid grounding.

REFERENCES

1. I.W. Dand and A.M. Ferguson, The Squat of Full Ships in Shallow Water, *RINA Transactions* 237-247, 1973.
2. A. Millward, A Comparison of the Theoretical and Empirical Prediction of Squat in Shallow Water, *International Shipbuilding Progress* **39**, 1991.
3. A. Millward, A Preliminary Design Method for the Prediction of Squat in Shallow Water, *Marine Technology* **27**, 10-19, 1990.
4. I.W. Dand, Hydrodynamic Aspects of the Sinking of the Ferry Herald of Free Enterprise, *RINA Transactions* **131**, 145-165, 1988.
5. E.O. Tuck, Shallow Water Flow Past Slender Bodies, *Journal of Fluid Mechanics* **26**, 81-95, 1966.
6. I.A. Svendsen and P.A. Madsen, The Dynamics of wave Induced Ship Motions in Shallow Water, *Ocean Engineering* **8**, 443-479, 1981.
7. G.S. Baker, The Effect of Shallow Water on the Movement of a Ship, *TINA* **94**, 110-125, 1952.
8. I.W. Dand, On Ship-Bank Interaction, *RINA Transactions* **124**, 25-40,1988.
9. C.B. Barrass, The Phenomenon of Ship Squat, *International Shipbuilding Progress* **26**, 44-47, 1979.
10. M. Fuhrer and K. Romisch, Effects of Modern Ship Traffic on Inland and Ocean Waterways and Their Structures, PIANC XXIV, Leningrad, 79-93, 1977.
11. N.E. Eryuzlu and R. Hausser, Experimental Investigation Into Some Aspects of Large Vessel Navigation in Restricted Waterways, *Proceeding, Symposium on Aspects of Navigability*, Delft, the Netherlands **2**, 1-15, 1978.
12. A. Millward, The Effect of Water Depth on Hull Form Factor, *International Shipbuilding Progress* **36**, 283-302, 1989.
13. G. Hughes and J.F. Allen, Turbulence Simulation on Ship Models, *SNAME Transactions* **59**, 281-314, 1951.

APPENDIX

Four of the existing methods that can be found in the literature to estimate squat are presented:

1. Fuhrer and Romisch Method

The method calculates the squat for the bow and the stern at critical and other speed values as follows;
For critical the speed, the bow squat is;

$$S_{bcri} = 0.2\left[\frac{10C_B B}{L_{BP}}\right]^2 T \quad \text{(A.1)}$$

Squat for any speed other than critical speed;

$$S = 8\left(\frac{V}{V_{cri}}\right)^2\left[\left(\frac{V}{V_{cri}} - 0.5\right)^4 + 0.0625\right]S_{cri} \quad \text{(A.2)}$$

The critical speed values for various L_{BP} is calculated as below;

For $L_{BP} \leq 3b$ and $A_m/A_c<1/6$;

$$V_{cri} = \frac{1}{80}\left[\frac{h}{T}\frac{L_{BP}}{B}\right]^{\beta} \cdot (gh)^{2} \tag{A.3}$$

where;
$$\beta = 0.24\left(\frac{L_{BP}}{b}\right)^{0.55}$$

For $L_{BP}>3b$;

$$V_{cri} = \frac{1}{80}\left[\frac{h}{T}\frac{L_{BP}}{B}\right]^{0.125} \cdot (gh)^{1/2}$$

(A.4)

2. Millward Method
For midship squat;

$$S_{mid} = \frac{[12.22C_B \cdot B/L_{BP} - 0.46]F_{nh}^{\ 2}}{1-0.9F_{nh}} \tag{A.5}$$

For bow squat;

$$S_{bow} = \frac{[15.0C_B \cdot B/L_{BP} - 0.55]F_{nh}^{\ 2}}{1-0.9F_{nh}} \tag{A.6}$$

3. Eryuzlu and Hausser Method
Maximum bow squat is;

$$S_{max} = 0.113B\left(\frac{T}{h}\right)^{0.27}\left[\frac{V}{\sqrt{gh}}\right]^{1.8} \tag{A.7}$$

4. Barrass Method
Maximum bow squat is expressed by;

$$S_{max} = \gamma\ C_B\left[\frac{A_m}{A_c - A_m}\right]^{2/3} V^{2.08} \tag{A.8}$$

where $\gamma = 0.133$ for full size ships and $\gamma = 0.121$ for models.