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EXPERIENCE MEASURING FULL SCALE SQUAT OF FULL FORM VESSELS AT AUSTRALIAN PORTS

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The existence of ship squat has been known for many years and is a major factor in shallow water navigation and underkeel clearance (UKC). However there is still a great deal of uncertainty within the shipping community regarding the magnitude and location of maximum ship squat.

The importance of being able to accurately predict ship squat is of increasing concern, as ships become larger and the need to sail with deeper drafts grows.

With new technology advances in the area of Differential Global Positioning System (DGPS) it has become possible to measure full-scale ship squat with sub-decimeter accuracy.

Such measurements have been performed with excellent results, which help to dispel some of the myths regarding ship squat and increase the degree of confidence ship handlers have in squat prediction, and hence the UKC available to them.

1 NOTATION AND UNITS

B = Beam
C_B = Block coefficient = $\nabla/L_{BP}B$
F_{nh} = Froude depth number = $u/\sqrt{(gh)}$
g = Acceleration due to gravity (9.81 m/s^2)
h = Undisturbed water depth
L_{BP} = Length between perpendiculars
S_b = Squat at the bow
u = Speed in m/s
V_k = Speed in knots
∇= Immersed volume

2 INTRODUCTION

As a ship moves, it pushes water ahead of it, which returns down the sides and under the keel, causing an increase in fluid velocity. This results in a depression in the water level and a mean downward sinkage of the ship. Since the ship is not symmetrical there is also a difference in the pressure distribution between bow and stern which causes a ships trim to change either forward or aft.

Squat is the net result of sinkage and change in trim and is magnified in restricted water.

A well proven, however sometimes little known or accepted fact of squat is that full-bodied vessels such as bulk carriers and tankers squat more at the bow than at the stern. Fine-form vessels such as passenger ferries and container ships generally experience maximum squat at the stern.

Many equations for predicting ship squat exist; most are based on model scale testing which has produced a large scatter in results between researchers. Identifying which, if any, of these methods provides an accurate squat prediction is of great importance when sailing in shallow water.

It is also important that mariners and port planners become aware that 'rule of thumb' methods for predicting squat are not accurate and can be very dangerous.

3 EMPIRICAL MODEL

Dr. C. B. Barrass is perhaps the most well known authority on ship squat. Barrass (1) has developed several formulae over many years, of which two of the most common are:

$$S_b = \frac{C_B \times V_K{}^2}{100} \qquad (1)$$

and

$$S_b = \frac{C_B \times S_2{}^{\frac{2}{3}} \times V_K{}^{2.08}}{30} \qquad (2) \qquad \text{where } S_2 = \frac{A_S}{A_W}$$

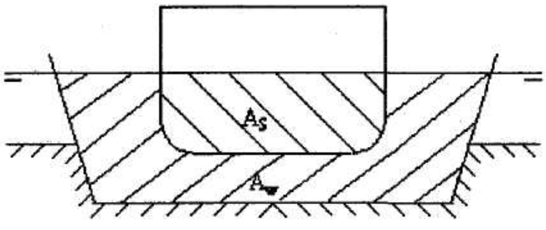

Figure 1: Ship-Waterway Relationship Definition

Barrass also proposed several different methods for calculating the 'blockage factors' in channels and canals. These included using an 'effective width' or 'width of influence' for channels and open water.

Barrass has performed model scale tests and some full-scale tests (using less accurate methods than is now available with DGPS) the results of which are the basis of his formulae. His work has identified many important issues concerning squat and provided valuable tools for squat prediction.

Millward (2) is also well known for his work in squat prediction. The two most common of his formulae for predicting squat are based on model scale testing results, one predicts bow squat eqn. 3 below, the other squat at midships.

$$S_b = \frac{\left[\left(15 \times C_B \times \frac{B}{L_{BP}} - 0.55\right) F_{nh}^{\ 2}\right]}{1 - 0.9F_{nh}} \qquad (3)$$

There are several 'rules of thumb' which are widely accepted and applied in practice, for example, 30 cm (a foot) of squat for every 5 knots; and squat in meters is equal to the square of the speed in knots/100. These two rules alone produce very different results.

Figures 2 and 3 below, show comparisons of the squat predictions from the following methods:

- Barrass (2)
- Millward (3)
- Speed squared/100
- 30cm for every 5 knots (Rule of Thumb)

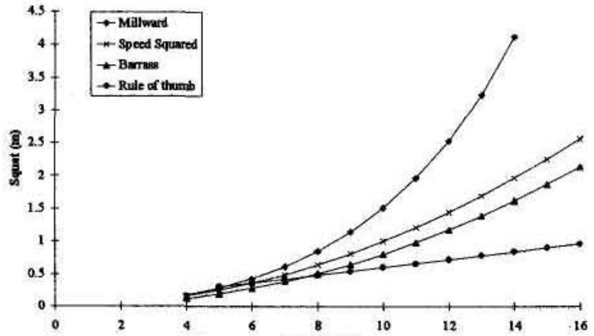

Figure 2: Open Water

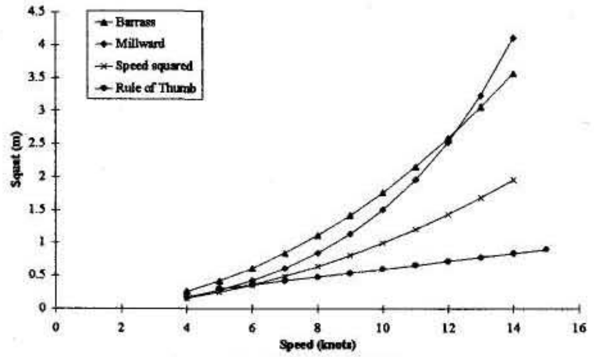

Figure 3: Restricted Water

A wide scatter in the results is apparent. The question remains, which is accurate?

Until recently it has been very difficult to validate the existing formulae with any degree of confidence as there has been no method of accurately measuring full-scale vessel squat. Advances in the area of DGPS have overcome this problem making full-scale squat testing not only possible but also highly accurate.

4 FULL-SCALE TESTING

Since 1997 O'Brien Maritime Consultants (OMC) has conducted full-scale squat measurements on 44 vessels in five different ports around Australia.

The vessels tested have primarily been bulk carriers, up to Cape size, and tankers. The range of conditions at each of these ports varies considerably, including narrow channels, undulating sea floors and variations in tide and wave conditions. Each study has highlighted the sensitivity of squat to the local conditions and individual channel configuration.

4.1 Equipment

DGPS equipment with On-The-Fly capabilities has been used for all of the testing carried out. This equipment is extremely accurate (within 10cm vertically) and easy to deploy.

To measure maximum squat three DGPS units are used, one is located on land and acts as a base station, the other two are temporarily set-up on the ship, one on the bow, the other on the monkey island. This technique measures both fore and aft squat and allows for the separate sinkage and trim components of squat to be quantified.

4.2 Full Scale Measurement Examples

Bow and Stern Squat

Ship squat at the bow and stern measured by the DGPS equipment is shown below in Figure 4. The oscillations shown indicate the dynamic motions (heave and pitch) of the vessel. The vessel squat is taken to be the mean of these oscillations.

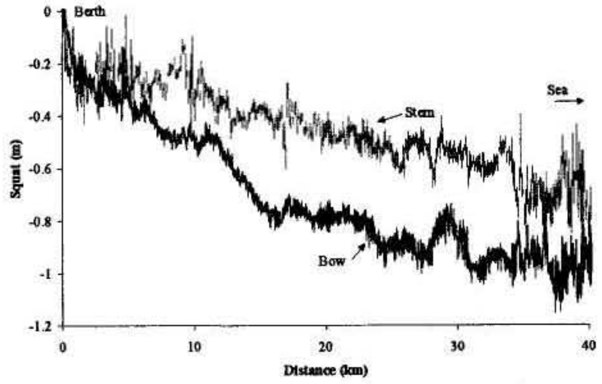

Figure 4: Measured Bow and Stern Squat

Clearly the bow of the vessel experiences greater squat than the stern.

Over the initial five kilometers of the transit the bow and stern squat are similar in magnitude, indicating that bodily sinkage is occurring. After this distance the ship began to increase speed and the vessel's trim altered to produce maximum squat at the bow.

This ship was loaded with an initial trim by the stern. This contradicts comments by Barrass that a vessel initially trimmed by the stern will experience maximum squat at the stern.

Empirical Formula Validation & Dynamic Motions

The method OMC has found to provide a close prediction to the full-scale squat measurements is that developed by Eryuzlu et. al. (3). This method was developed from full-scale trials in the St. Lawrence Ship Channel and model scale testing.

The predicted squat from the Eryuzlu empirical formula calculated using the actual speed of the vessel as measured by the DGPS is shown below in Figure 5 as the light line.

The dark line is the measured squat at the bow and shows large oscillations, indicating significant dynamic motions of the vessel due to wave action in the channel.

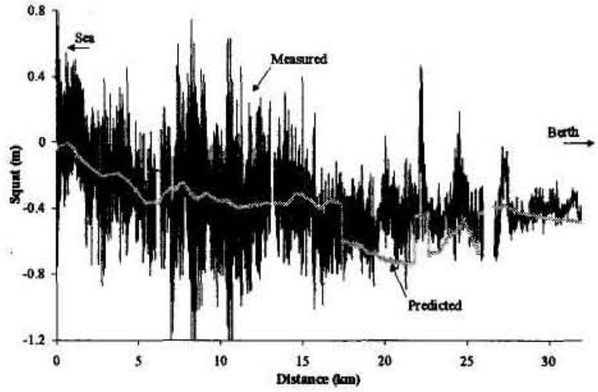

Figure 5: Empirical Squat Formula and Large Dynamic Motions

This example shows how accurate the Eryuzlu formula can be and is typical of the results obtained from the 44 vessels tested.

Comparisons between Eryuzlu's method and the empirical formulae discussed earlier are shown below in Figures 6 and 7.

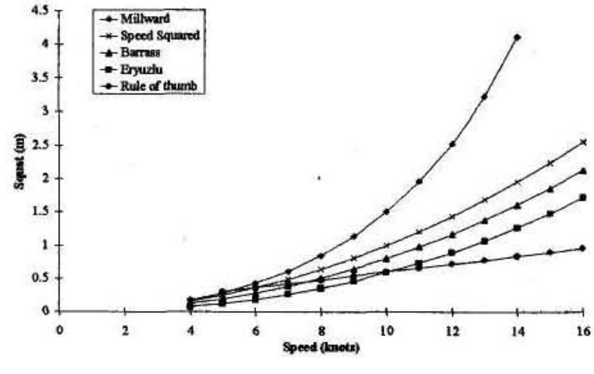

Figure 6 : Open Water

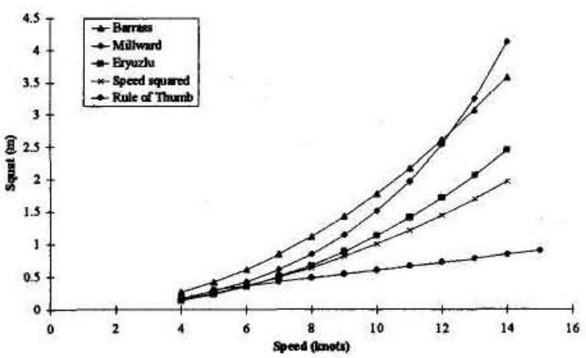

Figure 7 : Restricted Water

Given that the Eryuzlu squat formula is accurate, the comparisons in Figures 4 and 5 show that:

- The 30cm for every 5 knots 'rule of thumb' method dangerously under-predicts the squat of a vessel, particularly at speed in both restricted and open water.
- The 'square of the speed' method under-predicts squat in restricted water and is therefore dangerous and significantly over predicts it in open water.
- Millward's method significantly over predicts squat in both open and restricted water.
- Barrass's method is conservative in both restricted and open water. In open water the method provides a good indication of the squat, in restricted water the method significantly over-predicts the squat.

It is very important to be aware that the Eryuzlu formula was developed for use in a particular set of conditions where the channel width, depth of cut, batter slope etc. are strictly defined.

Although the formula produces accurate results when applied to these conditions, it requires adjustment when the channel configuration does not comply with the pre-defined characteristics that the formula was derived for.

Each channel has individual features that effect ship squat in different ways. How to take these into account within the general formula is one of the largest benefits of full-scale squat testing.

Occasionally there have been examples from the full-scale test results undertaken by OMC, where the empirical formula has not been accurate. Examples of when the formula requires adjustment before it can provide an accurate prediction under certain circumstances are shown below.

Effect of Rapid Acceleration

The effect of rapid acceleration on squat has not been thoroughly studied, however results from the full-scale testing show that it can be significant.

In one set of full-scale testing two similar ships (Vessels A and B) were squat tested, their speed profiles along the approach channel are shown below in Figure 8.

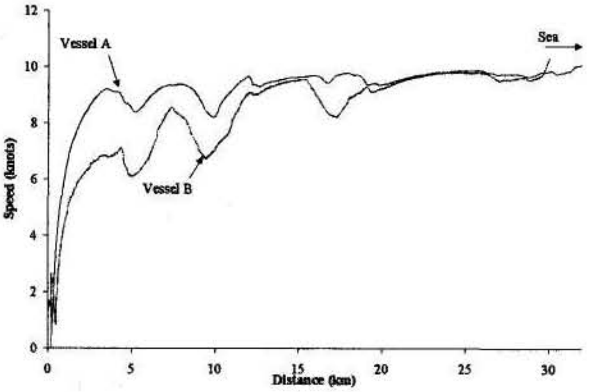

Figure 8: Speed Profile of Vessel A and Vessel B

As can be seen from Figure 8 the rate of acceleration between the two vessels is markedly different.

It is clear that Vessel A very quickly (within five kilometers) accelerates to 9 knots while Vessel B accelerates to the same speed over a much longer distance (approximately 12 kilometers).

The effect of this difference in vessel speeds on squat is shown in the squat profiles of Vessel A (Figure 9) and Vessel B (Figure 10).

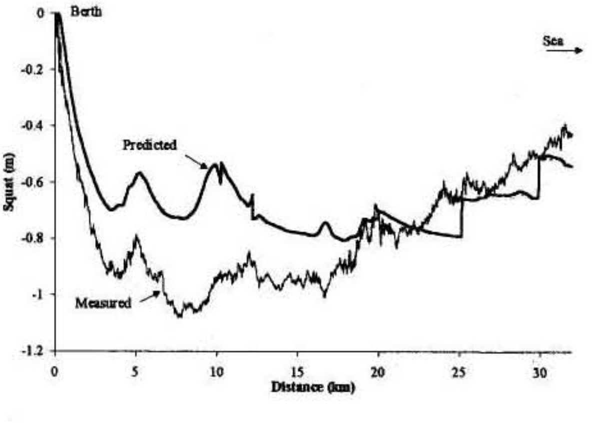

Figure 9: Measured Squat of Vessel A

The measured squat is shown to exceed the predicted squat significantly. Such a large increase in squat from predicted has the potential to be very dangerous if the Master/Pilot is unaware of the extra squat created from rapid acceleration.

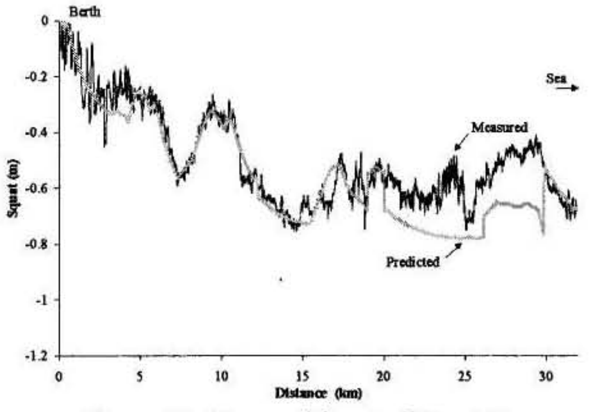

Figure 10: Measured Squat of Vessel B

The measured squat very accurately matches the predicted squat, clearly showing that by controlling the rate of acceleration, as well as the speed, the vessel squat can be accurately predicted.

Squat over an Undulating Sea Floor

The effect on squat of a change in sea floor topography is still very much unknown. The author conducted model scale squat testing over an undulating sea floor (4), the results of which correlated very well with Pilot experience of the particular situation.

It was found from this research that an undulating sea floor does have an effect on the squat of a ship, particularly at high speed and/or small underkeel clearance. While the fundamental squat behavior remains the same, that is the maximum squat is still by the bow, the magnitude of the squat is increased.

What is termed *dynamic squat* was found to exist, however at present there is no equation to model or predict this. Being aware of the occurrence of dynamic squat can ensure that caution is taken and allowances made where necessary.

An example of measured full scale squat over an undulating sea floor is shown below in Figure 11.

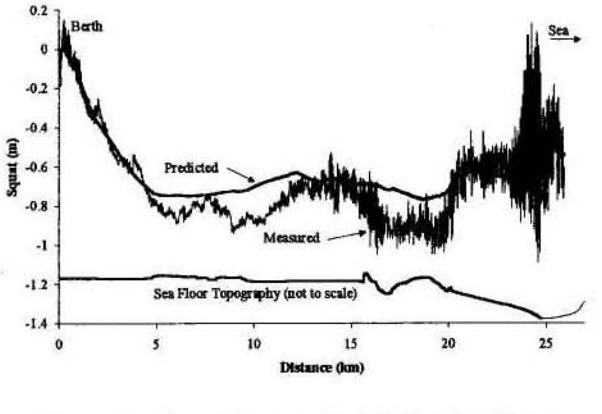

Figure 11 : Squat Over an Undulating Sea Floor.

The measured squat exceeds the predicted squat at two locations in the channel, between 5 - 12 kms, and between 17 - 20 kms.

Upon close inspection of these two areas the following were found:

- between 5 - 12 kms there was considerable siltation within the channel which had not previously been identified, thus reducing the water depth used to calculated the predicted squat.

- between 17-20 kms there is large patch of rock, shown on the schematic of the sea floor in Figure 11. This large area of rock constitutes an undulating sea floor and caused dynamic squat to occur in this case. While many ships were tested over this area, this was the only vessel exhibiting excessive squat. This was due to the speed of this vessel compared to the others tested. Over this area most vessels were travelling approximately two knots slower than the vessel shown above.

Again, this is an example where controlling the vessel speed will assist in ensuring that the vessel squat does not exceed that predicted and that the UKC remains adequate.

Alternatively, this result assists in highlighting areas that would benefit from localised dredging. By removing the high peak of rock and/or the area of siltation, the squat would be reduced and the available UKC increased.

4.3 Results

From the full-scale testing undertaken to date the following factors have been identified as **major** contributing factors in squat determination:

1) Vessel **speed** *through the water*. Vessel speed is the largest factor influencing ship squat, being approximately equal to the square of the speed. For a ship sailing in still water this is the same as the vessel speed over the ground. If there is a current present, the vessel speed *through the water* will differ from the vessel speed over the ground.

2) **The depth/draft ratio.** As the water depth under the keel decreases the squat increases.

3) **Channel width and depth of cut.** When considered in terms of ship beam and draft, this is known as blockage effect. In a confined channel the squat will be greater (increased blockage) than if the channel is wider or depth of cut is less.

6) **Configuration of the sea floor.** Undulations in the sea floor have been shown to considerably affect the squat, producing a dynamic effect, which can influence the vessel over several ship lengths.

7) **Acceleration and deceleration effects.** The effect of rapid acceleration was measured and showed an increase squat beyond that predicted. Rapid deceleration may also result in a *dynamic* response to the loss in speed, thus decreasing squat.

Other factors that have not been tested in the full-scale trials conducted by OMC but may need to be considered at some ports are:

4) **Changes in fluid density.** Squat over a muddy bottom is generally less than over a rock bottom.

5) **Passing and overtaking.** A vessel's squat is increased when in close proximity to another vessel, particularly at speed.

Accurate squat determination ensures safety, however there are added incentives to ensure that squat is predicted accurately.

Once ship squat can be accurately predicted it may be used to derive economic benefit without compromising safety. If it is known that the ship squat will be 60cm, yet 80cm is allowed based on an empirical formula, then there is scope for a safe draft increase without reducing the UKC.

This philosophy can be applied to all the factors affecting underkeel clearance, to ensure a safe margin is allowed without being over conservative.

5 SQUAT CONCLUSIONS

The full-scale measurements performed on full-form vessels have:

- provided an excellent record of the magnitude of squat experienced by full-formed vessels;

- proven that full form vessels squat by the bow;

- highlighted many factors that affect ship squat, and provided an understanding of how to ensure that predicted squat is not exceeded.

- emphasized that controlling vessel speed will, in most cases, ensure that the squat of vessels can be accurately predicted.

Conclusions that may be drawn from the full-scale tests compared to empirical formulae:

- in general, existing empirical formulae over-predict the squat of vessels. This is because the empirical formulae have primarily been derived from model-scale testing results.

- simple 'rule of thumb' methods to predict squat **should not be used** as they are inaccurate and can be very dangerous.

- full-scale squat measurements are necessary to calibrate empirical formulae for the individual characteristics of shipping channels.

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