CHAPTER 206

ON THE SQUATTING OF SHIPS IN SHALLOW AND RESTRICTED WATER

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1. INTRODUCTION

A major feature of the advances in marine technology is the increasing number, size and speed of ships and, consequently, an increased interest in hydrodynamic problems associated with water restricted in depth and/or lateral extent. The transport of dangerous cargoes and their impact on the benefits of resolving the areas of uncertainty.

Experience of 1,104 vessels of different flags and trades during 1978, shows that grounding/stranding is the third most frequent cause of damage[1]. An examination of the total expenditure of money and time required to repair the resulting damage shows this category to rank highly in both. Indeed, the total repair cost expended as a result of this cause rank top and account for more than 1/5th of the total. Although the shipowner bears a large proportion of the cost of lost revenue, grounding represents a significant cost to underwriters, shipowners and port authorities. The continuous increase in size and draught of vessels in relation to water depth ensures that this situation will continue unless there is a radical development in instrumentation.

To limit the risk of grounding it is extremely important to be able to predict which of a vessel's extremities will experience the greatest sinkage and ground. Where the underkeel clearance is low, reasonable accuracy is demanded in order to ensure safety and to avoid unduly reducing the earning capacity of the vessel by overcaution. This requires a sound knowledge of a vessel's tendency to 'squat'.

2. PRELIMINARY DEFINITIONS

All ships and offshore platforms, when underway, are subject to hydrodynamic pressure changes and friction induced trimming moments which alter their draught and trim in comparison with that when stationary. The term 'squat' includes both the change in draught and the contribution due to trim underway, at any hull extremity of interest. The usual approach to squat is to treat it as a steady-state problem, presenting curves for mean sinkage and trim at varying depths and speeds.

In the plotting of the results, certain non-dimensional parameters have been used:-

(a) The non-dimensional sinkage coefficient,

$$C_S = \frac{100(S_{FP} + S_{AP})}{2L}$$

(b) The non-dimensional trim coefficient,

$$C_\tau = \frac{100(S_{FP} - S_{AP})}{L} = 100\,\tau$$

where S_{FP} and S_{AP} are the sinkages measured at the forward and aft perpendicular, respectively, and τ is the trim angle at radians. Sinkage is assumed negative in the downward z-direction, while trim is defined negative when by-the-bow. Other terminology is explained more fully in reference[1].

3. THE PREDICTION

3.1 Theory

A comprehensive theoretical and experimental study of the ship-to-bottom interaction problem in both laterally restricted and unrestricted shallow water has been completed at the University of Glasgow[2]. It shows that, although both the hydrodynamic and hydraulic theoretical models provide a valuable insight into the squat problem (within the theoretical constraints of each case), a universally applicable theory which allows a routine solution with arbitrary Froude depth number and lateral restrictions, does not exist at present. The subsequent experimental work demonstrated limitations and illustrated features not apparent from the theoretical studies. A wide range of parameters affecting the vertical-plane forces in restricted water were examined, including effects of underkeel clearance, speed, self-propulsion, lateral restrictions, bulbous bow shape, initial trim, draught, a sudden variation in depth and the transverse location in the channel. A full discussion of the theoretical model developed is given in reference[2].

A computer program was written based on the above procedure. Figure 1 demonstrates its utility in predicting model squat in unrestricted shallow water by comparison with experiment. The method is broadly applicable to conventional full-form mono-hull models, towed or self-propelled at steady speed in shallow-water of uniform depth and any width.

3.2 Other Methods

Comparison in the laterally unrestricted shallow water between model data and two recent methods[3] shows that the BMT method gives the better predictions. The model used and the experimental data obtained are considered representative of the considerable data accumulated for the examined block coefficient range. The BMT method is recommended as the more accurate of the methods available and, on this evidence, could be used to derive GO/NO-GO curves, such as in fig. 2, for level or trimmed conditions of full-form vessels.

The inaccuracies of the Barrass formulae[4] stem from the fact that they do not take into account some of the important effects demonstrable by means of theory and model tests. It also appears that, by correlating results obtained on a wide range of hull features (ie, of varying geometry, static draught and trim, etc) and under different environmental conditions (such as water depth and/or lateral restrictions, etc) using various measuring apparatus, reliability has been unduly sacrificed in obtaining convenience. By comparison with model experiments the Barrass formulae are shown not to be conservative and not to possess sufficient limitations on their use under conditions which appear beyond their range of validity. As a result, under some circumstances their use may result in a false sense of security.

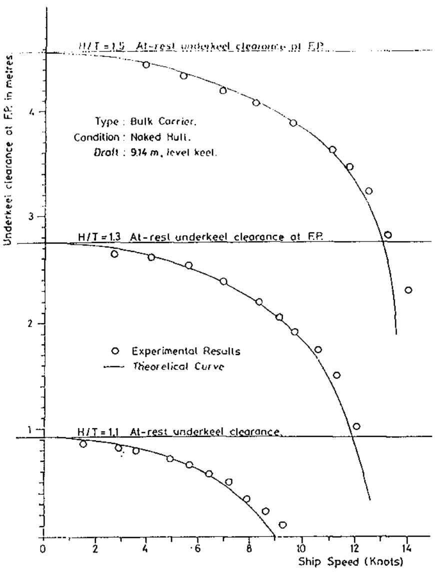


Fig 1: Results for 160m Geosim Ship

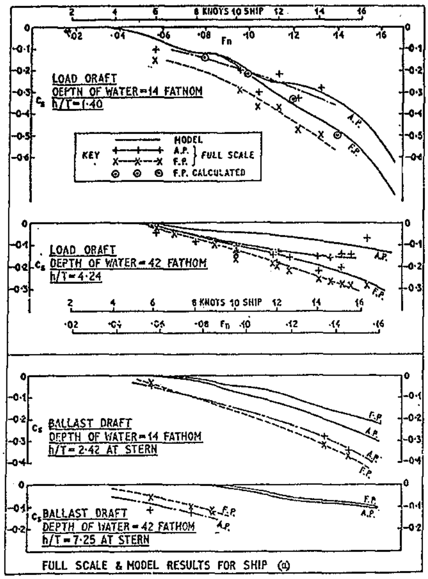


Fig 3

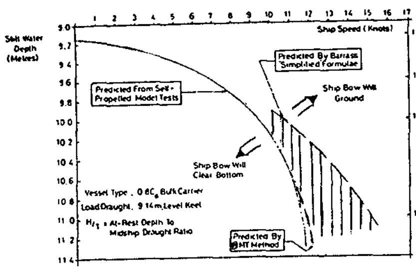


Fig 2: GO/NO-GO Predictions for Level Keel

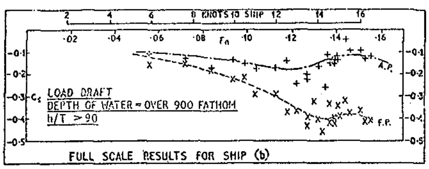


Fig 4

Ship	L_{BP} (m)	B (mld) (m)	D (mld) (m)	Cond	T (m)	Δ Tonnes	C_B	Trim (m by B/S)	H (m)	Location	Sea State
(A)	304.8	47.2	23.7	L	18.1	215,687	0.82	0	25.6	Cardigan Bay	3 (with long swell)
									76.8	St Georges Channel	
				B	9.2	109,137	–	2.8 S	25.6	Cardigan Bay	2
									76.8	St Georges Channel	
(B)	329.2	58.1	25.6	L	18.9	271,370	0.84	0.4 B	Deep	Off N Spain	3 (with long swell
(C)	329.2	51.8	25.6	L	19.1	274,309	0.84	0.1 B	41+23.5	50NM to Rotterdam	5 decr 3
(D)	313.0	43.7	24.6	L	18.8	195,000	0.84	0	70.0	26NM to Milford Haven	4 decr 2

Table 1: Full Scale Test Conditions

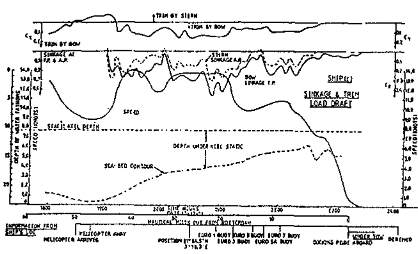


Fig 5

It is important to predict squat with reasonable accuracy particularly where the underkeel clearance is low in order to ensure safety and avoid unduly reducing the earning capacity of a vessel by overcaution. The reluctance of shipboard personnel to hazard vessels at depth-draught ratios less than 1.1 is easily understandable (particularly so when faced with two conflicting methods for predicting vessel behaviour). Because of this, the only significant advances in knowledge may be obtained by model tests.

4. FULL-SCALE MEASUREMENTS

4.1 Experiment Procedure for Full-Scale Measurements

To determine the sinkage and trim to forward speed at sea, it is necessary to record the change in trim and the change in vertical position of any part of the hull and, from such measurements, the sinkage at bow and stern can be computed. Changes in trim are relatively simple to measure and the method which was most successful in these experiments consisted of locating two micromanometers on the centreline of the ship approximately 10 metres apart, connected by a water or oil-filled tube. The recording of changes in sinkage necessitates a datum from which to measure the change in height (which arises from the motion) between a position on the hull and sea.

For this purpose, two ultrasonic transducers were mounted on a light portable boom extending forward from the stem at deck level. The boom was extended well clear of the bow wave system but it proved impossible to project it beyond the symmetrical disturbance of the water surface, which extends well ahead of the stem. The boom used for the most recent experiments extended 15.24m forward of the forward perpendicular. The pressure rise at this position is approximately 0.6m for a 200,000 tonne DW tanker at 14 knots and considerably less for ships of finer trim. Although this pressure rise represents a significant correction to the sinkage signal obtained from the transducer, it is generally accepted that the pressure rise due to the symmetrical disturbance of the water surface ahead of the ship scales linearly.

The effect of sea waves and pitching motion will appear as superimposed undulations on the ultra-sonic and trim signals. In this case, the sinkage and trim values are taken as the average values of the ultra-sonic and trim signals, respectively. To determine the influence of sea state on squat, measurements of ship motions have been included in later experiments.

The overall accuracy of full-scale measurements is estimated to be:-

(±60mm for the ultra-sonic transducer) +

(±30mm for the pressure rise) = ±90mm at the FP,

and (±90mm for the FP) + (±10mm for trim) +

(±70mm for any change in hog or sag under way) = ±170mm at the AP.

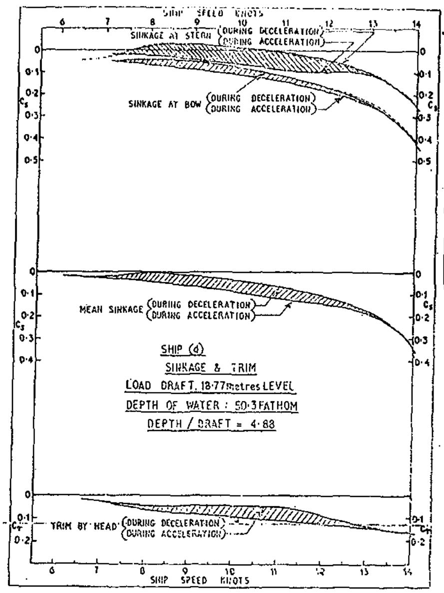


Fig 6: Accelerating and Decelerating

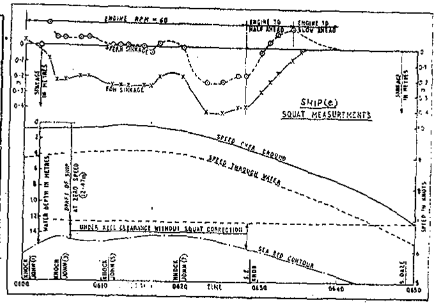


Fig 8

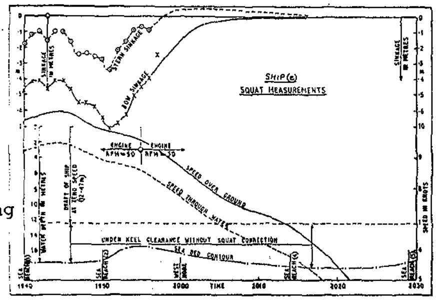


Fig 9

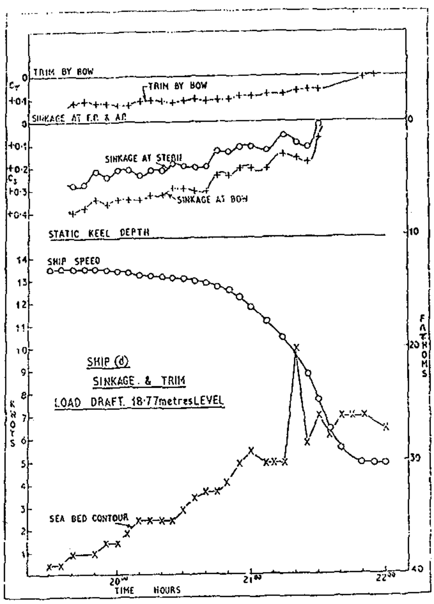


Fig 7

Draught	Incident		Ballast	
Bulb	Original	Glasgow	Original	Glasgow
h/T				
1·05	√ × (1·25)	√	√	
1·1	√ × (1·3)	√ × (1·3)	√	
1·2	√	√		
1·37			√ × (1·64)	√
1·44			√ × (1·70)	√ × (1·70)
1·57			√	√
2·00	√			
2·67			√	

where √ indicate experiments over the level-bed and × ( ) indicate experiments over sandbank with the depth-draught ratio clear of sandbank in parenthesis.

Table 2: Model Test Conditions

4.2 Full-Scale Results

Full-scale results were achieved for five ships, (see figs. 3-9). Ship characteristics and the test sequence for four of them are shown in Table 1. Ship (c) was a sister ship of ship (a).

5. MODEL EXPERIMENTS

It has been shown that even extensive and expensive full-scale tests, as described in the previous section, do not provide the systematic parametric coverage necessary to validate a predictive method close to the crucial point of grounding.

To provide the data needed for this and for the calibration of the squat indicator of section 7, extensive model tests have been undertaken. The Hydrodynamics Laboratory at the University of Glasgow has a 77m x 4.6m x 2.4m towing tank with a specially flat bed and has carried out many model tests in shallow water and restricted water conditions.

The results shown in figs. 10 to 13 are for a bulk carrier with the principal dimensions:

LBP = 160.0m   Breadth(mld) = 27.2m

Draught(mld) = 10.19m   Block coeff = 0.8

Displacement = 37,000 tonnes.

In this particular series the range of tests were as shown in Table 2 and involved two bulbous bows and level bed and simulated sandbank tests[5]. The tests were conducted with the model propelled by a screw propeller at the model self propulsion point for the speeds tested up to grounding.

6. FACTORS INFLUENCING SQUAT

6.1 Side Bank Interactions

Sway force and yaw moments depart from U^2 behaviour in shallow water with flooded banks. The yaw moment rises more steeply whereas the sway force can reverse at higher speeds. This is caused by the wave interaction between the bow and the bank and implies a higher rudder angle is required because of the bank effects. On some occasions with surface piercing banks, this leads to bodily rejection of a ship approaching a bank at a small incidence. At these times the trim changes from bow down to bow up as the bank approaches. With flooded banks the trim is slightly reduced relative to open water whereas the sinkage is significantly increased[6].

For a vessel travelling along the centre of a channel the effect of lateral restriction is shown in fig. 14. It is seen that sinkage is substantially increased but the effect on trim on this occasion is a small increase. It is found that the percentage changes may be generally used as correction factors to the open water results.

6.2 Underkeel Clearance

The effect of bed proximity is to increase the suction pressures applied to the ships hull and also to cause the ship's boundary layer to

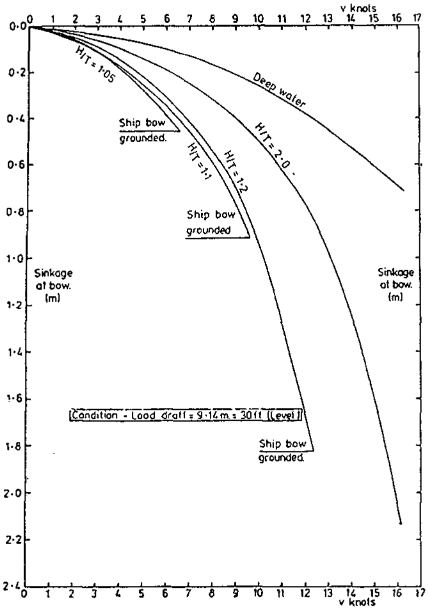


Fig 10

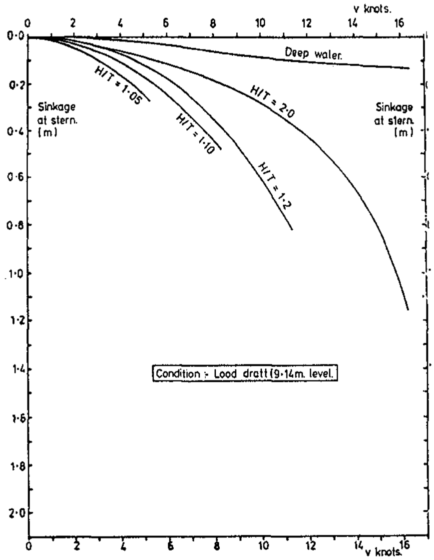


Fig 12

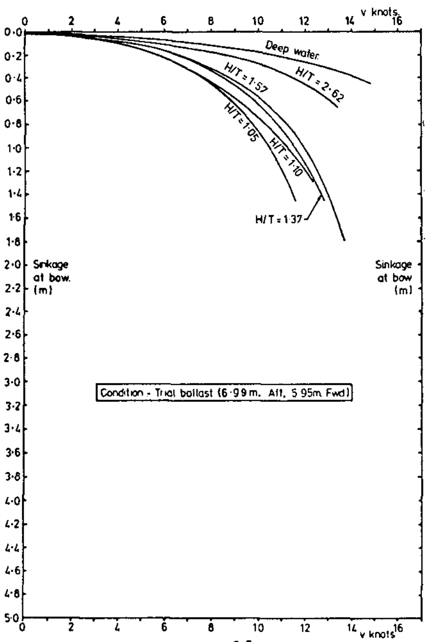


Fig 11

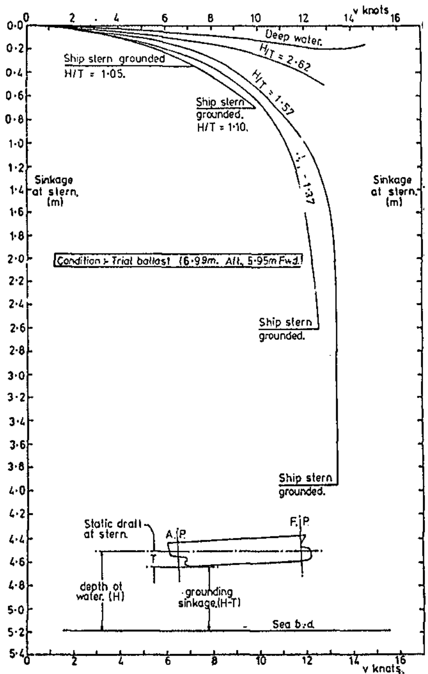


Fig 13

interact with the seabed boundary layer. These effects cause sinkage to increase as the water depth is reduced. Trim also changes rapidly but the manner of change depends on the initial trim as described in section 6.5.

6.3. Sandbanks

The approach to a sandbank leads to the vessel's pressure field interacting with the sandbank and consequently the vessel responds before the bank is reached. Model tests were conducted into a grounding of a bulk carrier in the River Plate. In this case the vessel in load draft experienced a transient trim by the bow (fig. 15) which caused the bow to dive into the sandbank more vigorously than would have been expected under level bed conditions. In ballast conditions (fig. 16) the bow after an initial sinkage is repelled as the stern is attracted leading to the stern being likely to ground almost on leaving the sandbank.

It is possible still to make use of the GO/NO-GO charts (figs. 2 and 17) which were deduced for level bed conditions proved the minimum depth over the sandbank is used.

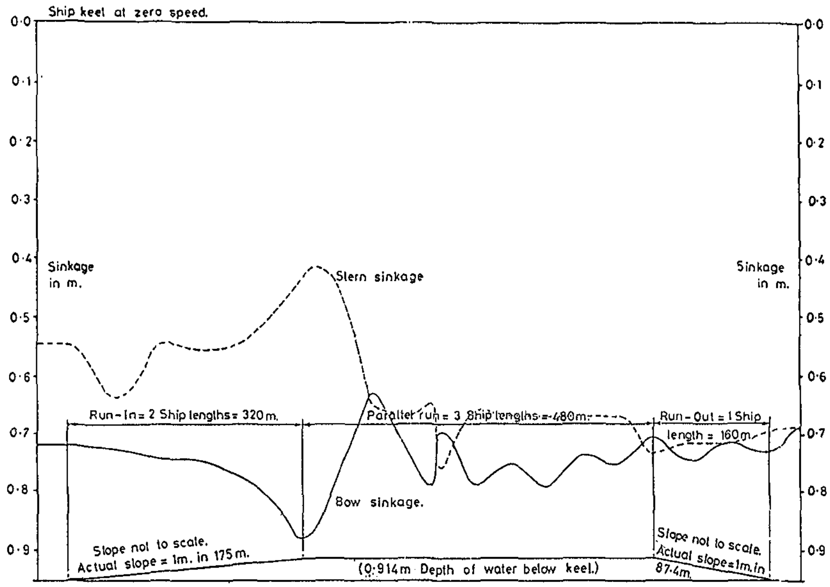
6.4 The Effect of Hull Geometry

Figure 18 presents a comparison of sinkage and trim data obtained on three models at the load draught, level-keel condition in unrestricted shallow-water. The models represent modern, full-form ships of varying hull parameters and displacement but with the block coefficient limited to between 0.8 and 0.9. The curves represent the mean of the data collected. Although no measurable effect on the mean sinkage may be observed, trim increases with increasing C_B and decreasing B/T ratio. These changes are confirmed by the comprehensive analysis of over 120 models by Ferguson[7] which showed that within the ranges B/T and C_B examined negligible changes in sinkage but marked changes in trim are to be expected. For the most part, the data shows the same trends as the theory but theory indicates that squat is inversely proportional to the L/B ratio while the data suggests the opposite.

The comparison shows that the hull geometry must be incorporated into any prediction method and it is not satisfactory to use simpler measures of ship shape such as C_B or B/T ratio. Consequently, a purely empirical method based on a parent form should be used with caution unless the effects of variations in the hull form are accounted for.

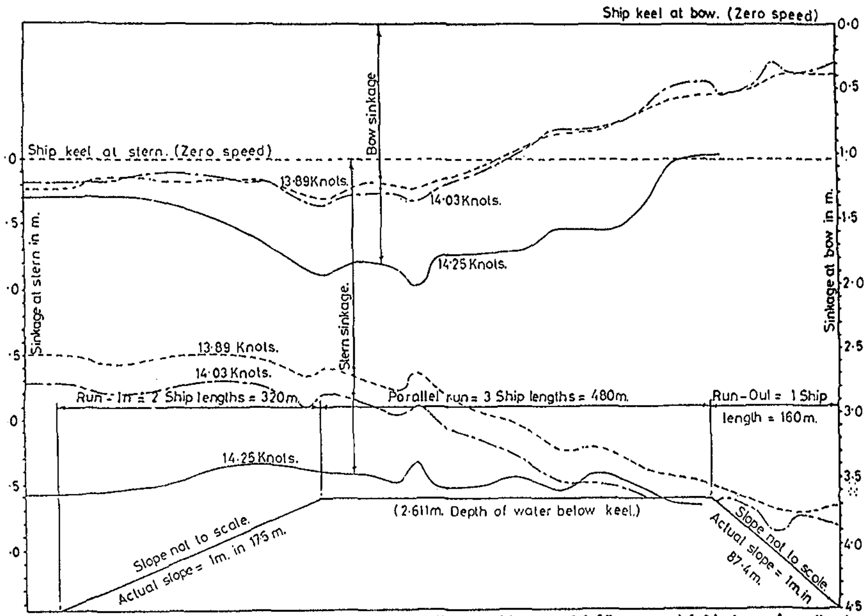
The observations support the view that sinkage results from the pressure changes due to the increased horizontal flow velocity around the hull. In the load draught, level keel condition, the flow velocity is dominated by the long parallel middle-body and negligibly affected by minor hull geometry changes aft and forward. The effect on trim is more complicated since it is the result of the form parameters and the resulting separated flow, depending on factors such as the bulbous-bow and type of propulsion.

The effect of fitting a radically different bulbous-bow design, as shown in fig. 19a, on the vessel's sinkage and trim was also examined by repeating a number of the original experiments[5]. A comparison of the two set of results, fig 19b being typical, showed that the modification leads to minor changes in the force distribution but not its overall magnitude. The resulting changes in close-to-grounding behaviour did not



Bow and stern squat over sandbank in the incident condition at a depth-draught ratio of 1·1 over and 1·3 clear of sandbank at a speed of 9·5 knots

Fig 15



Bow and stern squat in the ballast condition at a depth-draught ratio of 1·37 over and 1·64 clear of sandbank

Fig 16

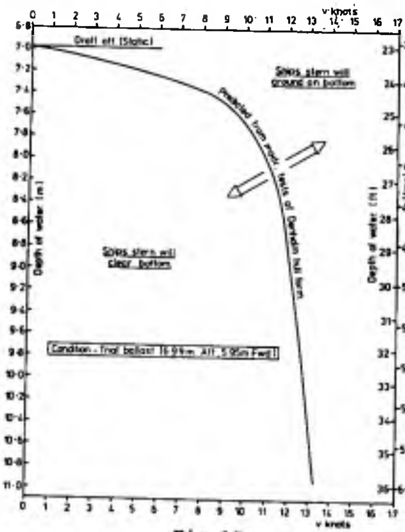


Fig 17

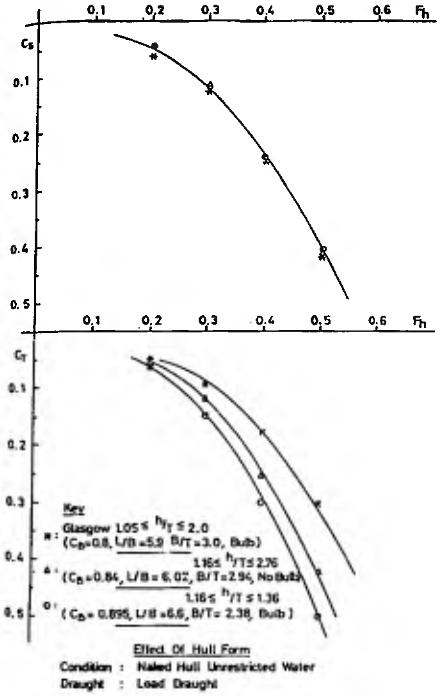


Fig 18

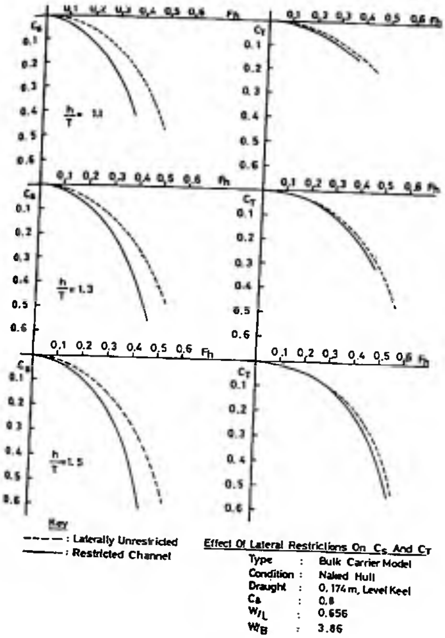


Fig 14

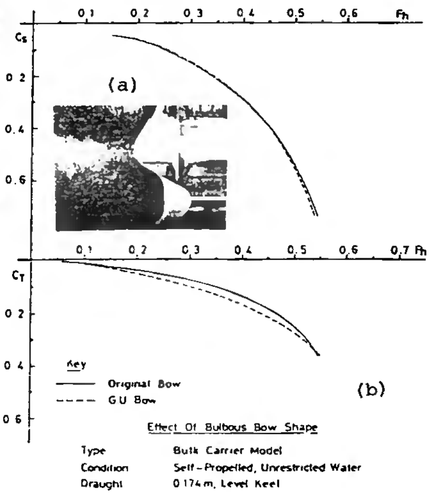


Fig 19

affect the grounding speed or qualitative behaviour and may be considered to have a very small effect and could be omitted from the input hull geometry. However, it should be borne in mind that effects of adding a bulb to an otherwise bulb-less hull will influence the boundary-layer development and the wave system along the hull. It is then to be expected that sinkage and, particularly, trim will be affected to a greater extent than by the above changes in shape.

6.5 Effect of Initial Trim

It is important to recognise that a fully loaded vessel, initially at a level keel in shallow water, will trim progressively by the head and ground with the bow first, whereas a vessel ballasted by the stern (to immerse the screw) will sink progressively with almost constant trim by the stern and ground by the stern, fig. 20. In deeper water the trim by the stern for the ballast condition will decrease with speed.

6.6 Squat and Trim Caused by Bed Mud

In general the sinkage forward and aft above mud appears to be less than above a hard bottom. Moreover, the sinkage values decrease with increasing thickness of the mud layer. There is no clear indication between sinkage above mud of 'winter' and 'summer' densities at the same layer thickness[8].

6.7 Acceleration and Deceleration

Full scale tests on ship(d) in deep water (fig. 6) showed that at moderate speeds an accelerating ship experiences increased sinkage but reduced trim by the bow whereas a decelerating ship sinks less and trims more. If this pattern of behaviour is repeated in shallow water, rapid deceleration could cause the ship to ground.

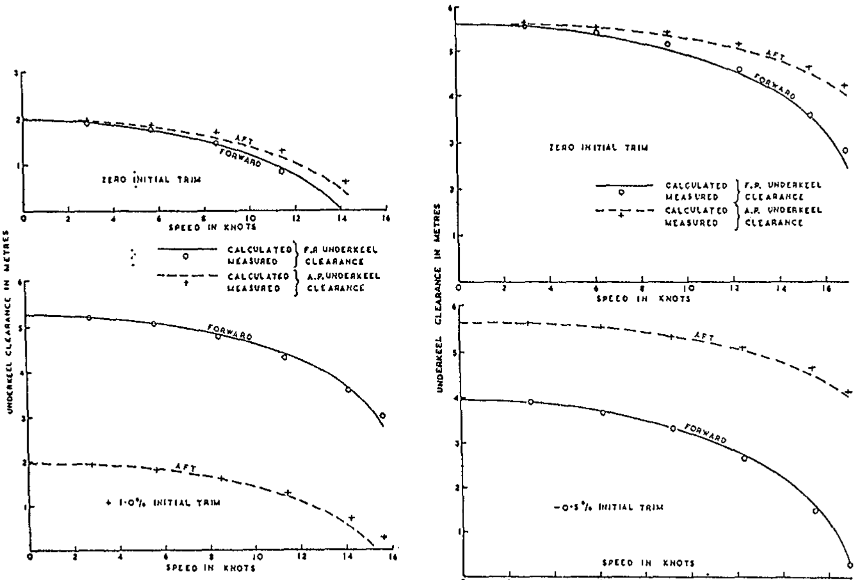
6.8 Self-Propulsion

The effects of self-propulsion are very important as a correction factor to the theoretical methods and for the model/full scale correlation. Figure 21 shows that sinkage is much increased while trim is substantially reduced.

7. EXTRAPOLATION TO FULL-SCALE

Owing to the significant amount of model data, the model-scale squat component of underkeel clearance is one of a deterministic character. The prediction of the full-scale sinkage and trim is still probabilistic. Consequently, the associated scaling problems present difficulties.

Full scale studies indicate that, at a depth-draught ratio of 1.42, correlation in the load-draught level-keel condition is very reasonable at speeds less than about 12 knots (fig. 3). This is particularly so for trim although the mean sinkage tends to be greater for the ship than for the model. Bearing in mind the importance of viscous effects to the scaling procedure in shallow water, this agreement is unexpected. Frictional resistance constitutes the major proportion of full-form ship resistance at low speeds and since the frictional coefficient is much lower on the full-scale, it is to be expected that model results for the trim component will over-estimate the full-scale. The good agreement is mainly because mean sinkage is almost entirely due to the predominance of pressure changes over the hull, allowing direct scaling of this



A. Model B, Load Draught $h/T_{AP} = 1{\cdot}10$, $C_B = 0{\cdot}83$
Results scaled to 330·71 L_{PP} Ship

B. Model B, Load Draught $h/T_{AP} = 1{\cdot}28$, $C_B = 0{\cdot}83$
Results scaled to 330·71 L_{PP} Ship.

Effect of Initial Trim on Underkeel Clearance

Fig 20

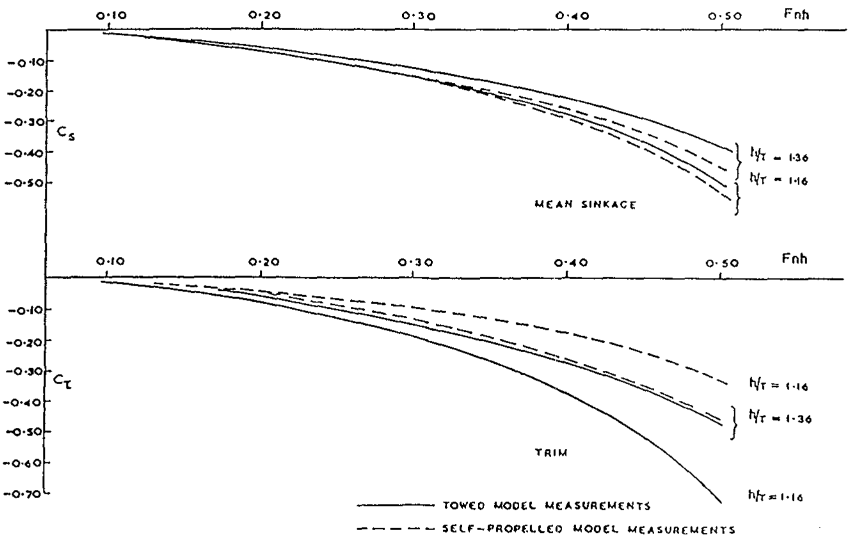


Fig 21 Effect of Self-Propulsion on Mean Sinkage and Trim of a Tanker Model

component without error of practical significance [9].

Although trim has an appreciable viscous component, this is probably counter-balanced by the pressure dominated self-propulsion effects. Any scaling difficulties in the self-propelled, load draught (level keel) condition, therefore, are effectively obscured. However, it is suggested that since the model scale boundary layers are relatively thicker than those at full-scale, they will interact at a greater depth-draught ratio and introduce scaling difficulties in very shallow water.

The model/full-scale comparisons in the self-propelled ballast (trim-by-stern) condition indicate that the normal extrapolation procedure may be in error. The bulb proximity to the free-surface will modify both the hull wave-system and the viscous flow and may induce vertical sinkage or lift forces [9]. It is suggested that since the magnitude of the complex changes induced by the proximity to the free-surface is uncertain, extrapolation to full-scale will be unreliable. Similarly, in the absence of self-propulsion, prediction for the towed, naked-hull condition will be generally unreliable for the trim components in the ballast case.

These problems can only be overcome by careful correlation of model and full-scale results with an adequate computational approach.

8. PRACTICAL NAVIGATION AID

During the trials described in Section 4 it became evident from discussions with Masters and Navigation Officers, that a bridge instrument capable of continually displaying the true dynamic draft, or the amount of squat, would be a useful aid to navigation and contribute to the safe handling of the ship in shallow or restricted waters.

8.1 A Continuous Reading True Draught Indicator

One of the results of the research reported in the preceding sections has been the development of a number of variations of instrumentation systems capable of continuously displaying either the true draught of the vessel, corrected for squat, or the amount of squat present continuously displayed as an increment of draught to be added to the static draught on the ship's bridge.

There is no practical method of obviating squat even though it may be reduced by a given vessel by decreasing speed or, more drastically, by designing a vessel with a higher B/T. Naturally, most operators of large vessels are aware of the dangers and speed is reduced by rule-of-thumb or by the use of squat diagrams posted on the bridge. These diagrams are useful (when accurate) but are easily ignored or overlooked. An instrument capable of continually displaying either the true draught (corrected for squat) or the squat (as an increment to be added to the static draught) would be more useful and more likely to be used. The development of such an instrument is described in Ref 1. Following discussion with tanker fleet operators, the present system is designed to be virtually maintenance free

The signal used is a measure of the water velocity next to the hull. This is responsible for the changes in pressure which cause the squat. In the same way as a particular pressure change results in a particular squat so will the water velocity next to the hull causing that pressure change have a fixed relationship with squat.

The system is shown schematically in fig. 22 and by a block circuit diagram. In an attempt to keep the installation and maintenance costs to a minimum the velocity transducer adopted is an ultra-sonic device which transmits through the hull and reads the velocity close to the hull surface.

8.2 Procedure to Calibrate and Commission the Squat Meter

(a) Using the program described in Section 3 the geometry of the hull is used to compute a complete set of squat information for the practical range of speed and depth of water.

(b) With the instrument properly installed on the ship (an operation which can be carried out during a normal voyage), the ship is sailed over a range of speeds at two or three depths of water. At each combination of speed and depth of water a reading will be displayed on the bridge instrument. This reading is adjusted, using the keyboard input, to read the correct squat according to the computer.

The squat meter should then read the true squat, or dynamic draught if the static draught is keyed in, regardless of the depth under hull and speed combinations even for combinations of speed and depths not covered in the calibration.

9. CONCLUSIONS

The squatting of larger vessels can be an important cause of marine casualties with a serious impact on ship owners and port managers alike. Many factors have a role to play and it should be amphasised that:-

(1) Approaching or leaving port with a trim by the stern does not lead to a more level keel at speed in shallow water.

(2) Transients approaching sandbanks can lead to groundings which may otherwise have been avoided.

(3) Restricted width of fairways has a range of effects and the side forces can exceed the ability of the rudder to control the ship.

(4) Rapid deceleration can lead to larger sinkage at the bow in the short term.

(5) A muddy layer on the seabed reduces sinkage and the idea of effective depth may be necessary for predictions.

It has been demonstrated that a combination of model tests, full scale tests and computer analysis have led to the situation where satisfactory predictions can be made of deterministic squat. The more probabilistic problems involving uncertainties regarding true seabed position, etc, can be ameliorated by a navigational aid as described.

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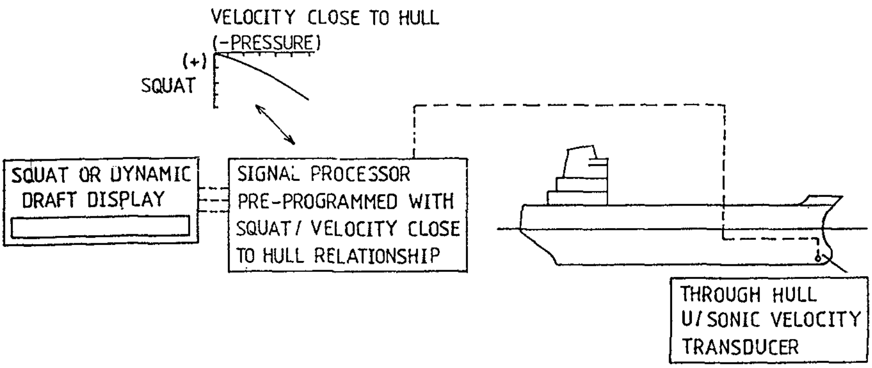

Fig 22