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ABSTRACT

There are several methods for the determination of sinkage and trim of ships sailing in restricted water described in literature. Two main categories can be distinguished: methods which enable the designer to calculate the water-level depression and methods by which the sinkage can be calculated. In the former category it is normally assumed that water-level depression and sinkage are equal. In this paper the results of 12 methods are compared with the results of model investigations. Conclusions are given concerning the methods which can best be used to calculate sinkage, trim and water-level depression with respect to the channel width/ship's beam ratio.

1 INTRODUCTION

Sinkage is defined as the average vertical translation of a sailing ship. Adding the trim results in the ship's squat. Determination of squat is of interest for designers calculating the required depth of access channels or inland navigation fairways. In this respect the total sinkage of the critical point of the ship (i.e. bow or stern) has to be known, hence both sinkage and trim have to be calculated. Another application is in the design of bank protection. Several models have been developed which describe the water-level depression and the back flow velocity. The results can be used in either speed predictions or in the determination of hydraulic boundary conditions for design of bank protection. These models are based on the assumption that sinkage and water-level depression are equal.

Based on this assumption the induced water-level depression can be determined by applying a sinkage determination method, which will actually be carried out.

In Table 1 a survey is given of the various methods analyzed, their theoretical background, calculation aims and limits to which the results apply.
The main aims of this paper are a comparison and verification of results of water-level depression sinkage and squat prediction methods with measurements recorded in hydraulic models.

On the basis of the measurements some conclusions are drawn on the influence of propeller action on squat, width restriction and the relation between measured mean water-level depression and sinkage.

In Chapter 2 the methods, indicated in Table 1, are elaborated. The measurement programme, the hydraulic models, the ship models and some model results are presented in Chapter 3.

Author	litt.	theoretical background	primary aim of calculation	validity range		ship types
				width, A_m/A_c	depth	
Schijf	[13]	conservation of energy	water level depression	restricted	restricted	all types
Constantine	[5]	conservation of energy	water level depression	restricted	restricted	all types
Tothill	[16]	conservation of energy	water level depression	restricted	restricted	all types
McNown	[12]	conservation of energy	water level depression	restricted	restricted	all types
Schijf (incl. α)	[13]	conservation of energy, empirics	water level depression	restricted	restricted	all types
Gates	[10]	conservation of energy	water level depression	restricted	restricted	all types
Balanin	[1]	conservation of energy	water level depression	restricted	restricted	all types
Bouwmeester	[4]	conservation of momentum, empirics	water level depression	restricted	restricted	all types
Sharp	[14]	conservation of momentum	water level depression	restricted	restricted	all types
Tuck	[17]	slender body potential theory	sinkage and trim	$A_m/A_c<0.15$	$h/T<2$	all types
Dand	[6]	conservation of energy, empirics	sinkage and trim	unrestricted	$h/T<1.5$	$0.8<c_b<0.9$
Führer	[9]	conservation of energy, empirics	sinkage and trim	$0.032<A_m/A_c<0.43$	$1.19<h/T<2.29$	all types
Soukhomel	[15]	empirics	sinkage and trim (stern)	unrestricted	unrestricted	all types
Eryuzly	[8]	empirics	maximum squat (bow)	unrestricted	$1.08<h/T<2.8$	VLCC
Barras	[3]	empirics	maximum squat (position undefined)	unrestricted	$1.1<h/T<1.5$	all types

Table 1 Summary of calculation methods analyzed

In Chapter 4 model measurements and calculations are compared. Finally, in Chapter 5, conclusions are drawn and some recommendations given.

2 CALCULATION METHODS

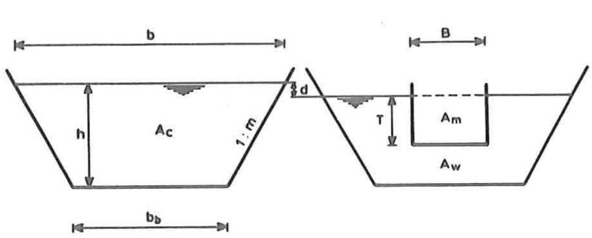
Table 1 shows two main calculation categories. The first has been developed to predict the water-level depression in restricted waterways. In this category the water-level depression is assumed to be equal to the sinkage of the ship. The second category consists of methods giving a direct prediction of the sinkage and/or trim of ships. In the two categories both theoretical and empirical approaches are used for the mathematical prediction of the phenomenon. All methods have been written into computer programs. As far as possible each program has been tested on data published by the author. A short description of each method is given below.

2.1 Prediction of water-level depression

2.1.1 Energy approach

Schijf [13], Constantine [5], Tothill [16] and McNown [12] have developed methods for the prediction of the water-level depression in narrow channels on the basis of a one-dimensional consideration of Conservation of Energy (Bernoulli's Equation) and the Continuity Equation. The difference between the methods analyzed is in the schematisation of the channel section.

Schijf [13] and Constantine [5] used a rectangular cross-section, Tothill [16] a trapezoidal cross-section while McNown [12] a "power law" cross-section. However, in practice, it has been shown that results with the method of McNown are similar to those of Tothill if, in both methods, the slopes of the banks at the waterline are uniform. For this reason and the fact, that a rectangular cross-section can be considered as an extreme case of the trapezoidal cross-section, the energy approach will be described, in the present paper, by the method of Tothill [16].



Definition sketch

Assuming that the ship's speed is V and the back flow velocity is denoted by u_r, the Continuity and Bernoulli Equation give:

$$A_c V = A_w (V+u_r) \quad (1)$$

$$\tfrac{1}{2}\rho V^2 + \rho g h = \tfrac{1}{2}\rho (V+u_r)^2 + \rho g (h-d) \quad (2)$$

Equation (1), substituted in Equation (2) gives:

$$d = \frac{V^2}{2g}\{(\frac{A_c}{A_w})^2 - 1\} \quad (3)$$

in which A_w can be written as:

$$A_w = b_b(h-d) + m(h-d)^2 - A_m \quad (3)$$

The water-level depression (d) and back flow velocity can be computed using an iteration procedure. From diagrams in which the ship speed is plotted as a function of the water-level depression (see Ref. [16]) it can be seen that the curve has a maximum value of ship speed, the so-called critical speed (V_{crit}). By differentiating Equations (3) and (4) with respect to d it is possible to develop a high order equation for the critical water level depression (d_{crit}) which can be solved numerically by computer. This expression is of the following form:

$$2A_c^2 (\frac{dA_w}{d(d)})_{crit} \cdot \frac{d_{crit}}{A_{w,crit}} + A_c^2 - A_{w,crit} = 0 \quad (5)$$

in which:

$$(\frac{dA_w}{d(d)})_{crit} = - b_b - 2m(h-d_{crit}) \quad (7)$$

$$A_{w,crit} = b_b(h-d_{crit}) + m(h-d_{crit})^2 - A_m \quad (8)$$

Substitution of the solution, d_{crit}, in Equation (3) gives the critical ship speed (V_{crit}).

Balanin and Bykov [1] have presented a good approximation for the energy approach. Their method has been based on measurements of Soukhomel [15]. They state:

$$V_{crit} = (1-0,325\,\frac{mh}{b}) * \sqrt{8gh\cos^3[\tfrac{1}{3}\{\pi + \arccos(1-\frac{A_m}{A_c})\}]} \quad (9)$$

Furthermore Balanin and Bykov [1] give an approximation method for the determination of the water-level depression and the back flow velocity. The following equation can be used for a first approximation for the water-level depression:

$$d = \frac{V^2}{g}\,\frac{\frac{A_c}{A_m} - 0.5}{(\frac{A_c}{A_m} - 1)^2} \quad (10)$$

In the subsequent iterative stages the following equations can be used:

$$u_r = V\,\frac{A_m + db}{A_c - A_m - db} \quad (11)$$

$$d = \frac{1}{g}(V + 0.5\,u_r)u_r \quad (12)$$

Gates and Herbich [10] presented a method on the basis of the energy approach in which the boundary layers formed both on the hull of a ship and on the channel banks and bed were also taken into account. This means that the effective cross-sectional area, A_W, (see Figure 1) is decreased. For both boundary layers the authors used the turbulent boundary layer development along a flat plate with zero pressure gradient:

$$\delta = \frac{0.37\ x}{R_x^{1/5}} \tag{13}$$

in which x is the distance from the bow of the ship. It should be noted that the boundary layer along the hull is affected by the ship's speed, and the boundary layer along the channel banks and bed by the back flow velocity.

Finally, it should be noted that Schijf [13], for wider channels in which the assumption of equal velocity over the cross-section is too rough, uses a coefficient α such that the water-level depression will increase. He adapted Equation (3), as follows:

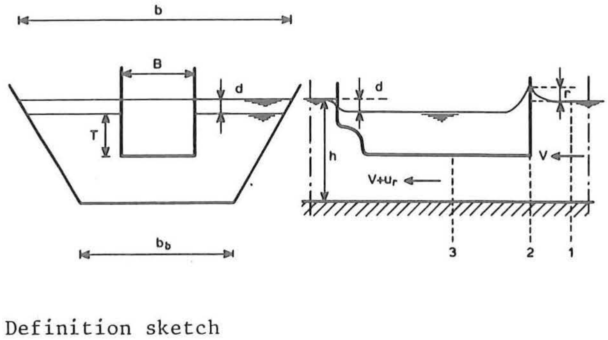
$$d = \frac{V^2}{2g}\ \{\alpha(\frac{A_c}{A_w})^2 - 1\} \tag{14}$$

with:

$$\alpha = 1.4 - 0.4\ \frac{V}{V_{crit}} \tag{15}$$

2.1.1 Momentum approach

Bouwmeester [4] and Sharp and Fenton [14] each developed a method for the calculation of the water-level depression and the back flow velocity in channels on the basis of a one-dimensional consideration of the Conservation of Momentum and the Continuity Equation. Bouwmeester [4] developed his method for trapezoidal cross-sections and also took into account the water-level rise in front of the bow. Sharp and Fenton [14] developed their method for rectangular cross-sections and neglected the effect of the water-level rise in front of the bow. It is clear that the method of Sharp and Fenton [14] is a special case of the method of Bouwmeester [4]. For this reason the method of Bouwmeester and also the special case, representing the method of Sharp and Fenton, will be discussed here.



Definition sketch

The forces acting on the control water volume between Sections 1 and 2 (see Definition sketch) are determined by integration of the hydrostatic pressure in the Verticals 1, 2 and 3:

$$F_1 = \tfrac{1}{2}\rho g b h^2 - \tfrac{2}{3}\rho g m h^3 \tag{16}$$

$$F_2 = \tfrac{1}{2}\rho g B (r+d+T)^2 \tag{17}$$

$$F_3 = \tfrac{1}{2}\rho g b (h-d)^2 + \rho g m (h^2-d^2) d - \tfrac{2}{3}\rho g m (h^3-d^3) - \tfrac{1}{2}\rho g B T^2 \tag{18}$$

The momentum in the verticals 1 and 3 yields respectively:

$$M_1 = \rho A_c V^2 \tag{19}$$

$$M_3 = \rho A_w (V+u_r)^2 \tag{20}$$

Because the Conservation of Momentum has to be satisfied the following equation holds:

$$F_1 - F_2 - F_3 = M_3 - M_1 \tag{21}$$

The Continuity Equation for the steady flow case is:

$$A_c V = A_w (V+u_r) \tag{22}$$

In case that the water level rise (r in Equation (17)) in front of the bow is known, the water-level depression and back flow velocity can be calculated from Equations (4), (16), (17), (18), (19), (20), (21) and (22).

Bouwmeester [4] has found experimentally that

$$r = \frac{T.b}{A_c}\ \frac{V^2}{2g} \tag{23}$$

Sharp and Fenton [14], whose method holds only for rectangular canal cross-sections, neglect the contribution of the water-level rise in front of the bow. This implies that r = 0 and m = 0 in Equations (4), and (16) to (22) inclusive.

2.2 Prediction of sinkage and trim

2.2.1 Slender body potential theory

Tuck [17] gives a solution for sinkage and trim of ships in wide shallow water on the basis of a slender body theory. He obtained the following results:

$$S = c_s\ \frac{\nabla}{L_{pp}^2}\ \frac{F_h^{\,2}}{\sqrt{1-F_h^{\,2}}} \qquad \text{(sinkage)} \tag{24}$$

$$\tau = c_\tau\ \frac{\nabla}{L_{pp}^2}\ \frac{F_h^{\,2}}{\sqrt{1-F_h^{\,2}}} \qquad \text{(trim angle)} \tag{25}$$

in which c_S and c_τ are complicated expressions for the geometric characteristics of the ships considered. By using reasonably accurate analytical expressions for the ship's shape Vermeer [18] developed the following approximations:

$$c_s = \frac{1}{6\pi c_w c_p} (32 - 40\, c_w - 40\, c_p + 75\, c_w c_p - 980\, k_w i_p c_w c_p) \quad (26)$$

$$c_\tau = \frac{7}{18\pi k_w^2 c_w c_p} (20\, i_p c_p + 24\, i_w c_w + 45\, i_p c_p c_w - 39\, i_w c_w^2) \quad (27)$$

Huuska [11] found from experimental data for restricted shallow water, that the sinkage and trim computed with Equations (24) and (25) have to be multiplied by:

$$\varepsilon = 7.45 \frac{A_m}{A_c} + 0.76 \quad (28)$$

The correction factor ε holds for

$$0.032 \leq \frac{A_m}{A_c} \leq 0.15$$

2.2.2 Energy approach

Dand [6] developed a semi-empirical method to predict sinkage and trim on the basis of the one-dimensional energy theory (see Section 2.1.1). His method is limited to the prediction of squat of full-form ships in shallow water. However using the unmodified one-dimensional theory the method can be applied to predict squat in restricted channels. He assumed a fairway of rectangular cross-sectional area A_c and a ship with a sectional area A(x). Using the energy approach of Section 2.1.1 it is possible to compute the water-level depression d(x) for any x-coordinate.
When sinkage and trim are considered as a result of a vertical force and moment they can be expressed in the following way:

$$S = \frac{\int d(x).B(x)dx}{\int B(x)dx} \quad (29)$$

$$\tau = \frac{\int x d(x).B(x)dx}{\int x\, B(x)dx} \quad (30)$$

where B(x) represents the beam of the vessel on water-line at Section x and all moments are taken with respect to the centre of flotation of the waterplane at which the vessel floats at rest.

For a hull moving in shallow-water of infinite width Dand [6] assumed an effective channel width to be 0.975 L_{pp}. On the basis of this assumption and from model tests he determined correction factors for both the sinkage and the trim, depending of the Froude-Number F_h. The influence of self-propulsion was taken into account by a further correction factor. It was found that an increase of the sinkage by 10% was adequate to represent the propeller effect over the range of F_h for all values h/T. For the trim, however, a correction factor, dependent on both F_h and h/T, was necessary to represent the propeller effect.

Führer and Römisch [9] developed a method for the calculation of squat from extensive model investigation. This calculation was carried out into two steps:

1. Evaluation of the squat at the critical speed of the ship as a function of the draught.
2. Elaboration of a speed-dependent coefficient which allows the squat to be determined at any speed.

It was found that:

$$S_{b,crit} = 0.2 \left(\frac{10 C_B B}{L_{pp}}\right)^2 T \text{ (sinkage at the bow)} \quad (31)$$

$$S_{s,crit} = 0.2\, T \text{ (sinkage at the stern)} \quad (32)$$

The following empirical relationship has been developed to describe the squat at any speed of the ship:

$$S = 8\left(\frac{V}{V_{crit}}\right)^2 \left\{\left(\frac{V}{V_{crit}} - 0.5\right)^4 + 0.0625\right\} S_{crit} \quad (33)$$

Three critical ship speeds ranges have been identified:

1. $L_{pp} \leq 3b$ and $\frac{A_m}{A_c} \geq 1/6$

   V_{crit} is calculated using the energy approach described in Section 2.1.1.

2. $L_{pp} \leq 3b$ and $\frac{A_m}{A_c} < 1/6$

$$V_{crit} = \left\{1/80 \left(\frac{h}{T} \frac{L_{pp}}{B}\right)\right\}^\beta \quad (34)$$

$$\text{with } \beta = 0.24 \left(\frac{L_{pp}}{b}\right)^{0.55} \quad (35)$$

3. $L_{pp} > 3b$

$$V_{crit} = \left\{1/80 \left(\frac{h}{T} \frac{L_{pp}}{B}\right)\right\}^{0.125} \quad (35)$$

Führer and Römisch [9] determined the effect of self-propulsion on the critical ship speed by comparative scale model tests with towed and self-propelled ship models. They found:

$$V_{crit,p} = 0.92\, V_{crit} \text{ for } \frac{A_m}{A_c} \geq 1/6 \quad (37)$$

$$V_{crit,p} = 0.95\, V_{crit} \text{ for } 1/15 < \frac{A_m}{A_c} < 1/6 \quad (38)$$

$$V_{crit,p} = 1.00\, V_{crit} \text{ for } \frac{A_m}{A_c} \leq 1/15 \quad (39)$$

2.1.3 Some experimental methods

Barras [3] proposes the following formula for the calculation of the maximum squat (bow or stern squat is not indicated) of a ship on the basis of model and prototype measurements for depth-restricted waters ($1.1 \leq \frac{h}{T} \leq 1.5$):

$$S_{max} = \gamma c_B \left(\frac{A_m}{A_c - A_m}\right)^{2/3} V^{2.08} \quad (40)$$

in which γ = 0.133 for prototype
γ = 0.121 for model

For ships in laterally-unrestricted waters (depth-restrictions only) Barras derived an expression for the effective width from electrical analogue experiments:

$$b_{eff} = \{7.7 + 45(1-c_w)^2\}B \quad (41)$$

Soukhomel and Zass [15] distinguish two water depth/draught ratio ranges on the basis of experimental data for ships in laterally unrestricted waters.
They determined the following formulas for the calculation of sinkage:

1. $$S = 12.96\ k \sqrt{\frac{T}{h}}\ V^2 \quad \text{for } \frac{h}{T} > 1.4 \quad (42)$$

2. $$S = 12.96\ k\ V^2 \quad \text{for } \frac{h}{T} \leq 1.4 \quad (43)$$

in which k can be approximated to:

$$k = 0.0143 \left(\frac{L_{pp}}{B}\right)^{-1.11} \quad \text{for } 3.5 < \frac{L_{pp}}{B} < 9 \quad (44)$$

To calculate the maximum sinkage at the stern Soukhomel and Zass [15] give the following relations:

$$S_{max} = 1.10\ S \text{ for } 9 > \frac{L_{pp}}{B} \geq 7$$
$$S_{max} = 1.25\ S \text{ for } 7 > \frac{L_{pp}}{B} \geq 5 \quad (45)$$
$$S_{max} = 1.50\ S \text{ for } 5 > \frac{L_{pp}}{B} \geq 3.5$$

Eryuzlu and Hausser [8] have carried out model tests with three self-propelled ships (VLCC's). The navigation basin was so wide that all tests could be characterized as unrestricted in width (the range of $\frac{b}{B}$ lying between 31 and 42). The waterdepth/draugh ratio ($\frac{h}{T}$) varies between 1.08 and 2.78. For all their experiments they found a maximum sinkage at the bow. For this maximum sinkage they derived the relation:

$$S_{max} = 0.113B\left(\frac{T}{h}\right)^{0.27} \left(\frac{V}{\sqrt{gh}}\right)^{1.8} \quad \text{(at the bow)} \quad (46)$$

3 MEASUREMENTS

An extensive series of measured data were required for a proper check and comparison of the methods discussed in the previous chapter.
These data could, for a small part, be obtained from model investigations already carried out at the Delft Hydraulics Laboratory (DHL). Some data were also obtained from the Maritime Research Institute (MARIN), (see Section 3.2).

These data however were not sufficient to relate squat to the water depth/draft and channel width/beam ratios. For this purpose a flume at the DHL was fitted with movable vertical banks which could be repositioned, within limits, to any required channel width. The water depth in the flume could also be adjusted within limits. A systematic series of tests is described briefly in the following section.

3.1 Systematic series

Investigations were carried out with models of a VLCC (scale 1:100) and a LNG carrier (scale 1:125). Data on these model ships are given in Table 2.

The tests were performed in a flume with length 55.0 m, width 6.0 m and maximum water depth 0.23 m.
The ships were self-propelled and steered by a cable-pilot system, to guarantee reproducibility. Bow and stern sinkages were measured with profile-indicators: the sensors of these instruments are a fixed small distance from the flume bottom and indicate the fore and aft sinkages when sailing (see Figure 1).

The Froude Numbers during the tests varied between $0.2 < F_h < 0.6$ which can be considered as normal operating conditions. The ships only sailed along the centre line of the channel.

The following channel width/beam ratios (b/B) for the tanker were tested: 5.13, 6.16, 7.19, 8.21, 9.24, 10.27, 11.29, 13.32. Only three water depth/draft ratios (h/T) could be tested: 1.35, 1.30, 1.15, per channel width.

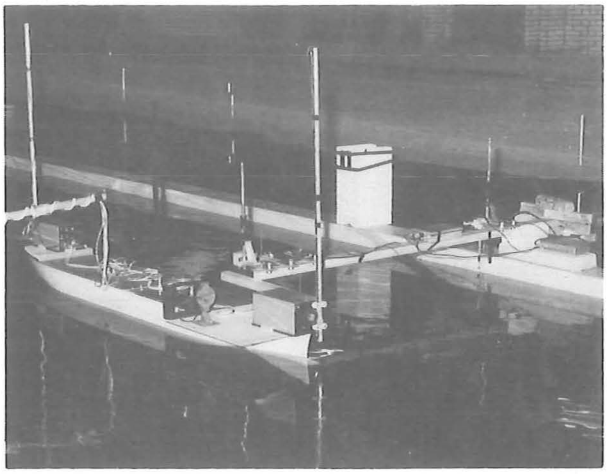


Figure 1 Lay-out of experimental set-up

For the LNG carrier the test conditions were:
b/B = 5.84, 7.01, 8.17, 9.34, 10.51, 11.68, 12.84
h/T = 1.15, 1.30, 1.50, 1.70.

The various combinations of b/B and h/T resulted in so much data on sinkage and trim that it was decided to use a computer system for data compilation and further elaboration.

The water-level depression was measured at three locations with wave height meters: next to the ship, near the (vertical) bank, and in between these locations.

3.2 Survey of measurement conditions

Rijn-Hernecanal vessel

A number of tests had been performed previously with a self-propelled model of a Rijn-Herne-canal vessel, scale 1:25 (for dimensions see Table 2). These tests were carried out in a hydraulic model of a push-tow canal with vertical banks (bottom width 125 m, waterdepths 5 and 6 m) and also with slopes 1:4 (bottom width 120 m, water depth 6 m). The results of the runs along the channel axis have been added to the squat data file. Simultaneous induced water-motion recordings are also available.

LPG-carrier

Some squat results, obtained with a self-propelled LPG carrier, scale 1:100 have also been used (for dimensions, see Table 2). These tests were carried out in a hydraulic model of a navigation channel, the bottom width being 350 m ($b/B = 9.87$) with a water depth of 13.2 m ($h/T = 1.04$).

Crude oil tanker

Some tests on a model tanker were carried out with a scale 1:82.5 to verify the results obtained with the 1:100 VLCC model and to measure the influence of the propeller on the squat. These tests took place in a towing tank. Replacable vertical banks were installed so that different channel widths could be tested. Two channel width/beam ratios were applied: 5.30 and 7.42, and three water depth/draft ratios: 1.15, 1.30 and 1.35. Water-level changes during the passage of the ship were recorded.

Test no.	ship	scale	L_{pp} (m)	B (m)	T (m)	C_b	centre of buoyancy (forward of midship) (m)
1	VLCC	1:100	316.00	48.70	20.30	0.850	+ 11.0
2	LNG	1:125	270.36	42.82	10.97	0.740	+ 0.3
3	LPG	1:100	226.20	35.47	12.75	0.795	+ 3.2
4	TANKER	1:82.5	310.00	37.17	18.90	0.850	+ 6.3
5	Rijn-Herne C. (inland motorvessel)	1:25	77.42	9.50	2.50	0.872	+ 1.4
6	KEMPENAAR (inland motorvessel)	1:12.5	49.00	6.50	2.35	0.847	+ 0.9

Table 2 Some data on ship-types tested

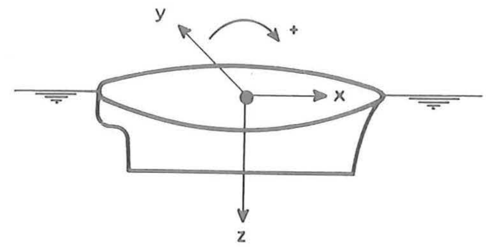
Kempenaar

Some results of tests carried out with a Kempenaar were used for analysis. These data were obtained from MARIN. The following conditions were adopted:
b/B: 2.58, 4.06, 5.59, 8.24
h/T: 1.28, 1.49, 1.57.

3.3 Model results

The observed sinkage at bow and stern were converted into mean sinkage and trim (see Definition sketch). The trim is defined as:

$$\tau = \frac{S_b - S_s}{L_{pp}}$$



Definition sketch

3.3.1 Water-level depression

To get a better insight into the phenomena (un)restricted width tests were carried out at various b/B ratios. The water-level depression was measured near the ship and near the bank. The depression at the bank has been expressed as a fraction of the depression measured at the ship, see Figure 2. Fractions are averaged over a range of h/T values and velocities ($0.2 < F_h < 0.6$). The deviations are indicated.

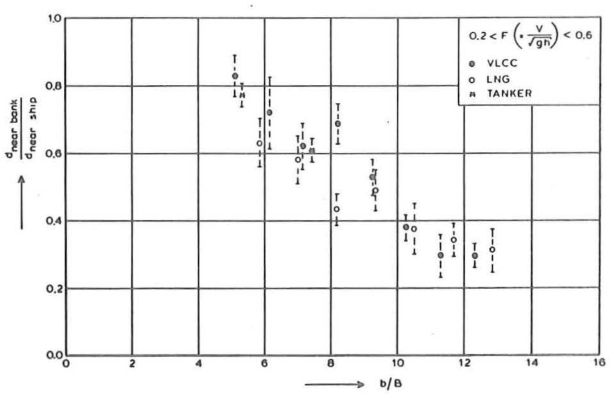


Figure 2 Depression at the bank as a fraction of the depression near the ship

This means that, in the widest channels tested, about one third of the water-level depression near the ship remains at the bank. From this it can be concluded, that the prevailing water-level depression (and thus the sinkage) is still slightly affected by the presence of the banks. The influence of the banks on the sinkage in smaller channels is evident.

On the basis of a good prediction of the mean water-level it is possible to compute the water-level depression near the ship with the aid of Figure 2. For small values of the b/B ratio the mean water-level depression can be assumed to be equal to the mean value of the water-level depression near the ship and the bank. However, with increasing b/B ratio, the curvature of the water-level depression in the lateral direction should be taken into account.
From the model tests mentioned in Section 3.2 the water-level depression mid-way between ship and bank was compared with the mean water-level depression computed from the values near the ship and the bank.

It was found that the ratio $\frac{2d_{middle}}{d_{ship} + d_{bank}}$ decreases with increasing b/B, following the empirical relation:

$$\frac{2d_{middle}}{d_{ship} + d_{bank}} = 1 - \frac{1}{90}\left(\frac{b}{B} - 1\right) \qquad (48)$$

This means, for example, that the deviation between d_{middle} and $\frac{1}{2}(d_{ship} + d_{bank})$ is 15 percent if b/B = 13, which must be taken into accout in the computation of the mean channel water-level depression.

3.3.2 Relation between water-level depression and sinkage

Near the ship the lengthwise-averaged water-level depression and ship's sinkage have the same value. It can be expected, that in relatively small channels, the discrepancy between average water-level depression and sinkage will be small.
However, in wider channels this will not be the case: if the channel has unrestricted width, the average depression will approximate to zero while the sinkage may have a very substantial value.

The sinkage/average water-level depression ratios have been averaged over the range $0.2 < F_h < 0.6$. In Figure 3 these ratios with the calculated deviations are given as a function of channel width for the VLCC and the LNG carrier.

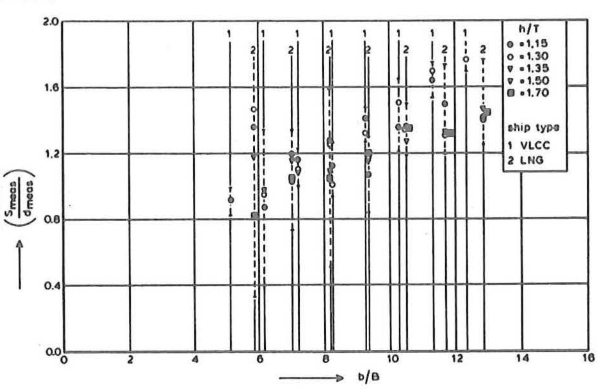


Figure 3 Average sinkage/water-level depression ratio as a function of channel width

It can be seen that, up to b/B ≈ 7, the discrepancies are relatively small. This conclusion coincides with the earlier conclusion that in channels with a width equal to the ship's length the water-level depression is only slightly decreased, see Section 3.3.1 above.

As expected, the deviation between S and d increases when b/B increases.

3.3.3 Relation between squat and water depth/draught ratio

The influence of the water depth/draught ratio on squat can, in fact, only be determined in unrestricted channel widths. This situation as follows from the analysis has unfortunately not been investigated.

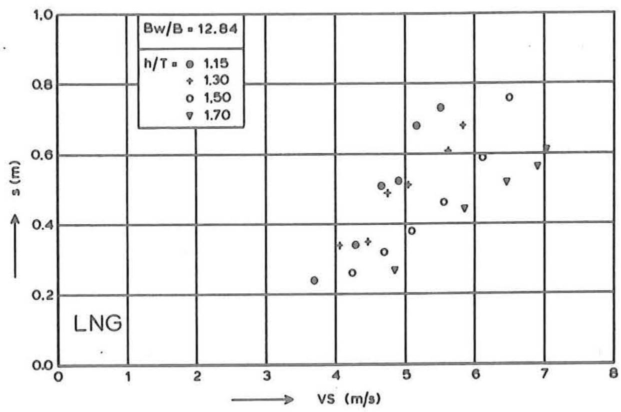


Figure 4 Influence of h/T on squat.

In Figure 4, the bow squat is presented as a function of ship's speed. The influence of different h/T values on the squat is clearly demonstrated. It should be kept in mind, that these results may exaggerate the reality because of the width restriction.

Obviously, at a h/T value of 1.7 the channel bottom still affects the squat.

3.3.4 Influence of propeller on squat

Tests with the model tanker have been carried out for self-propelled and towed model ships. Analysis of these results shows some influence of the propeller action:
- the mean sinkage increases in the order of 5 to (extreme) 10 percent, but
- the bow squat increase is only slight, up to (extreme) 5 percent.

Due to the propeller action i.e. the eccentric propulsive force and the creation of an area of lower pressures in front of the propeller a moment is exerted on the ship which counteracts the trim moment. Thus the total squat is only slightly affected by the propeller, although the sinkage overall has been increased.

4 COMPARISON OF CALCULATIONS WITH MEASUREMENTS

4.1 General

All methods described in Chapter 2 have been written into computer programs. Using the data file of measurements, computer comparisons could then easily be made. In principle three comparisons have been carried out:
- calculated and measured water-level depressions,

- calculated and measured sinkages, and
- calculated and measured squat.

Water-level depressions can, in fact, only be calculated using specific methods for this purpose. However, by assuming that water-level depression and sinkage are equivalent it can be calculated by any method used for calculating the sinkage.
Similarly the sinkage, based on the same assumption, can be determined with a water-level depression calculation method.

Despite the fact that the validity of the assumption is very restricted in its applicability, see Section 3.3.2, the comparison has been carried out on this assumption.

For each of the three comparisons, basic plots were produced, see Figure 5, indicating the ratios of calculated and measured water-level depression (or sinkage, or squat) to the Froude-Number (F_h) as a function of the b/B ratio. Differences in h/T are indicated in the plots.

Conclusions are drawn on the validity of the methods considered in the three following sections.

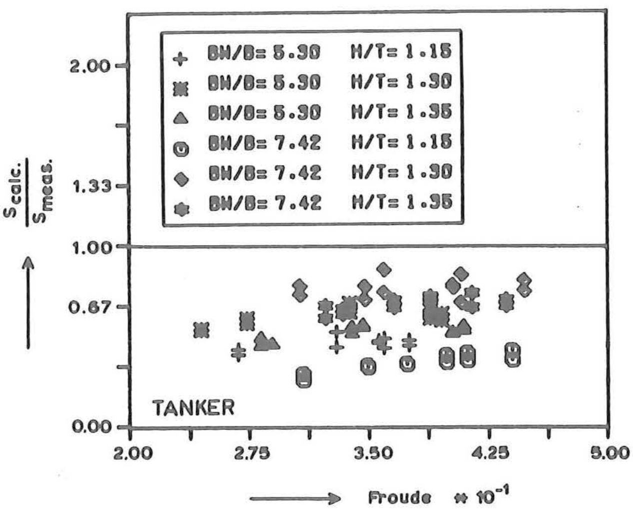


Figure 5 Basic plot presenting the Soukhomel method

4.2 Water-level depression

4.2.1 Water-level depression calculation methods

Energy

A survey of methods used is given in Section 2.1.1. Calculated results have been compared with measured data as mentioned above in Section 4.1 resulting in a number of basic plots.

The information for these plots has been condensed into overall-plots, by determining the average per h/T value per basic plot. At the same time the standard deviation has been determined.

In these plots the calculated and measured ratios are presented as functions of b/B. Distinction is made for different ship types and h/T values.

From these plots it appears that Tothill, Schijf, McNown, Constantine, Balanin and Bykov, Gates and Herbich give similar results.

The calculated results underestimate the measurements over the whole range of b/B values. It should be noted that the deviations become less (of the order of 10 percent) for smaller channels. It can be extrapolated, that the agreement is fairly good for channels with b/B < 5.

With the method of Schijf which includes the effect of the α coefficient, the calculated values become too high.

Momentum

Overall plots, similar to those established for the energy approach, have been established for the momentum approach.
The methods considered (see Section 2.1.2) are those of Bouwmeester [4] and Sharp and Fenton [14].

The Sharp and Fenton results are very similar to these which follow from the energy approach. However the ratio values are slightly closer to unity (about 5 percent).

Bouwmeester introduced, see Section 2.1.2, a drag-coefficient (r). The effect of this coefficient is that the calculated results are in good agreement with the measured results. This holds for the entire b/B range. However, there is a divergence which increases with decreasing values of b/B (see Figure 6).

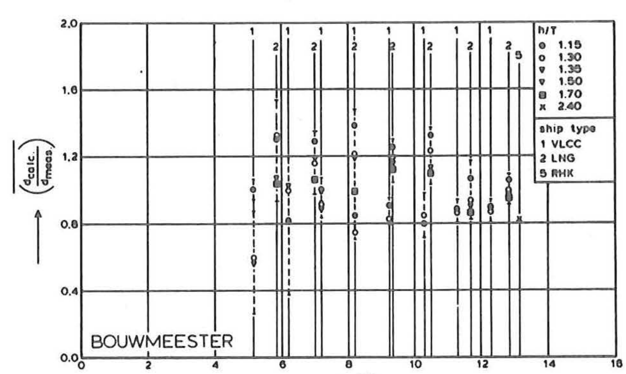


Figure 6 Calculated water-level depressions - based on Bouwmeester

4.2.2 Sinkage calculation methods

It is emphasized again that the methods mentioned below have been set up to calculate sinkage and not water-level depression.

Slender body

The results of Tuck give reasonable agreement only in the b/B range 6.5 to 7. Above this range the calculations are up to 40 percent too high.

Energy

Dand and Führer and Römisch calculate the sinkage using an empirical extended energy approach (see Section 2.2.2).

The Dand method is restricted to ships with a block coefficient between 0.8 and 0.9. This means that the results of the LNG carrier cannot be considered. Focussing on the remaining information it follows that the prediction is good for a b/B range of 7 to 10. Below b/B = 7 the Dand approach is the same as the Schijf method, taking however the form of the hull into account. The results correspond with Schijf in this area. In the b/B range 7 to 10 the Schijf results are increased by the influence of the effective width which results in a good agreement. For higher values of b/B the influence of the effective width becomes too strong and the predicted water-level depression becomes much larger than the measured values.

The results of Führer and Römisch are, for the whole range investigated, far too high (20 to 100 percent), compared with the measured values.

Experimental method

Soukhomel gives reasonable results for b/B ratios of 6 to 7. For lower ratios the prediction is too low and for higher ratios too high compared with measured values.

4.3 Sinkage

For sinkage the same approach is applied as for water-level depression. Similar overall-plots have been composed per method. In the sinkage case it should be kept in mind that the water-level calculation methods cannot be strictly applied here.

4.3.1 Water-level depression calculation methods

Energy

Tothill, Schijf, McNown, Constantine, Balanin and Bykov, Gates and Herbich give similar results as was the case with the water-level calculations, Section 4.2.1, compared with the measured values. The prediction of sinkage is reasonable for smaller channels (b/B ≤ 5) and too low for b/B > 5, while the divergence increased with increased values of b/B.

When the α factor is applied to Schijf the divergence increases such that the method can no longer be considered reliable.

Momentum

The Bouwmeester method gives, for b/B ranges greater than 5 and less than 8, a reasonable prediction of the sinkage. This result is not unexpected considering the points given in Section 3.3.2. The spread of results in the stated range however, is considerable.

Sharp and Fenton give results which are slightly higher than the results of the energy methods. However, the results are about 20 percent lower then those of Bouwmeester clearly illustrating the effect of Bouwmeester's drag-coefficient.

4.3.2 Sinkage calculation method

Slender body

Results obtained with Tuck's method are good for the range b/B > 5. For smaller channels the predicted values are too low, however, the method cannot be used in this range (see Table 1). The spread of results is appreciable (see Figure 7).

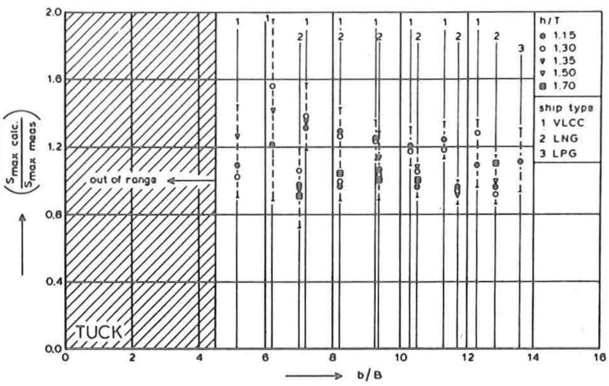


Figure 7 Calculated sinkages - based on Tuck

Energy

Dand's method gives good agreement with measurements for small values of b/B (i.e. less then 5) and for values of b/B < 7. The standard deviation (see Figure 8) is negligible.
The agreement is not so good in the range 5 < b/B < 7 (see Energy approach, Section 4.2.2).

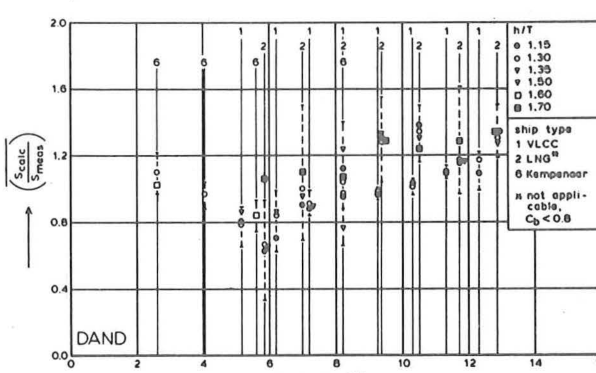


Figure 8 Calculated sinkages - based on Dand

The results of Führer and Römisch are generally high compared with the measured values. However it should be noted that they tend to have better agreement for higher Froude-Numbers, as is illustrated in the basic plot presented below (Figure 9).

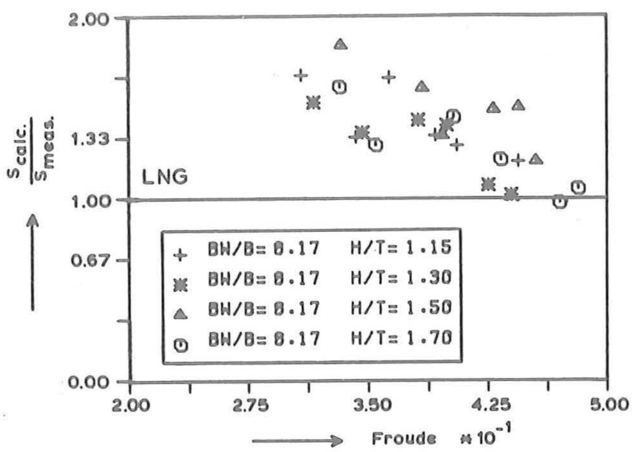


Figure 9 Calculated sinkages - based on Führer and Römisch

Experimental method

Soukhomel gives good results for b/B greater than 6, for the fuller ship ($C_B > 0.8$). The spread in results is 10 to 20 percent in this case.

4.4 Squat

Only a limited number of methods include the calculation of trim. Purely one-dimensional approaches (Energy, Momentum) are, of course, excluded.

The direction of the trim depends, generally, on the location of the centre of buoyancy with respect to the midships. If this point is situated sufficiently forward from $\frac{1}{2}$ L_{pp}, then bow squat dominates. However, if this distance is relatively small (see LNG carrier, Table 2) then the situation is more complicated.

From the measurements it appears that, for all the ship types considered, the bow squat dominates. Only in the case of the LNG carrier, in relatively wider channels b/B ≥ 6), does the stern squat generally dominate; the bow squat (again generally) dominates in narrower channels (b/B < 6).

4.4.1 Slender body

According to the calculations carried out for the LNG carrier the stern squat dominates. This means that the dominating bow squat, observed for b/B = 5, cannot be taken into account. For the other ship types calculated and measured trim directions are similar.
Standard plots have been prepared by averaging and compiling the data of the basic plots.

The stern squat prediction for the LNG carrier is good throughout the b/B range investigated (excluded b/B = 5). The standard deviation is about 20 percent for b/B = 7, decreasing to 10 percent for the widest channels (see Figure 10).

The predicted values of bow squat for the VLCC are relatively high compared with measured values. The deviation decreases from 40 percent at b/B = 6 to 20 percent for the widest channels investigated. The spread of values shows the same tendency (see Figure 10).

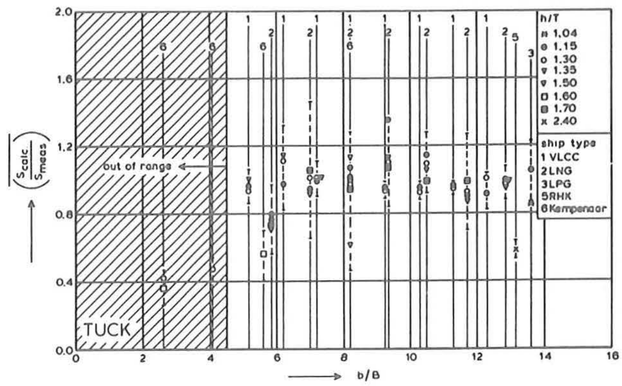


Figure 10 Calculated squat values - based on Tuck

4.4.2 Energy

The method of Dand (restricted to the VLCC) gives good results for b/B > 7, the standard deviation being relatively small (of the order of 10 percent). For lower values of b/B the calculated squat values are too low, with exception of b/B values below 5.

The direction of the trim of the LNG carrier is, according to Führer, such that the bow squat dominates always. This is incorrect and therefore these calculations are omitted. Considering only the fuller ships, it appeared that the predicted values are generally too high. For increasing channel widths the divergence decreases to about 10 percent for the widest channel.

4.4.3 Experimental methods

Soukhomel only consideres the dominating stern squat. Consequently only the LNG carrier for b/B greater than 6 can be considered. The analysis showed that the calculated values through the b/B range are 20 to 80 percent higher than the measured values.

Eryuzlu considers only full ships (VLCC's) and the results, for these kind of ships, are satisfactory for b/B ranges greater than 6. The spread in values is about 10 percent.

Barras considers only the maximum squat without indicating the position (bow or stern). His prediction method has been based on a great range of measurements using different ship types, but full form ships dominate. The analysis showed that good results with a spread of about 10 to 15 percent are obtained over the whole b/B range for the VLCC with dominating bow squat in contrary to the LNG carrier with a realtively small trim angle. In the latter case the computed maximum squats were about 20 to 30 percent higher than the measured maximum squats, while the spread is also of the order of 20 to 30

percent.
It seems probable that on the basis of the analysis the method of Barras only can be applied for ship types with dominating bow squat.

5 DISCUSSIONS

Table 3 shows the main results given in Chapter 4.

Generally, the Momentum approach with an empirical coefficient, as introduced by Bouwmeester, can best be used to predict water-level depressions and, thus, back flow velocities. For determination of sinkage and squat the Tuck approach is the most appropriate. For VLCC type ships other methods are also applicable.

For details is referred to Table 3.

For very small channels (b/B less than 5) it follows that water-level depression and sinkage have similar magnitude: the induced water motion has a predominant one-dimensional character.

On the basis of the analysis carried out it is concluded, that a b/B ratio of about 13 cannot be considered as infinite in width. Although for the tests with smaller Froude-Numbers the influence of such a width restriction is not significant, for higher Froude-Numbers without any doubt, some effects can be expected. This leads to the recommendation for the verification of methods with results obtained with ships sailing in wide channels (up to b/B of 30). In this light it is also recommended that the range of water depth/draught ratios, $\frac{h}{T}$, should be extended to get a better insight into the restriction of water depth.

In order to compute the water-level depression near the ship from a prediction of mean water-level (e.g. Bouwmeester) use can be made of:

1. Figure 2 giving the ratio $\frac{d_{bank}}{d_{ship}}$, and

2. Equation (48) with which the curvature of the water-level depression, in the lateral direction can be quantified.

Although the methods presented are not very complicated, hand calculations are generally not possible and, particularly, the iterative calculation schemes of Dand [6] and Tuck [17] demand a numerical computerized approach. These methods require, in addition, numerous data concerning the ships. Consequently, in many cases, a designer will not be able to apply these methods. This leads to the recommendation that a series of coefficients, as function of types of ships, and environmental conditions, should be prepared in order to give the method wider applicability.

The Eryuzly and Hausser [8] and Barras [3] methods for computing the squat of a VLCC are relatively simple to use.

It appears that a lot of data on VLCC-type ships is available in literature but that data on other types of ships are scarce. It would be interesting to include more ship types into the systematic analysis. In this respect results of reliable prototype measurements would be interesting.

Author	range of applicability (b/B): 1 2 3 4 5 6 7 8 9 10 11 12	prediction of:	restrictions with respect to ship types
Schijf, Constantine, Tothill, McNown, Gates and Herbich, Balanin and Bykov	2–4.5	water level depression	-
Sharp and Fenton	2–4.5		-
Bouwmeester	2–>12		-
Tuck, Huuska, Vermeer	6.5–8		-
Dand	2–4.5; 7–10		VLCC
Soukhomel	6–7		-
Schijf, Constantine, Tothill, McNown, Gates and Herbich, Balanin and Bykov	2–4.5	sinkage	-
Sharp and Fenton	2–4.5		-
Bouwmeester	5–8		-
Tuck, Huuska, Vermeer	5–>12		-
Dand	2–4.5; 7–>12		VLCC
Soukhomel	6–>12		-
Tuck, Huuska, Vermeer	6–>12	squat	-
Dand	7–>12		VLCC
Eryuzlu and Hausser	6.5–>12	squat (bow)	VLCC
Barras	5–>12	maximum squat	VLCC

Table 3 Survey of ranges of application

Finally it should be noted, that each prediction method has its own limited applicability because of the assumptions made in the theory and/or the experiments. It is therefore recommended that a 3-dimensional model is developed to compute the water movement around a moving ship. With such a model it is also possible to compute the exact pressure distribution acting on the ship's hull. From this pressure distribution the sinkage and trim can be determined accurately.

ACKNOWLEDGEMENT

The authors like to thank Rijkswaterstaat (Dutch Public Works Department) for their permission to publish some results of a systematic research carried out at the Delft Hydraulics Laboratory. This systematic research concerns mainly the ship induced water motion in and the attack of banks and bottoms of fairways.

NOTATION

A_c	Wetted area of channel cross section before squat	m^2
A_m	Area of midship section of ship	m^2
A_w	Wetted area of channel cross-section after squat minus area of midship section	m^2
$A(x)$	Area of a ship section	m^2
b	Waterline width of channel	m
b_b	Bottom width of channel	m
B	Beam of ship	m
c_B	Block coefficient of ship	-
c	trim coefficient	-
c_p	prismatic coefficient	-
c_s	sinkage coefficient	-
c_w	waterplane coefficient	-
d	water level depression	m
F_h	Froude number $(= \frac{V}{\sqrt{gh}})$	-
g	gravitation acceleration	ms^{-2}
h	water depth	m
i_p	longitudinal centre of buoyancy	-
i_w	longitudinal centre of flotation of waterline	-
k_w	longitudinal radius of gyration of waterline	-
L_{pp}	Length between perpendiculars	m
m	slope of embankment	-
r	Rise of waterlevel for ship's bow	m
R_x	Reynolds number	-
S	sinkage	m
S_b	sinakge at the bow	m
S_s	sinkage at the stern	m
T	draught of ship	m
u_r	back flow velocity	ms^{-1}
V	ship's speed	ms^{-1}
x	distance from ship's bow	m
∇	immersed volume of ship	m^3
τ	trim of ship $(= \frac{S_b - S_s}{L_{pp}})$	-
δ	boundary layer thickness	m
ρ	density	kgm^{-3}

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