AN OVERVIEW OF SQUAT MEASUREMENTS FOR CONTAINER SHIPS IN RESTRICTED WATER

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Abstract

Squat is an important issue for ships navigating with limited under keel clearance in restricted waterways such as channels and canals. The admittance policy for containerships on the Western Scheldt, a tidal estuary in the Netherlands giving access to the port of Antwerp (Belgium), is based on a minimal static under keel clearance to ensure safe passages on the river. A large number of captive model tests executed in the Towing Tank for Manoeuvres in Shallow Water (co-operation Flanders Hydraulics Research – Ghent University) have been evaluated to determine squat prediction formulae. Measured sinkage and trim depend on a number of parameters like ship velocity components, ship loading condition, propeller action, blockage of the waterway, bank geometries and characteristics of other shipping traffic. The derived mathematical models have been implemented in the ship manoeuvring simulators of FHR to visualize the dynamic under keel clearance during real-time simulations at different locations on the Western Scheldt.

1. INTRODUCTION

1.1 Accessibility of Containerships on the Western Scheldt

The waterways giving access to Belgian harbours are characterised by restrictions in both vertical and horizontal dimensions. In particular deep drafted containerships sailing through the Western Scheldt estuary (Figure 1) - the shipping route to the port of Antwerp – have to wait for the right tidal window to ensure a minimum (static) under keel clearance (UKC) of 12.5% of the ship's draft T along the trip. After realisation of the deepening of the Western Scheldt the tidal independent draft will be increased to 13.1 m which nevertheless do not equal the maximum draft of 16 m for the largest existing containership. Therefore, to determine the accessibility policy of this river for large containerships, a realistic prediction of squat (sinkage and trim) is of utmost importance.

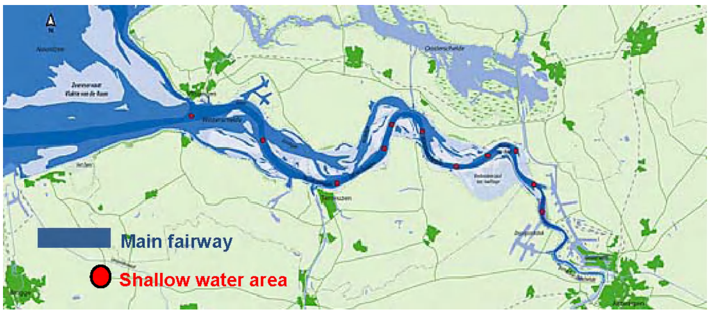


Fig.1 Western Scheldt estuary with main fairway and shallow water areas

1.2 Squat: Combination of Sinkage and Trim

Due to the hydrodynamic pressure field around a sailing ship's hull and, hence, a change of the water level around the ship (Figure 2), the vertical positions of the bow (z_F) and the stern (z_A) are modified. A distinction is made between the static sinkage by loading (z_{SF} and z_{SA}) and the dynamic sinkage or running sinkage due to ship motion which can be formulated depending on the mean sinkage z_{VM} (positive downwards) and the trim t_V (positive bow down).

$$\begin{cases} z_{VF} = z_{VM} + t_V \dfrac{L_{PP}}{2} \\ z_{VA} = z_{VM} - t_V \dfrac{L_{PP}}{2} \end{cases} \tag{1}$$

Fig.2 Definition of ship squat as combination of sinkage and trim

Sinkage and trim due to squat depend on a large number of parameters: the ship geometry and loading condition, the channel bathymetry, a number of operational parameters like ship velocity components and propeller action, and the presence of other ships in the fairway. Taking into account the importance of these parameters for a containership travelling the Western Scheldt Flanders Hydraulics Research (FHR) had ordered Ghent University (UGent) to derive squat formulae incorporating these effects based on model tests. This research was part of a larger project concerning the accessibility policy of the port of Antwerp for large containerships within the length range of 350 to 400 m.

1.3 Prediction of Squat based on Captive Model Tests

In order to investigate the behaviour of large container vessels in shallow and restricted waterways, comprehensive captive model test programs were carried out in the *Towing tank for manoeuvres in shallow water (co-operation Flanders Hydraulics Research – Ghent University)* in Antwerp (Figure 3). Model tests were executed with different draft and water depth in order to determine mathematical models suitable for manoeuvring simulations, but also interaction with banks and with other ships has been investigated. During these tests, the ship models were free to heave and pitch, so that valuable information on squat was collected.

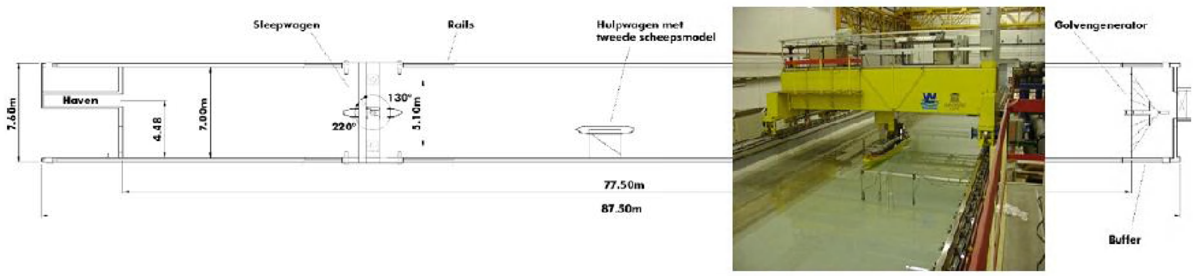


Fig.3 Towing tank for manoeuvres in shallow water (co-operation FHR – UGent)

An overview of the container ship models is given in Table 1. All models have been used for the determination of squat dependence on kinematical and control parameters, while model U has mainly been tested for ship-bank interaction. Model D has been used for ship-ship interaction as well, in combination with full-sized ship bodies [2]; unfortunately, no encounters of two containerships have been investigated so far.

Table 1 Dimensions of container ship models

Model	L_{PP} [m]	B [m]	L_{PP}/B
D	3.864	0.536	7.2
F	3.800	0.640	5.9
U	4.106	0.530	7.7

2. OBSERVED SQUAT DEPENDENCES DURING MODEL TESTS

Most theoretical, numerical, and experimental studies examining and predicting squat take only one parameter into account, the ship's forward speed, and therefore assume that the ship is following a straight course at constant speed in the centreline of the channel. In reality (Figure 4), a ship may be subject to drift (e.g. due to lateral wind or current), needs to accelerate and decelerate, and has to perform bends. In two-way channels, the ship's trajectory is eccentric, and the ship's hydrodynamics are influenced by interaction with other vessels during encountering and/or overtaking manoeuvres. In this chapter, an overview will be given of important dependences observed during captive model tests, which will be implemented in the mathematical modelling in chapter 3. All captive model tests are executed above a solid bottom which means that the static UKC is measured at rest between the ship's keel and the bottom of the towing tank. No mud layers are present so that the nautical bottom – in many harbours or channels used to determine the minimal required UKC or maximum draft of the vessel entering – is identical to the solid bottom.

Fig.4 Shipping traffic on the Western Scheldt

2.1 Dependence on Ship's Forward Speed and Ship Geometry/Loading Condition

The relationship between squat and ship's forward speed in Figure 5 is presented based on the widely used Tuck parameter T_{nh} and Froude depth number Fr_h:

$$T_{nh} = \frac{Fr_h^2}{\sqrt{1 - Fr_h^2}} \quad (2)$$

with

$$Fr_h = \frac{u}{\sqrt{g\,h}} \quad (3)$$

Based on this Tuck parameter a linear relationship between sinkage at fore and aft perpendicular (FP and AP) and ship's forward speed is observed where a decreasing water depth (from 100% to 10% static UKC) gives an increasing sinkage. In addition, for one containership the loading condition will determine the value and the sign of the trim angle: in deep water and a maximum draft of 14.5 m a trim angle "bow down" is found for ship model U while trim is opposite for an intermediate loading condition of 12 m draft; however, in shallow water "bow up" trim is measured for both loading conditions. In conclusion, a change of draft (or loading condition) results into another wetted hull geometry which can give as deviating squat values as can be seen between two different containerships.

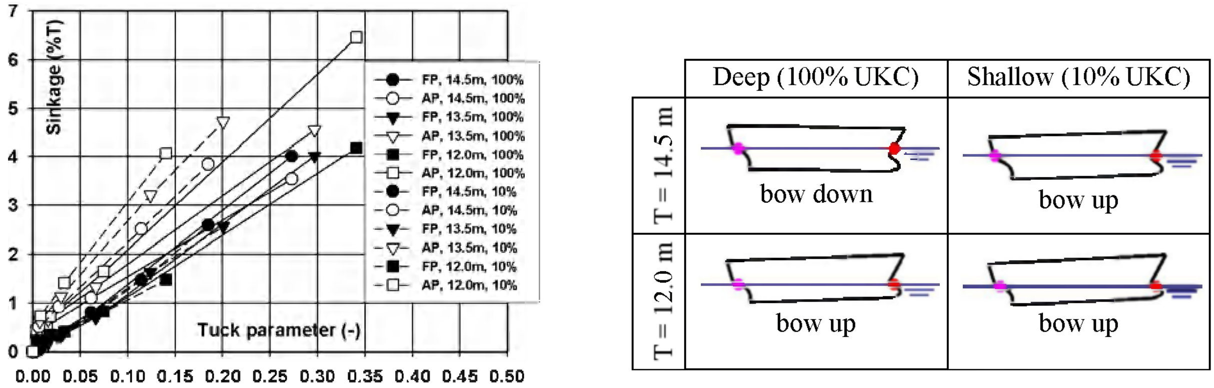


Fig.5 Model U, squat measurements as function of the Tuck parameter for different loading conditions (T = 14.5, 13.5 and 12.0 m) in deep and very shallow water (100% and 10% UKC)

2.2 Horizontal and vertical restrictions of the fairway

The influence of the available water depth is shown in the previous paragraph for an open water condition. Taking into account not only the vertical but also the horizontal restrictions of a river or channel, squat will be determined by the blockage m of the fairway as well (Figure 6). The blockage is defined as the maximum transverse area of (model) ship A_S divided by the channel or tank cross section area A_C. In [1] a function is presented based on the beam B of a ship and the Froude depth number Fr_h dividing the fairway into regions with significant influence of banks or horizontal restrictions and regions without influence. The relationship between water depth, blockage and the critical speed, shown on Figure 6, illustrates that a containership with 14.5 m draft, sailing on the Western Scheldt at the lowest permissible UKC, will reach the critical speed range at a speed of 17.5 kn, taking account of the range of the blockage factor (m = 0.05). In more restricted channels or canals, on the other hand, (0.2 < m < 0.3) the speed through the water must be reduced to approximately 10 kn.

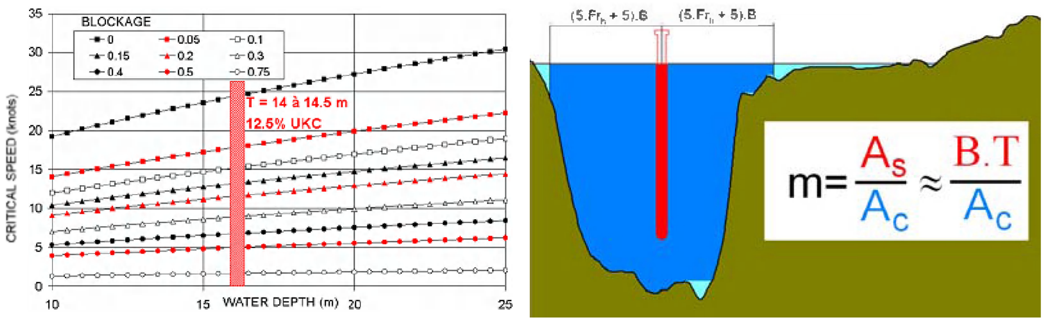


Fig.6 Influence of blockage and water depth on the critical speed

2.3 Dependence on drift and yaw rate angle

Compensating the influences of current and wind and even sailing along a bend, the ship will be subject to sway and yaw motions. Examining measured sinkages at bow and stern for ship model U during pure sway tests (Figure 7) in both deep and shallow water, bow sinkage is more sensitive to the drift angle with increasing sinkage for non-zero drift angles. At 10% UKC and a speed range of 10 to 12 knots, bow up trim at zero drift angle modifies into bow down trim due to drift, reducing the static UKC to 4 à 5% of the ship's draft. In real situations as simulated in paragraph 4.2, the maximum drift angle during a voyage in very shallow water will be restricted to approximately +/-5 degrees so that when realising a speed reduction the residual UKC will be larger.

During a starboard turn in open and deep water, a positive rate of turn is combined with a positive drift angle; opposite signs are found for a port turn (Figure 8). For these combinations, results of PMM yaw tests with constant drift angle show a reduction of the trim with an increasing (absolute value of the) yaw rate angle starting at $\gamma = 0$ so that an even keel sinkage or zero trim is reached at a value depending on the water depth and the ship's speed (about $|\gamma|$ = 2.5 - 4 deg for 100% and 7.5 - 10 deg for 10% UKC).

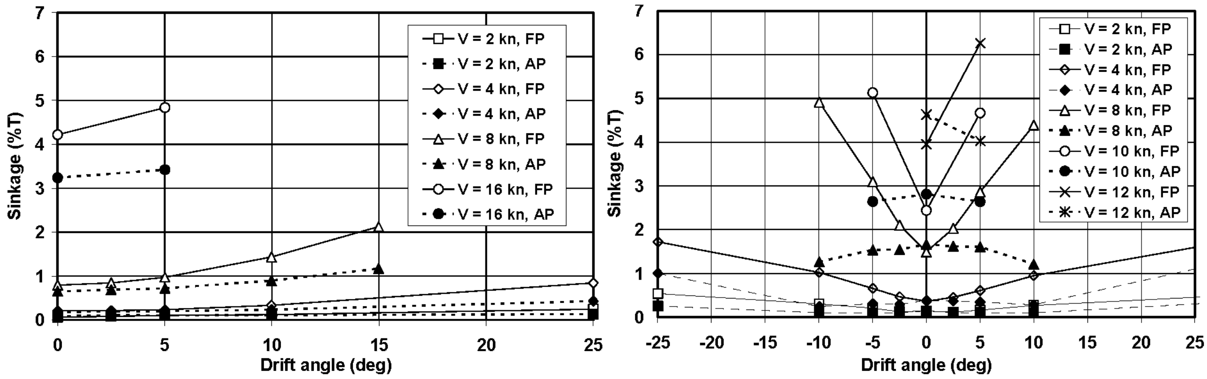


Fig.7 Model U, T = 14.5 m, influence of sway motion or drift angle on measured sinkage at bow and stern in deep (100% UKC, left) and shallow (10% UKC, right) water

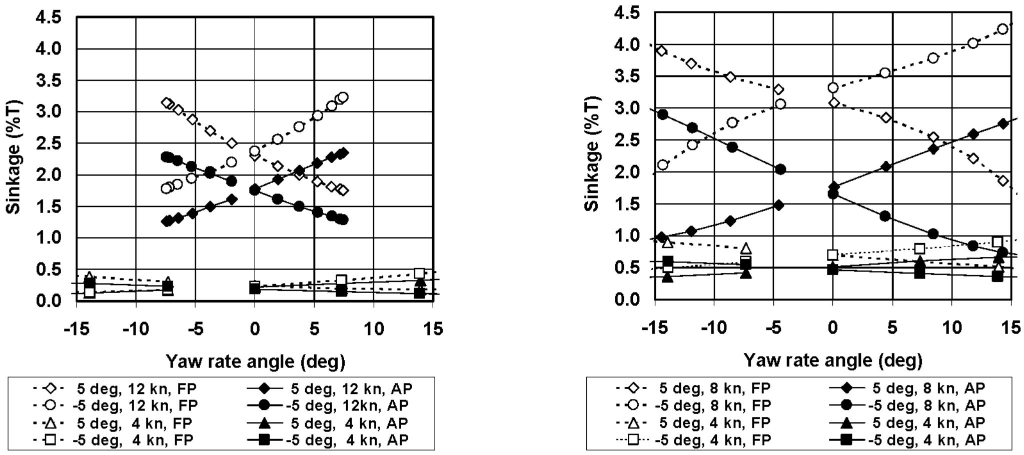


Fig.8 Model U, T = 14.5 m, influence of yaw motion on measured sinkage at bow and stern for different drift angles and ship speeds in deep (100% UKC, left) and shallow (10% UKC, right) water

2.4 Dependence on propeller action

The influence of the propeller on sinkage during the normal working condition with positive rate of turn and positive ship's forward speed is an increasing sinkage aft z_{VA} due to the pressure reduction at the stern induced by the propeller flow. On Figure 9 two speed values – 8 and 16 knots – are combined with several rates of turn at full scale – 0 to 80 rpm – which correspond to engine's telegraphs from stop to harbour full ahead. Manoeuvres on the river Scheldt are indeed characterised by consecutive accelerations and decelerations to be able to control the ship in the restricted fairway and to ensure safe passages of inland and seagoing ships. The additional sinkage due to propeller action increases with decreasing UKC for all propeller rates while an intermediate draft gives a little higher increase with increasing propeller rate in terms of percentages compared to the fully loaded ship.

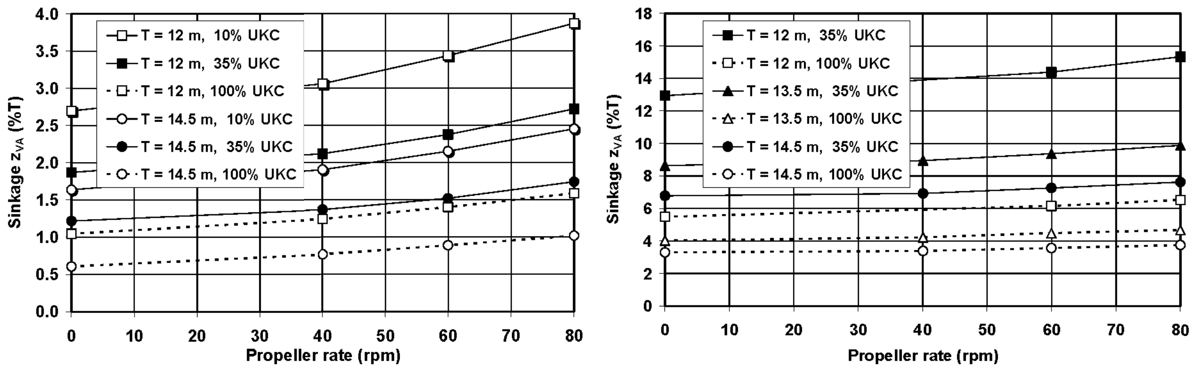


Fig.9 Model U, several drafts, additional influence of propeller action on sinkage at the stern for speed values of 8 knots (left figure) and 16 knots (right figure)

2.5 Dependence on ship-ship interaction

Figure 10 illustrates the effect on the squat of a container ship caused by a head-on passing encounter with a bulk carrier. The sinkage of bow and stern are displayed as functions of the non-dimensional relative longitudinal position. The abscissa takes values of -1 and +1, respectively, when the bows and the sterns are located at the same longitudinal position. When the two bows meet, the ship's bow sinkage increases, while the stern is lifted, resulting in trim by the bow. The trim changes sign when the midship sections of both ships are at the same position. During the second part of the meeting, the sinkage aft is increased while the bow is lifted. In the selected case, the sinkage increases with 50 to 100% during the meeting manoeuvre, depending on the forward speed of the other vessel

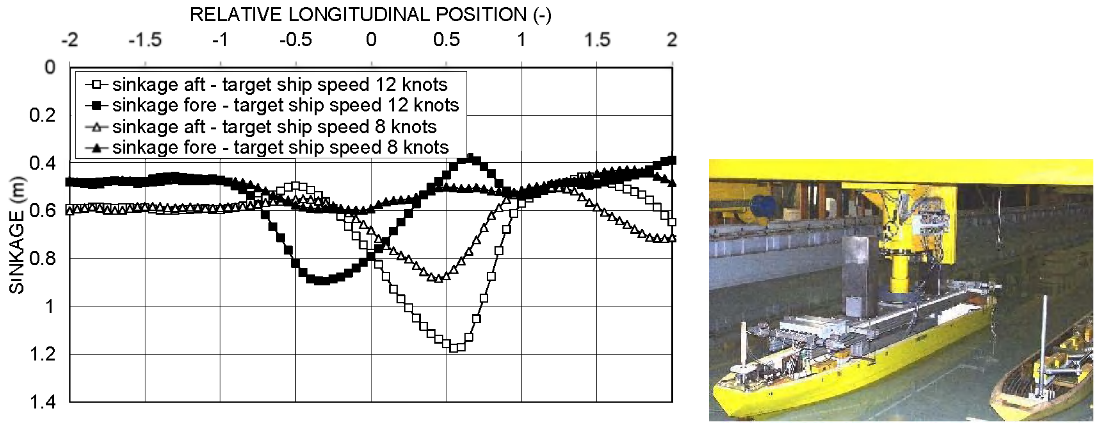


Fig.10 Squat of a containership (L_{OA} = 291.3 m, B = 40.3 m, T = 13.5 m) sailing at a forward speed of 12 kts, caused by a head-on passing encounter with a bulk carrier (L_{OA} = 310.6 m, B = 37.8 m, T = 13.5 m) sailing at different forward speeds. Lateral distance between centrelines: 114.5; water depth: 17.1 m. [3]

2.6 Dependence on bank geometry

Approximately 11000 tests were carried out in the towing tank to evaluate the influence of different bank geometries on ship manoeuvring and have been used to determine the prediction formulae for squat of model U. Tests were conducted at different ship speeds and drafts, distances to the bank and water depths. The influence of the distance to a sloped surface piercing bank is visualized for model U on Figure 11 within a speed range of 8 to 14 knots. A gradual increase of the sinkage at bow and stern with decreasing distance to the bank can be observed; the initial open water sinkage appears to be doubled when the ship is navigating above the sloped bank with speeds above 10 knots.

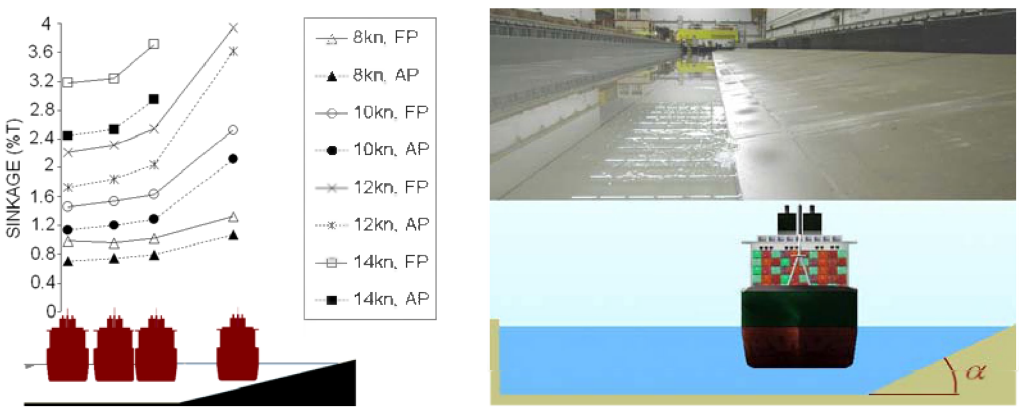


Fig.11 Model U, T = 14.5m, slope = 1/8, influence of distance to bank on sinkage in deep water (100% UKC)

3. MATHEMATICAL MODELLING OF SQUAT DEPENDENCE

Based on the extensive model tests discussed in chapter 2 a mathematical model for squat has been developed. The model incorporates a large number of parameters that can be organised into four groups (Table 2): ship dependent parameters, environmental parameters, operational parameters, and the presence of other shipping traffic.

The base of the mathematical model is a formula to calculate the sinkage z_{VA} and the trim t_V influenced by the longitudinal speed component, draft, water depth, and blockage. Preference is given to the sinkage at the stern compared to the mean sinkage because of the clear relationship between z_{VA} and the Tuck parameter. The critical speed V_{crit}, defined as the upper limit of the subcritical speed range, is obtained by introducing two additional coefficients with k_m a blockage correction coefficient and k_s a ship dependent coefficient.

$$V_{crit} = \sqrt{k_m k_s\, g h} \tag{4}$$

with $$k_m = \left[2\sin\left(\frac{\mathrm{Arc}\sin(1-m)}{3}\right)\right]^3 \tag{5}$$ and $$k_s = C_{Xi} + \frac{T}{B} C_{X(i+1)} \tag{6}$$

The sinkage z_{VA} is made non-dimensional based on a reference draft T_{ref}. Both sinkage and trim are a linear function of the Tuck parameter depending on the Froude number Fr_m. Coefficients C_{Si} for the sinkage and C_{TRi} for the trim are determined based on a regression analysis of model test results.

$$\frac{z_{VA}}{T_{ref}} = \left[\left(C_{S1}\left(\frac{T-T_{ref}}{T_{ref}}\right) + C_{S2}\right)\frac{T}{h} + C_{S3}\left(\frac{T-T_{ref}}{T_{ref}}\right) + C_{S4}\right] \frac{\dfrac{Fr_m^2}{C_{S5} + \frac{T}{B} C_{S6}}}{\sqrt{1 - \dfrac{Fr_m^2}{C_{S5} + \frac{T}{B} C_{S6}}}} \tag{7}$$

$$t_V = \left(C_{TR1}\left(\frac{T-T_{ref}}{T_{ref}}\right) + C_{TR2}\frac{h}{T} + C_{TR3}\right) \frac{\dfrac{Fr_m^2}{C_{TR4} + \frac{T}{B} C_{TR5}}}{\sqrt{1 - \dfrac{Fr_m^2}{C_{TR4} + \frac{T}{B} C_{TR5}}}} \tag{8}$$

with $$Fr_m = \frac{u}{\sqrt{k_m g\, h}} \tag{3}$$

Besides these formulae the influence of propeller action, bank effects, lateral and yawing velocity and ship-ship interaction have been superposed on the initial squat.

Table 2 Parameters taken into account in the mathematical model

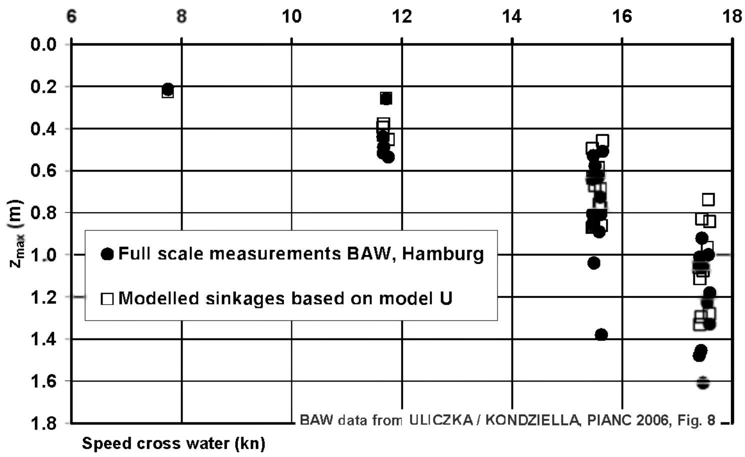
SHIP DEPENDENT PARAMETERS	ENVIRONMENTAL PARAMETERS	OPERATIONAL PARAMETERS	OTHER SHIPPING TRAFFIC
draft	water depth	velocities u, v, r	draft of target ship
displacement	distance to banks	yaw acceleration	displacement of target ship
block coefficient		lateral force	block coefficient of target ship
midship section area		yawing moment	lateral distance between ships
		propeller rate	longitudinal velocity of target ship

4. VALIDATION BASED ON FULL SCALE MEASUREMENTS AND REAL-TIME SIMULATIONS

4.1 Full scale measurements

In February 2004 the Bundesanstalt für Wasserbau (BAW) in Hamburg conducted several full scale measurements on different vessels sailing on the river Elbe resulting into a large amount of squat measurements of which a selection was published in [4]. Thanks to a scientific co-operation (MoU) between BAW and FHR/UGent, the authors could use the original field measurement data to validate the mathematical model for squat. On Figure 12 the containership "CMS Berlin Express" was selected for the comparison due to the very similar dimensions with ship model U.

From the large amount of full scale measurements 29 results at four different ship speeds were selected and compared to the predictions calculated with the mathematical model based on model U. All effects except the influence of other shipping traffic were taken into account. A good correspondence is obtained for the maximum values within the speed range of 8 to 18 knots although maximum sinkages are measured at the bow for the CMS Berlin Express while the modelled maxima occur at the stern. An explanation for the bow trim observed at speeds above 8 knots was given in [4].



Ship	L_{PP} [m]	B [m]
U (scale = 80.8)	331.8	42.8
CMS BERLIN EXPRESS	320.4	42.8

Fig.12 Comparison between full scale measurements [4] and modelled maximum sinkages

4.2 Real-time simulations

Real-time simulations have been executed on the ship manoeuvring simulators of FHR (SIM225 and SIM360+) to evaluate the accessibility of the Western Scheldt for large containerships with a length over all of 366 – 380 – 400 m. A lack of experience with these ship sizes could consequently be filled in and the simulation results will help policymakers to make decisions in future. Both simulators were coupled so that with two operating bridges the encounters are as realistic as possible.

During encounter 39 (maximum flood current, wind SW 5Bf) a downstream containership (366 m x 48.8 m x 13.1 m) passes a larger ship (400 m x 56.4 m x 14.5 m) in the bend of Bath on the river Scheldt (Figure 13). The encounter occurred with a lateral distance equal to 56m and a relative speed through the water for both ships of approximately 12 knots. The velocity parameters and sinkages of the downstream ship can be studied based on the graphs in Figure 13. The lowest obtained static UKC along the whole trajectory is approximately 50% while the maximum sinkage occurs at the stern with a maximum UKC reduction of approximately 10% of the ship's draft.

Encounter 95 took place at the Europaterminal in the harbour of Antwerp at ebb current (downstream ship 366 m x 48.8 m x 13.1 m, upstream ship 400 m x 56.4 m x 13.1 m) with a lateral distance of 132m. The available water depth is smaller with a minimum static UKC of 14.5 % of the ship's draft. Thanks to a speed reduction from 12 knots (value relative to the water) at the start of the simulation to a value lower than 10 knots at the lowest water depth (15 m) the sinkage at the stern can be restricted to 0.5 m (Figure 14).

As ship models were free to heave and trim during the model tests executed in the towing tank, the mathematical manoeuvring models take already into account the effect of a dynamic UKC and thus the reduction of the available water depth due to squat. Modeled squat values are visualized to ensure the availability of sufficient water under the keel and to confirm the admittance policy for the Western Scheldt.

5. CONCLUSION

The squat values summarised on pilot sheets for both deep and shallow water are mostly based on conservative prediction formulae which take into account ship's speed and some ship and environmental dependent parameters (e.g. blockage). Based on an evaluation of a large number of captive model tests executed in the Towing Tank for Manoeuvres in Shallow Water (co-operation Flanders Hydraulics Research and Ghent University) squat as a combination of sinkage and trim is considered to depend on at least four groups of parameters: ship dependent, environmental, operational and other shipping traffic parameters.

These dependencies have been transformed into mathematical models mainly based on the Tuck-parameter T_{nh} with a linear relationship between sinkage/trim and T_{nh}, a function of the Froude depth number. The derived math models have been validated based on full scale measurements, placed to the authors' disposal by BAW Hamburg, and have given a good correspondence for the absolute value of the maximum sinkage. The location of this maximum is for the tested ship models nevertheless situated at the aft body while bow down trim is measured for the selected containerships on the river Elbe. Real-time simulations executed at the ship manoeuvring simulators of FHR show a realistic change of sinkage at bow and stern during passages through the Western Scheldt and can help policymakers in evaluating the accessibility of deep drafted containerships. A validation at full scale can nevertheless give additional information about the degree of uncertainty in these restricted areas.

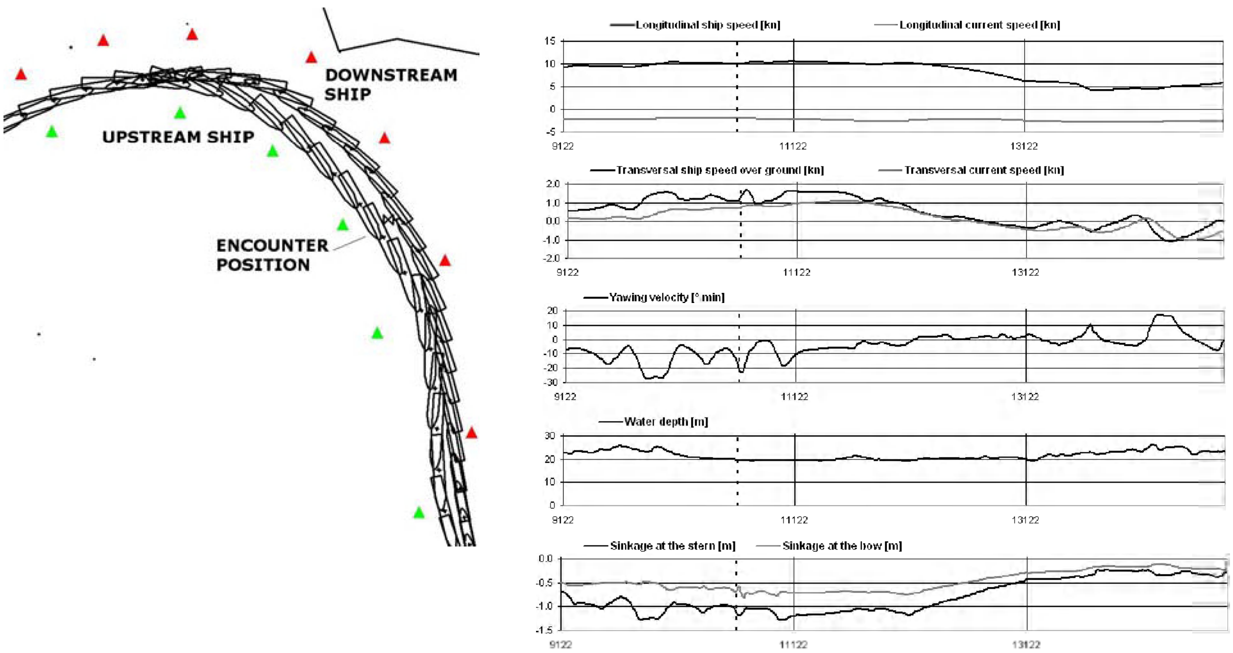


Fig.13 Real-time simulation of an encounter at the bend of Bath during flood tide: trajectories of both ships during the total manoeuvre and parameters of the ship sailing downstream with the encounter position indicated with a dashed vertical line on the graphs

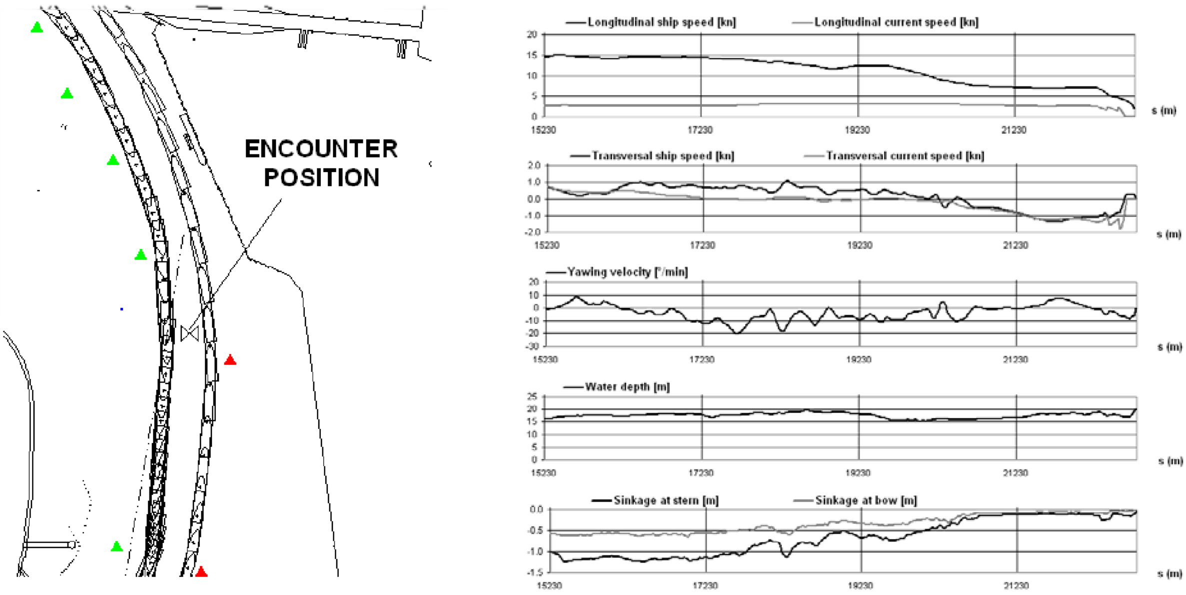


Fig.14 Real-time simulation of an encounter at the Europaterminal during ebb tide: trajectories of both ships during the total manoeuvre and parameters of the ship sailing downstream

NOMENCLATURE

A_S maximum transverse area of (model) ship (m^2)
A_C transverse area of channel or tank (m^2)
B ship's beam (m)
C_{Xi} regression coefficients (-)
Fr_h Froude depth number (-)
Fr_m Froude depth number corrected with k_m (-)
g gravity acceleration (m/s^2)
h water depth (m)
k_m blockage correction coefficient (-)
k_s ship dependent coefficient (-)
m blockage (-)
T ship's draft (m)
T_{nh} Tuck parameter based on Fr_h (-)
t_V dynamic trim due to ship motion (10^3 mm/m)
u longitudinal velocity component (m/s)
UKC under keel clearance, percentage of ship's draft (%)
V_{crit} critical speed (m/s)
z_F sinkage at the bow (m)
z_A sinkage at the stern (m)
z_{SF} static sinkage by loading at the bow (m)
z_{SA} static sinkage by loading at the stern (m)
z_{VF} dynamic or running sinkage due to ship motion at the bow (m)
z_{VA} dynamic or running sinkage due to ship motion at the stern (m)
z_{VM} mean dynamic or running sinkage due to ship motion (m)
z_{VA} dynamic or running sinkage due to ship motion at the stern (m)

γ yaw rate angle (deg) with $\gamma = \text{Arc}\tan\left(\frac{rL_{pp}}{2u}\right)$

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