

Ship-Bank Interaction Induced by Irregular Bank Geometries

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SUMMARY

The forces and moments induced by the vicinity of banks on a sailing vessel are known as *bank effects*. An extensive set of model tests have been carried out in a towing tank to investigate bank effects induced by irregular bank geometries. Tests along sloped surface-piercing as well as submerged banks are carried out. A mathematical model (for the longitudinal force, sway force, yaw moment and sinkage) found on these tests is formulated. This model copes with the geometry of the banks tested and not tested bank geometries. This paper emphasises on the mathematical model and on two parameters of this mathematical model: The distance between ship and bank $d2b$ and the equivalent blockage m_{eq} such that the properties of an irregular bank geometry are taken into account.

I. INTRODUCTION

For years a continuous increase of the main dimensions of different ship types can be observed. The dimensions of access channels, rivers, canals and ports frequented by these vessels often do not increase at the same rate. As a result, the manoeuvring behaviour of ships calling or clearing harbours will increasingly be influenced by restrictions of the waterways, both in horizontal and in vertical sense, due to the proximity of banks and of the bottom, respectively.

The flow pattern around a navigating or manoeuvring ship is affected significantly by the water depth. In open and unrestricted water this flow is fully three dimensional, as a significant part of the displaced water flows under the ship. The stream pattern of a ship sailing in very shallow water, on the other hand, tends to be two dimensional.

A ship sailing at the centre line of a symmetric canal or channel will encounter an increased resistance and a modified sinkage and trim as a result of the increased relative velocity between the water and the ship due to the increased blockage, but no lateral forces will be induced by the banks because of reasons of symmetry. When sailing in an asymmetric environment, however, the asymmetric flow pattern around the ship will induce a sway force and a yaw moment. In general, the water at the

ship's side at the closest bank will have a higher speed. As a result the water level will decrease more than at the other ship's side and the ship will be attracted to the closest bank; as the resulting force tends to apply aft of the midships section, a bow-away moment will be experienced as well.

Due to the sign of the lateral force, ship-bank interaction effects are often called *bank suction*. Nevertheless, this terminology will be avoided, as in very shallow water bank repulsion – although combined with a bow-away moment – may occur. Alternatively, the phenomena caused by the horizontal restrictions of the navigation area will be referred to as *bank effects*.

The latter depend on a large number of parameters, such as bank shape, water depth, ship-bank distance, blockage, ship characteristics, ship speed, and propeller action.

The Flemish Government (Belgium), being responsible for the safety and efficiency of shipping traffic in the access channels to the harbours of Antwerp, Ghent, Ostend and Zeebrugge, prefers a scientific base for its admittance policy to these ports. A reliable prediction of bank effects is of great importance to determine the limiting conditions in which a ship can safely navigate a waterway. However, the knowledge of the bank effects induced by banks that are typical for navigable rivers with irregular shape is very limited. As bank effects

are considered to be a decisive factor for the admittance policy, a research project was initiated by the administration of the Flemish Government.

In the period January 2006 – January 2007 a comprehensive model test program has been carried out at the fully automated towing tank of Flanders Hydraulics Research (Flemish Government, Antwerp, Belgium). The mathematical model that has been developed based on these tests takes account of complex bank geometries, such as irregular natural banks, fairways with a dredged centre canal, flooded banks, and other bathymetries such as in the access channel to the port of Zeebrugge, Belgium (Figure 1).

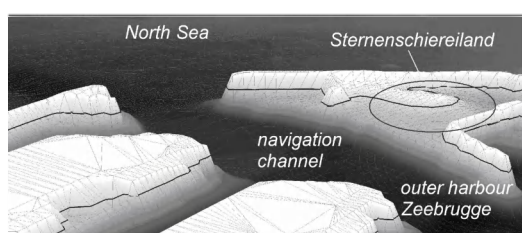


Figure 1 The bathymetry of the harbor of Zeebrugge (Belgium)

In the present paper, the mathematical model for bank effects will be described, emphasizing on two important parameters:

- ⌚ an equivalent distance between ship and bank, which is unambiguously defined for a ship sailing along irregular bank geometries;
- ⌚ an equivalent blockage, that will be defined such that the whole bank geometry (width, depth, bathymetry) is taken into account, and not only the cross sections of ship and channel; as a result, the blockage will be different for a deep narrow canal compared to a shallow wide canal, even if both canals have the same cross section.

II. EXPERIMENTAL PROGRAM

All the results discussed in this paper are obtained by captive motion model tests carried out in the *Towing Tank for Manoeuvres in Shallow Water* (cooperation *Flanders Hydraulics Research – Ghent University*). The main dimensions of the towing tank are 88 x 7 x 0.5 m³.

This fully automated towing tank allows executing captive tests up to 35 runs a day (24/7). Because of the installation of two consecutive bank configurations in the towing tank (Figure 2), up to 70 test conditions a day are obtained, so that more than 10.000 test

conditions on bank effects have been executed in 2006. Captive motion model tests are carried out in the towing tank at a constant forward speed.

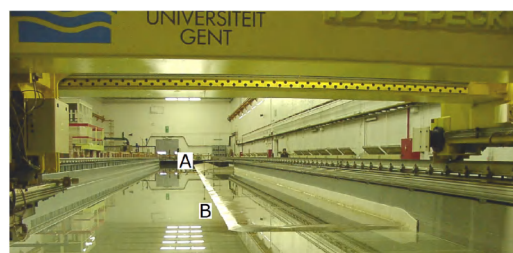


Figure 2 Both installed banks in the Towing Tank for Maneuvers in Shallow Water. The submerged platform is not submerged in this almost empty tank.

Seven different bank geometries have been installed in the towing tank. Two different types of banks can be distinguished (see Figure 3):

- ⌚ surface piercing banks (A), characterised by a constant slope from the bottom up to the free surface;
- ⌚ banks with platform submergence (B), composed of a sloped part with height h_0 and a horizontal, submerged platform at a depth $h_1 (= h - h_0)$.

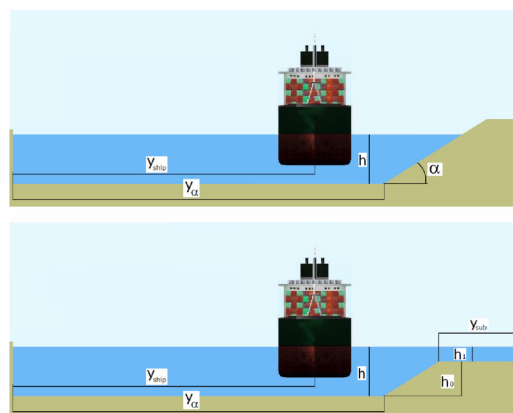


Figure 3 Surface piercing bank and a bank with platform submergence

The slopes and height of the submerged platform of the installed banks are shown in Table 1. A graphical overview is given in Appendix A.

Table 1 Overview of the geometry of the tested banks

h_0	α	Name	y_a
surface piercing	vertical wall	I	6.330m
surface piercing	1/3	VII	5.730m
surface piercing	1/5	II	4.030m
h_{01}	1/5	III	4.030m
h_{02}	1/5	IV	4.030m
surface piercing	1/8	V	4.030m
h_{01}	1/8	VI	4.030m

Bank I is a vertical wall analogous to a berthing quay wall. Bank VII is surface piercing with a slope of 1/3. These are common banks on manmade canals or in harbours. The banks with slope 1/5 (II, III and IV) are a simplified representation of the bathymetry at the *Tern Peninsula* (Sternschiereiland) in the outer harbour of Zeebrugge (Figure 1). A slope of 1/8 (V and VI) is very common for natural river banks, such as the Western Scheldt.

All these banks cover a wide range of bank configurations from a quay wall up to a naturally sloped river bank.

Three ship models are used in this test program: two models, a container carrier and a LNG-carrier, for the systematic tests along the installed banks, and a smaller tanker model for the investigation of the horizontal reach. LNG-carriers are of importance for the harbour of Zeebrugge, while large (+7000 TEU) container carriers frequent daily the harbours of Zeebrugge and Antwerp.

The main dimensions of the container carrier are listed in Table 2. The model of the 8000 TEU container carrier is tested extensively at two even keel conditions. A concise test program has been executed with the ship model in initially trimmed condition.

Table 2: main dimensions of the tested ships

	8000 TEU container carrier			LNG carrier	tanker
L_{OA} [m]	350.0	350.0	350.0	280.0	173.1
B [m]	42.90	42.90	42.90	41.60	22.13
T_F [m]	12.00	14.50	13.00	11.00	13.35
T_A [m]	12.00	14.50	14.50	11.00	13.35
C_B [-]	0.65	0.66	0.65	0.77	0.8
Scale [-]	1/80	1/80	1/80	1/70	1/75

The second model is a LNG-carrier. Table 2 shows the main properties of this carrier. This

LNG-carrier is tested at one even keel condition only.

For the container carrier tests have been carried out at three different water depths: 10%, 35% and 100% under keel clearance (UKC) so as to cover the UKC range encountered by a container carrier approaching or leaving the Belgian harbours.

The LNG-carrier is tested at 35% and 70% UKC only, according to the present practice at Zeebrugge.

Analogous to the container carrier the tanker is tested at 10%, 35% and 100% UKC.

Two test programs can be distinguished: the regular bank effects test program, in which the container and the LNG carrier models were involved, and a series of tests performed with the tanker model in order to investigate influence width, as will be clarified in Section III.

The speed range for both models of the regular test program varies between 6 knots up to 16 knots full scale. Most of the tests have been conducted at 8, 10, 12 and 14 knots. When physically possible 16 knots was added. When tests could not be executed at 12 knots, tests at 6 knots are added.

The regular tests are carried out for a wide range of distances to the bank:

- ⌋ as close as practically possible to the bank;
- ⌋ with amidships above the toe of the sloped bank (y_a);
- ⌋ with the ship's side above the toe of the sloped bank (y_a);
- ⌋ at the centre of the towing tank;
- ⌋ at the lateral position where the bank effects for sway force and yaw moment induced by the installed bank on one hand, and by the wall of the towing tank on the opposite side on the other, are expected to counteract.

Both models are single screw models. The propeller rate is systematically changed from 0%, 40%, 60% up to 80% of the maximum propeller rate.

The main input parameters of the regular test program are summarised in Table 3.

Table 3 Overview of the input parameters of the regular test program

Draft fore [m]	Draft aft [m]	Water depth [%]	Bank name	Speed [knots]	Propulsion	Lateral distance
11.0	11.0	200	I	0	0%	Centre towing tank
12.0	12.0	170	II	(6)	40%	Hydrodynamic centre
13.0	14.5	135	III	8	60%	Ship side at toe
14.5	14.5	110	IV	10	80%	Mid ship at toe
			V	12		Maximal
			VI	14		
			VII	(16)		
LNG-carrier						
Container carrier						
Both ships						

All measurements are conducted at the steady state condition. After sailing the distance of 2 to 5 ship lengths (depending on the speed and distance to the bank) along one bank geometry a steady state condition is approximately obtained.

The tests carried out in the towing tank are captive motion model tests. During a test run the model is free to heave and pitch, and rigidly connected to the motion mechanism according to the other degrees of freedom. The registered motions, moments and forces are:

Hull:

- ↪ Sinkage z [m]
- ↪ Trim θ [m/m]
- ↪ Longitudinal force X [N]
- ↪ Sway force Y [N]
- ↪ Yaw moment N [Nm]
- ↪ Roll moment K [Nm]

Propeller:

- ↪ Propeller thrust T_p [N]
- ↪ Propeller torque Q_p [Nm]

Rudder:

- ↪ Rudder normal force F_{Nr} [N]
- ↪ Rudder tangential force F_{Tr} [N]
- ↪ Rudder angle δ [deg]

Furthermore three wave gauges were installed to register the wave pattern between the ship model and the bank at different lateral but at the same longitudinal position.

More information on this test program, including a selection of video recordings, is available at www.bankeffects.ugent.be.

III. MATHEMATICAL MODEL

Based upon the model tests carried out in the towing tank a mathematical model has been formulated for the sway force, the yaw moment, the longitudinal force and the sinkage induced by the vicinity of irregular bank geometries.

Mathematical models for sloped and semi-submerged banks have been developed in the past by Norrbin [1] and others (e.g. [2]). Norrbin [1] proposed a parameter y_B in the models for the sway force and yaw moment to determine the distance between a ship and (sloped) bank. This parameter is based of the distances between the ship and discrete points of the sloped bank. A disadvantage of this method is the high sensitivity of the parameter at these discrete positions and the absent sensitivity at other positions.

To overcome these disadvantages a new distance to bank parameter d_{2b} and an equivalent blockage parameter m_{eq} are proposed taking into account the entire geometry of the bank. This d_{2b} and m_{eq} are defined in such a way that all realistic bank geometries and water depths are covered.

Horizontal reach

A bank will only affect the pressure distribution on a ship if the distance between ship and bank is sufficiently small. As a result, for a particular ship in a particular condition a value for the ship-bank distance can be defined as the boundary between open and confined water. This distance is called the horizontal reach. If the ship-bank distance exceeds this value, no (significant) influence of the bank on the forces and moments on the ship will be observed. The horizontal reach has been investigated by Barrass [3] and Römisch [4]. Both proposed an expression based on a main parameter of the ship (ship length [4] or block coefficient [3]) and independent of the ship's speed.

A systematic series of tests is carried out to define a (speed dependent) expression of the horizontal reach. Therefore a (small) ship model of a tanker (Table 2) is towed in an 'empty' towing tank at different speeds, water depths and lateral positions. The width of the towing tank is about 24 times this ship's beam.

Tests are conducted at different distances between the closest wall of the towing tank and the ship's centreline, for each run varying systematically between 3.5, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 11 and 11.9 times the ship's

beam. Speed values of 5.7, 8.4, 12.7 and 16.9 knots at full scale are chosen.

For each combination of speed and UKC, the measured variables can be plotted as a function of the distance between the ship's centreline and the closest wall; an example is given in Figure 4.

In this specific case at distances between the ship and bank of more than eight times the ship's beam there is almost no yaw moment induced by the bank (the wall of the towing tank in this case). At distances smaller than or equal to 6 times the ship's beam there is a more than linear relation between the yaw moment and distance to the bank. Three ranges can be determined:

- If the distance to the bank is sufficiently large, the influence of the closest bank on the ship is negligible (\blacktriangle);
- Close to the bank, a significant influence is generated (\blacksquare);
- In between, the influence is measurable but not significant (\blacklozenge).

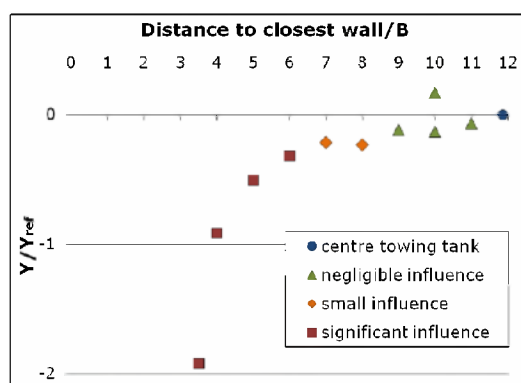


Figure 4 Yaw moment vs distance from centreline to closest wall for UKC 35% and 16.9 knots

Such a division in three ranges is carried out for all UKC – speed combinations. The results are summarised in one graph, see Figure 5, as a function of the non-dimensional distance between the closest bank and the ship's side relative to the ship's beam, and the water depth related Froude number.

$$Fr_h = \frac{V}{\sqrt{gh}} \quad (1)$$

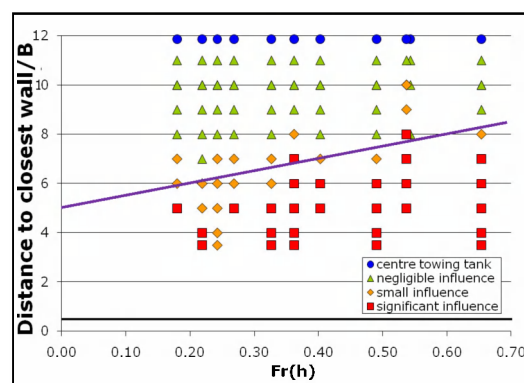


Figure 5 Horizontal reach vs $Fr(h)$ with all three “influence regions”

The dividing line between combinations with significant influence and without significant influence shows dependency on the Froude depth number Fr_h .

$$y_{infl} = B(5Fr_h + 5) \quad (2)$$

Equation (2) can be considered as the (half) width of the influence zone for bank effects. As a result, a ship sailing at a distance larger than the horizontal reach y_{infl} from the closest bank does not encounter significant bank effects.

Water depth

Analogous to the horizontal reach a water depth exists where no significant difference on the manoeuvrability of the ship between unrestricted and restricted water depth is found. PIANC [5] takes $h = 3I'$ or UKC = 200% as the separation between deep and restricted waters. New tests on this boundary have not been carried out due to the restricted water depth of the towing tank of FHR.

No unambiguous definition of the water depth can be formulated when a ship sails above an irregular bathymetry but a clear definition of the water depth is important to calculate parameters such as Fr_h .

The average water depth at midship from port to starboard side is chosen as water depth h of a ship sailing above an irregular bottom (Figure 6).

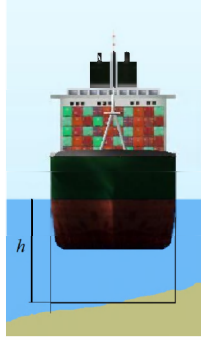


Figure 6 “average” water depth h under ship

The effective water depth h_{eff} takes into account the decrease of water level caused by squat. Therefore the water depth h is decreased by the maximal sinkage (fore or aft).

$$h_{eff} = h - z_{max} \quad (3)$$

So, an effective under keel clearance UKC_{eff} can be defined:

$$UKC_{eff} = \frac{T}{h_{eff} - T} \quad (4)$$

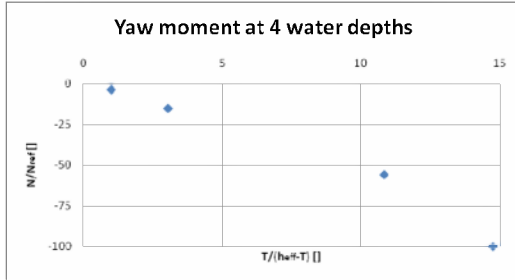


Figure 7 Yaw moment at four different water depths for the container carrier ($T=14.5m$) sailing at 8 knots with the ship's side at the start of sloped (1/5) Bank II.

In Figure 7 the yaw moment at four different water depths is shown. The container carrier is sailing at 8 knots with her ship's side above the start of the slope in all four conditions. The drastic influence of the water depth on the induced yaw moment is not only caused by the restriction of the flow under the vessel but also because of the different blockage at the sloped bank. In this case the yaw moment at 100% UKC is more than 25 times smaller than the yaw moment at 10% UKC.

Weight factor and weight distribution

The weight factor is a value between 0 and 1 which indicates the influence of a water particle on the manoeuvrability of a ship.

A water particle close to the hull will have a value close to 1. The weight factor will tend to zero once the water particle is out of the horizontal reach. The deeper the water particle the smaller the weight factor of that water particle gets.

At the centre line of the ship and on the free surface the weight factor should be 1. Because of the absence of water the section taken by the ship has weight factor 0.

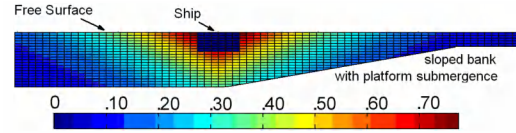


Figure 8 A graphical representation of the weight distribution

The weight distribution is defined as a decreasing exponential function, analogous to Norrbin's factor [1]. The expression of the weight distribution in the ship bound coordinate system is:

$$e^{-a|y|-b|z|} \quad (5)$$

The coefficient a is dependent on the horizontal reach:

$$a = \frac{3}{y_{infl}} \quad (6)$$

The coefficient b is dependent on the draft of the ship.

$$b = \frac{1}{3T} \quad (7)$$

A water particle at position (y,z) will have a weight factor equal to:

$$e^{-\left(\frac{3|y|}{y_{infl}} + \frac{|z|}{3T}\right)} \quad (8)$$

The ‘weight’ χ of a rectangle with coordinates $(y_1,z_1)(y_2,z_1)(y_2,z_2)(y_1,z_2)$ is defined as:

$$\begin{aligned} \chi_{rect} &= \int_{z_1}^{z_2} \int_{y_1}^{y_2} e^{-(ay+bz)} dy dz \quad (9) \\ &= \frac{1}{ab} (e^{-ay_1} - e^{-ay_2}) (e^{-bz_1} - e^{-bz_2}) \end{aligned}$$

The ‘weight’ of the water displaced by a ship χ_{ship} with beam B and draft T is:

$$\chi_{ship} = 2 \int_0^T \int_0^{b/2} e^{-(ay+bz)} dy dz \quad (10)$$

$$= \frac{2}{ab} \left(1 - e^{-ab/2}\right) \left(1 - e^{-bT}\right)$$

The ‘weight’ has a non-infinite solution at infinite. The weight of an infinite deep and infinite wide ocean is:

$$\chi_{ocean} = 2 \int_0^\infty \int_0^\infty e^{-(ay+bz)} dy dz \quad (11)$$

$$\chi_{ocean} = \frac{2}{ab} = 2 \cdot y_{inl} T$$

Equivalent blockage m_{eq} .

The blockage indicates the amount of space a ship takes in the cross section of a fairway. Conventionally, the blockage is defined as the ratio between the cross sectional areas of the ship and the fairway. This is the ratio between the underwater part of the ship and blue surface in Figure 9. In open water the blockage becomes zero. The blockage of a panamax in the Panama lock can reach 0.93.

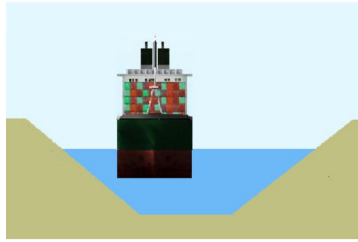
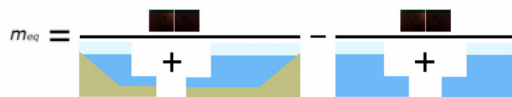


Figure 9 A ship sailing in a waterway with a high blockage

This definition is independent of the distance to the bank. The blockage becomes zero when sailing along only one bank, no matter how close. A ship sailing in a rectangular cross section will have the same blockage sailing in a section with width X and depth Y as in a section with width Y and depth X.

To overcome these insensitivities an equivalent blockage m_{eq} is proposed. This equivalent blockage is analogous to the ‘classic’ blockage but it takes into account the weight distribution. The equivalent blockage is defined as:

$$m_{eq} = \frac{\chi_{ship}}{\chi_p + \chi_s} - \frac{\chi_{ship}}{\chi_{ocean} - \chi_{ship}} \quad (12)$$



This equivalent blockage takes account of the position and speed of the ship. The m_{eq} of a

canal with width X and depth Y will be different from m_{eq} of a canal with width Y and depth X. A change in the configuration of a fairway close to the ship will have a higher impact on m_{eq} than the same change in the bathymetry further away.

Finally this new blockage will be non-zero when sailing along a single bank and zero when sailing in open and deep water.

Distance to bank $d2b$

The distance between a ship and bank is only unambiguously defined when sailing along a vertical bank at one side, while the navigation area is unlimited at the other side. A clear definition of the distance between the ship and an irregular bank geometry is not this straightforward. In the past the distance between ship and bank at half the draft or at other (averages of) discrete positions were chosen. The disadvantage of this method is the high sensitivity of the distance to bank on these points. On the other hand, the influence of important properties of the bank geometry might be excluded in the distance to the bank.

Figure 10 shows the relation between the distance between the centre of the ship and the bank at half the draft ($y_{T/2} - y_{ship}$) and the sway force. This is done for all banks for the container carrier at 10 knots, UKC 100% without propeller rate.

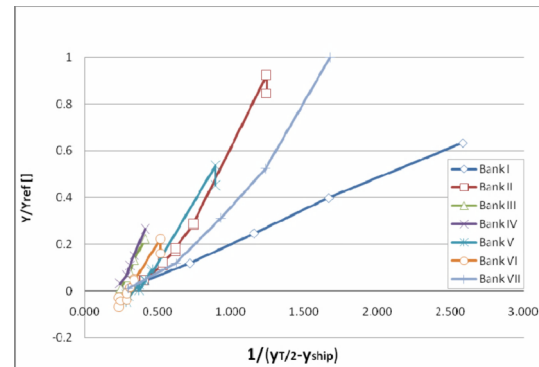
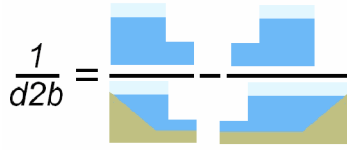


Figure 10 Relationship between the lateral distance between container ship's centre and bank at T/2 and the sway force

The distance between the ship and bank at half the draft does not seem to cope with the finesses of the bank geometry.

The parameter proposed in this paper is more robust and sensitive to the entire bathymetry. This parameter is called $d2b$ (distance to bank) and defined as:

$$\frac{1}{d2b} = \frac{1}{2} (\chi_{ocean} - \chi_{ship}) \left(\frac{1}{\chi_p} - \frac{1}{\chi_s} \right) \quad (13)$$



This expression takes into account all the details of the entire bathymetry without being oversensitive. $\frac{1}{d2b}$ will be zero when sailing at the centerline of a symmetric canal. $\frac{1}{d2b}$ is

very sensitive for changes in the bank geometry close to the ship and is almost insensitive for changes further away.

Furthermore the mathematical model will be simplified because only one parameter ($1/d2b$) will cope with all the complexities of all types of irregular bank geometries. An example is given.

The parameter $1/d2b$ will be smaller for a ship sailing at a certain distance from the toe of a bank with slope 1/8 (Bank V) than sailing at the same distance from a bank with a steeper slope (e.g. 1/5 Bank II).

The influence of a submerged platform is also taken into account in the parameter $1/d2b$. Sailing along a surface piercing bank will always induce a higher $1/d2b$ than sailing (in the same conditions) along a bank with the same slope but with a submerged platform as in Figure 3. The width of this submerged platform y_{sub} is also taken into account. Making a very wide submerged platform more wide will almost have no influence on $1/d2b$ but widening a small submerged platform will have a significant influence on $1/d2b$ as long as these submerged platforms are within the horizontal reach.

The sway force induced by the vicinity of all banks for the tests shown in Figure 10 are plotted in Figure 11 as a function of $1/d2b$. Figure 11 shows a satisfying linear relation between the parameter $1/d2b$ and the sway force induced by a wide variety of bank types. Vertical wall, steep sloped bank (1/3), gentle sloped banks (1/8), surface piercing and semi-submerged types of banks are included.

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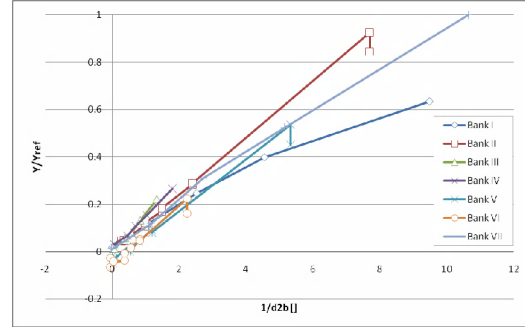


Figure 11 Sway force vs $1/d2b$ for the container carrier ($T=14.5m$) sailing at 10kts with 100% UKC

Propeller action and forward speed

A propeller action ahead increases the flow velocity around the ship's stern. As a result the bow-away yawing moment will be increased. The sway force due to propulsion ahead will always be directed towards the closest bank, which usually implies an amplification of the sway force and yaw moment induced by the vicinity of banks. In some cases a propeller action in very shallow water ($UKC < 35\%$) changes an attraction sway force to the closest bank into a repulsion away from the closest bank.

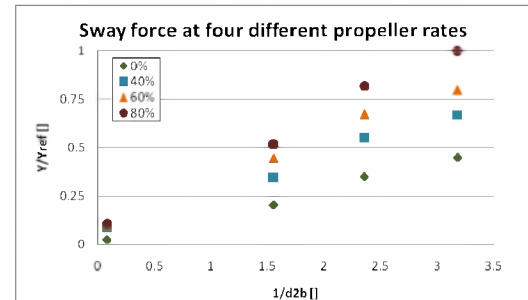


Figure 12 Sway force at four different propeller rates (% of sea full) for the container carrier ($T=12.0m$) UKC 35%, 12 knots along bank III

An example of the influence of the propeller rate on the sway force is shown in Figure 12. The propeller rate is expressed as a percentage of the propeller rate at sea full (100rpm full scale). In this example the sway force induced without propeller rate is half the sway force induced with a propeller rate 80% of sea full.

To take into account the effect of the propulsion in the mathematical model the speed V_T is introduced based upon the propeller thrust and propeller diameter.

$$V_T = \text{sign}(T_p) \sqrt{\frac{8T_p}{\rho\pi D^2}} \quad (14)$$

This speed represents in a simplified way the axial speed in the flow field behind the propeller induced by the propeller. The flow around a hull will increase due to the forward propeller action. A fraction of the speed V_T is added to the forward speed of the vessel to take into account these propeller effects.

$$V_{eff} = V + \zeta V_T \quad (15)$$

The speed is made non-dimensional by the Froude number using the length between perpendiculars.

$$Fr_{eff} = \frac{V_{eff}}{\sqrt{g \cdot L_{pp}}} \quad (16)$$

Sinkage

The sinkage fore z_f and sinkage aft z_a are calculated separately. This method is preferred over a model for mean sinkage and trim. The proposed model calculates the total sinkage and not the sinkage induced by the vicinity of banks only.

The total sinkage depends on the forward speed of the ship, the propeller rate and the entire bathymetry. The latter is taken into account in formula (17) by the equivalent blockage m_{eq} , while the forward speed of the ship and the propeller action are reflected in the effective Fr_{eff} .

$$z = T Fr_{eff}^2 (m_{eq} (\zeta_{z1} Fr_{eff}^2 + \zeta_{z2}) + \zeta_{z3} Fr_{eff}^2 + \zeta_{z4}) \quad (17)$$

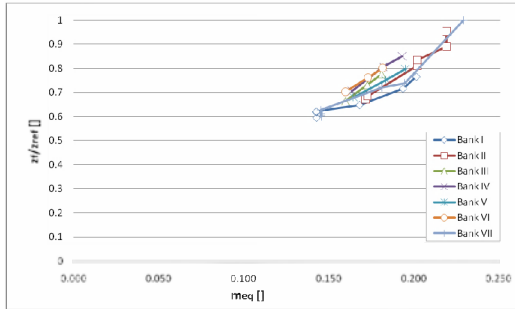


Figure 13 Sinkage fore in function of m_{eq} for LNG-carrier at 10 knots, UKC 35% , no propeller rate, along all tested banks at all tested distances

The sinkage fore is shown in Figure 13 in function of the equivalent blockage. In this figure the sinkage is shown of the LNG carrier at 10 knots, UKC 35% without propeller rate and along all tested banks at all tested distances. Remark that the conventional blockage is not because it changes at different distances to the bank.

Longitudinal force

A ship sailing in a restricted waterway will experience a higher resistance than sailing in open water. The mathematical model for the longitudinal force takes into account this increase of the resistance and the influence of the hull, propeller, water depth and entire bank geometry. The bank effects and shallow water effects are taken into account by the equivalent blockage m_{eq} . As a consequence the influence of the banks and water depth are not calculated independently.

$$X_{total} = \frac{1}{2} \rho V^2 L T (\zeta_{X1} + \zeta_{X2} Fr^2 m_{eq}^2) + (1 - \zeta_{X3}) T P \quad (18)$$

Only three (ship dependent) coefficients are used in formula 18.

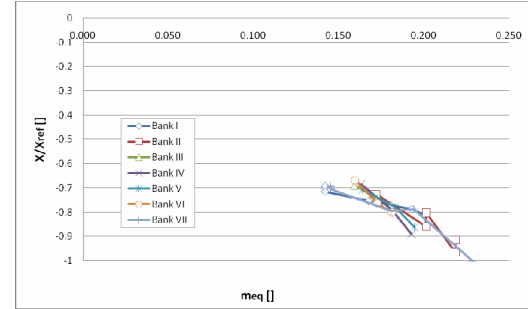


Figure 14 Longitudinal force in function of m_{eq} for LNG-carrier at 10 knots, UKC 35% , no propeller rate, along all tested banks at all tested distances

In Figure 14 the longitudinal force at the same test conditions as Figure 13 is shown in function of m_{eq} . Again the conventional blockage is constant for all tests along the same bank. The equivalent blockage takes into account the influence of the distance to a bank and the geometry of a bank on the longitudinal force.

Sway force

The flow along a ship's hull disturbed by the vicinity of a bank will induce forces on her. When a ship sails within the horizontal reach of a bank, she will be attracted to the closest bank when the under keel clearance exceeds a minimum value. When sailing in very shallow water she will be pushed away from the closest bank.

$$Y_{bank} = \frac{1}{2} \rho V_{eff}^2 L T \frac{1}{d2b} \left((\zeta_{Y1} Fr_{eff} + \zeta_{Y2}) \frac{T}{h_{eff} - T} + (\zeta_{Y3} Fr_{eff} + \zeta_{Y4}) \right) \quad (19)$$

The transition from attraction to repulsion of the sway force (without propeller rate) is in the UKC_{eff} range of 15% to 20%. An active propeller decreases this limit so the ship is attracted to the closest bank up to smaller UKC_{eff} .

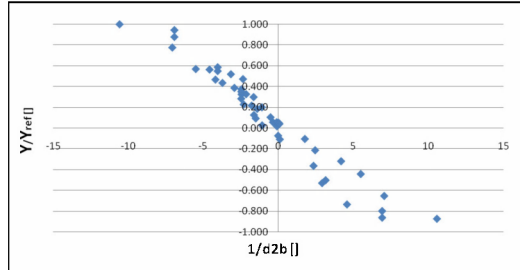


Figure 15 Sway force of container carrier (T=14.5m) with 40% propeller rate at 10 knots, UKC 35% along all banks at all tested distances as a function of $1/d2b$

The sway force in Figure 15 is plotted in function of $1/d2b$. The tests are conducted at 10 knots with the container carrier (14.5m) along all banks and at all distances. The water depth on the flat bottom of the towing tank is 1.35 times the draft of the container carrier at rest. The effective under keel clearance will be different for these tests.

The measurements are fairly predicted for the container carrier using formula (19) but this formula should be improved for the LNG-carrier.

Yaw moment

The proximity of banks does not only cause a sway force but also a yaw moment on the ship. This yaw moment is always directed so the ship's bow is pushed away from the closest bank, even at very shallow water conditions.

$$N_{bank} = \frac{1}{2} \rho V_{eff}^2 L^2 T \frac{1}{d2b} \frac{T}{h_{eff} - T} (\xi_{N1} + \xi_{N2} Fr_{effN} + \xi_{N3} Fr_{effN}^2) \quad (20)$$

In formula (20) it can be seen that a higher than quadratic speed dependency was necessary to obtain satisfying results. The formula shows good consistency at lower $1/d2b$ values but more variation at higher $1/d2b$. Overall the formula is satisfying taken into account its simplicity and lucidity.

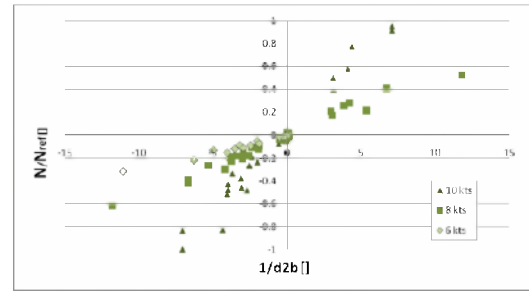


Figure 16 Yaw moment of container carrier along all banks and bank distances, UKC 10%, 60% propeller rate, at three speeds.

The yaw moment at three speeds is shown in Figure 16 as a function of $1/d2b$. As in formula 20 the yaw moment is linear to $1/d2b$ and increases with increasing speed. Remark that Figure 16 is at only one UKC but at different UKC_{eff} .

IV. VALIDITY OF THE MATHEMATICAL MODEL

The formulae proposed in this paper are valid for a wide range of bank geometries and speeds but some attention have to be made at specific conditions.

Restriction on equivalent blockage and $d2b$

A ship can (unfortunately) run aground and run into a bank. The mathematical model presented in this paper is not valid for such extreme conditions. It also does not cope with very high blockages as in a narrow lock or extremely close to a quay wall. The minimal tested ratio between the 'weight' at port χ_p or starboard side χ_s and half of the weight of the ship

$$\frac{\chi_{ship}}{2} \text{ is } 0.90.$$

$$\left[\begin{array}{c} \chi_{p/s} \\ 0.5 \cdot \chi_{ship} \end{array} \right]_{\min} = 0.90 \quad (21)$$

This limiting ratio is for example the case for a test with the container carrier (T=12.0m) sailing with an UKC 10% with the ship's side at the toe of the sloped bank VII (slope=1/3). As seen in Figure 17 this is very close to a bank.



Figure 17 Drawing (in proportion) of the highest tested blockage

To limit the validity of this model it is only valid if χ_p and χ_s are smaller than $0.45 \cdot \chi_{ship}$.

Quadrant I

The model presented in this paper is based upon model tests with forward speed and non-negative propeller rates. The formulae are therefore only tested and validated for ships with forward speed and a non-negative propeller rate (=quadrant I).

Critical speed

The model was not satisfying for the container carrier (T=12.0m) at 14 knots and UKC 35%. The tendency was even wrong. Figure 18 shows the measured and calculated forward sinkage along installed bank IV. Similar results were obtained for the longitudinal force for ships sailing along the less steep banks than 1/3. The mathematical model for the steep banks (I and VII) are satisfactory modeled.

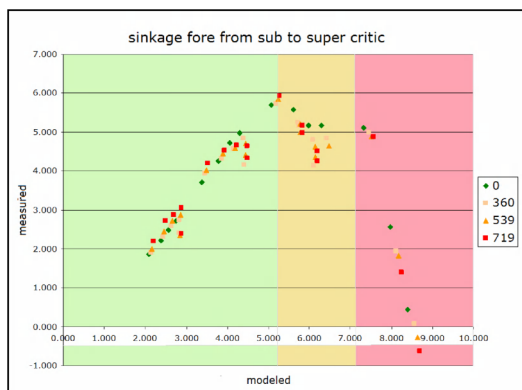


Figure 18 Measured vs calculated sinkage fore. Three regions can be distinguished.

Three regions can be distinguished in Figure 18: a subcritical (green), a supercritical (red) and a transient speed region (yellow).

When all tests are plotted on a graph with abscissa representing the ratio between speed and critical speed and ordinate the sinkage, Figure 19 is obtained. In this figure all tests with a satisfying mathematical model are plotted green. The non-satisfying tests red and the satisfying tests with bank I and VII, as mentioned before, blue. The critical speed is calculated as Schijf [6].

$$Fr_{crit} = \left(2 \sin \left(\frac{\arcsin(1-m)}{3} \right) \right)^2 \quad (22)$$

In formula (22) the (classic) blockage m is used. This is the ratio between the area of the cross section of the waterway and the multiplication of the ship's beam and draft. The so called 'weight factor' is not used.

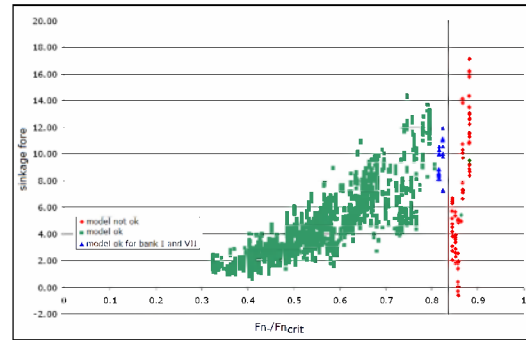


Figure 19 Sinkage fore vs ratio to critical speed. Satisfying modeled sinkages are plotted green, unsatisfying red

The most plausible explanation for the non-satisfying tests is the relatively high speed referred to the critical speed. In a wide speed range the sinkage fore and trim increase with increasing speed. At a certain speed the trim is increased so dramatically resulting in the bow to reposition in its original position. At this moment a significant mean sinkage is observed. It is expected that these trim and sinkage values are caused by the increased height and significantly longer extension of the bow wave, when the ship's speed is close to the critical speed resulting in a decrease in the sinkage fore.

A mathematical model coping with supercritical speeds is out of the original scope of this research. There is a relation between the behavior of the vessel and the ratio forward speed – critical speed. The proposed mathematical model is only valid when sailing slower than 84% of the critical speed.

$$Fr_h < 0.84 Fr_{crit} \quad (23)$$

Future plans

Tests with different ship types and bank configuration have been executed in the past (before 2006) at Flanders Hydraulics Research and other institutes. In the near future the mathematical model proposed in this paper will be improved by using these model tests and by using different computation methods.

For each tested ship model at a specific draft a set of coefficients is calculated. In the future formulae will be searched based upon the main properties of the vessels.

Because the model is not valid in locks or other extremely confined situations, the implementation of the model in a ship manoeuvring simulator is not straightforward. For this and other reasons the model should be extended as to cover these extremely high blockages.

V. CONCLUSIONS

An extensive model test program is being carried out and a model to predict the forces, moments and motions on a ship induced by the vicinity of a bank proposed. A mathematical model taking into account forward speed, propulsion, the entire bank and bottom geometry (=bathymetry) results from these model tests.

To calculate the increase in resistance and sinkage use is being made of a new defined blockage m_{eq} . This blockage is based upon a so-called ‘weight distribution’. This ‘weight distribution’ indicates the degree of influence of a water particle on the bank effects. The weight distribution varies from one to zero.

One of the advantages of this new blockage over the classic blockage is a non-zero blockage for a ship sailing in deep water along one bank and open water at the other side.

Analogous to the equivalent blockage m_{eq} , a new parameter called $d2b$ to indicate the distance between ship and bank in the mathematical models for the sway force and yawing moment has been proposed. The definition of $d2b$ is also based upon the ‘weight distribution’. Contrary to previous proposals on the distance between a ship and an irregular bank geometry, $d2b$ takes into account the entire bathymetry and not only distances to discrete points.

As a result of the m_{eq} and $d2b$ a robust and reliable mathematical model for the sway force, yaw moment, longitudinal force and sinkage is proposed.

VI. LIST OF SYMBOLS

a	[]	coefficient of the lateral position in the ‘weight factor’
b	[]	coefficient of the horizontal position in the ‘weight factor’
B	[m]	beam of the ship
C_B	[]	block coefficient
D	[m]	propeller diameter
$d2b$	[]	dimensionless distance to bank
Fn	[]	Froude number (length between perpendiculars)
Fn_h	[]	Froude number (water depth)
Fn_{VT}	[]	Froude number (speed in propeller wake)
Fn_{crit}	[]	critical speed
g	[m/s ²]	gravity
h	[m]	water depth
h_0	[m]	height of the sloped part
h_1	[m]	water depth on submerged platform
h_{eff}	[m]	water depth taking into account squat
L_{OA}	[m]	length over all
L_{PP}	[m]	length between perpendiculars
K	[Nm]	roll moment
m	[]	blockage
m_{eq}	[]	equivalent blockage
N	[Nm]	yaw moment
n	[rpm]	propeller rate
T_A	[m]	draft aft
T_F	[m]	draft fore
TEU	[]	twenty feet equivalent unit
T_P	[m]	thrust of the propeller
UKC_{eff}	[]	effective under keel clearance
V_T	[m/s]	speed in propeller wake
X	[N]	longitudinal force
Y	[Nm]	sway force
y_α	[m]	distance to start of the sloped bank
y_{ship}	[m]	distance to centre line of the ship
y_{infl}	[m]	horizontal reach
y_{sub}	[m]	width of the submerged part of the bank
z_a	[m]	sinkage aft
z_f	[m]	sinkage fore
α	[°]	slope of the bank
χ_{ocean}	[]	“weight” of an infinite wide and deep water way
χ_{ship}	[]	“weight” of the ship
χ_p	[]	“weight” of the fairway at port
χ_s	[]	“weight” of the fairway at starboard
χ_{rect}	[]	“weight” of a rectangle
δ	[°]	rudder angle
ρ	[kg/m ³]	density
θ	[°]	trim
ξ^n	[]	coefficient of the mathematical model

VII. ACKNOWLEDGEMENT

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APPENDIX A

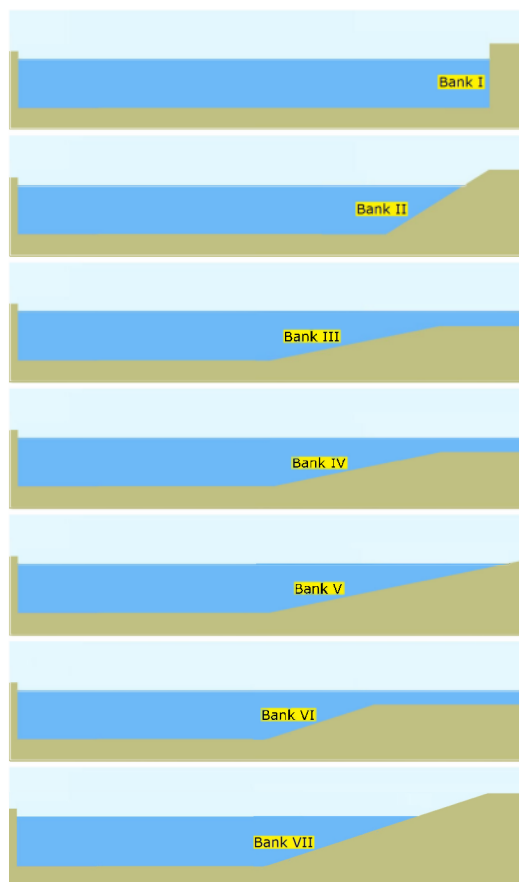


Figure 20 A non proportional overview of the tested bank geometries