HYDRODYNAMIC INFLUENCE OF DIFFERENT SLOPED BANKS ON AN INLAND VESSEL

L'influence hydrodynamique d'une rive inclinée sur les bateaux fluviaux

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ABSTRACT

Inland vessels typically spend most of their operation time in shallow and restricted waterways. For investigating the specific effects of such circumstances on ship hydrodynamics, ship model tests are carried out in the fully automated Towing Tank for Manoeuvres in Shallow Water (cooperation Flanders Hydraulics Research – Ghent University). In 2010, systematic captive model test series were carried out with a 1/25 scale model of a CEMT class Va inland vessel to provide the full bridge inland simulator Lara at Flanders Hydraulics Research with dedicated mathematical models for simulating the manoeuvring behaviour of this type of vessel. In particular, the effect of the presence of banks on ships navigating on a course parallel to these banks has been investigated. Based upon these model tests a mathematical model for the bank induced forces and moments has been developed. The influence on these bank effects is investigated and a mathematical model is implemented in the real time simulators at Flanders Hydraulics Research. The importance of bank effects on inland navigation is illustrated by means of a specific simulation project on the rivers Deûle and Lys in Northern France.The simulations mainly focused on the meeting of two inland vessels and the (hydrodynamic) consequences of the interactions (both ship – ship and ship – bank interactions). A comparison is made between alternative canal cross-sections which also meet the French internal waterways Circular, which led to the conclusion that solutions with a larger water depth are preferable with respect to the magnitude of bank effects.

KEY WORDS

Bank effects, shallow water hydrodynamics, towing tank, full mission bridge simulators

MOTS-CLEFS

Effets des rives, hydrodynamiques de l'eau peu profonde, bassin de carènes, simulateurs de navigation

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1. INTRODUCTION

Inland vessels sail on a wide range of navigation areas, varying from relatively wide and deep waters (e.g. in maritime ports) to waterways with reduced depth and restricted width. In order to stimulate the use of inland navigation, important efforts are made nowadays to adapt the dimensions of existing inland waterways to accommodate larger ships. As it is often not or hardly feasible to increase the width of existing natural or artificial waterways, reduced distances between ships and the boundaries of the waterways will by unavoidable. This will have an effect on the controllability of the ships which make use of these navigation areas: when sailing close to a bank the hydrodynamics of a vessel will be influenced by the asymmetry of the flow on both sides of the ship due to presence of the bank. A combination of a longitudinal force (i.e. an increased resistance), a lateral force and yaw moment acting on the vessel will be the result, the combination of which is known as *bank effects*.

In the Towing Tank for Manoeuvres in Shallow Water (co-operation Flanders Hydraulics Research and Ghent University) comprehensive systematic test series with ship models in parallel course to different types of bank have been carried out during the last decade to acquire more knowledge on ship-bank interaction. The present publication will focus on a comparison of the bank effects acting on a model of an inland barge navigating along banks with different slopes.

The results of the model test program were used to develop a novel mathematical model for the bank effects. This mathematical model was implemented in the ship manoeuvring simulators at Flanders Hydraulics Research (FHR). One of the simulators, “Lara”, is dedicated to studies for inland navigation, and is frequently used for assessing planned modifications to existing inland waterways. A typical example is the Seine – Scheldt connection in France, which needs an upgrade to make the existing canals between the Seine and the waterway network in North-Western Europe accessible for CEMT class Va vessels. One particular study project performed at the FHR simulators which will be used to illustrate the importance of both ship-bank and ship-ship interactions concerns the navigation of Va class vessels on the rivers Lys and Deûle in Northern France, which connect the French and the Belgian inland waterway networks. For determining the canal sections, the French Circular No. 76-38 relating to the characteristics of inland waterways was applied, which however leaves some room for variation. The bank effects induced by four different solutions for the geometry of the cross section according to the same circular are discussed.

2. MODEL TESTS

The model tests were performed in the fully automated towing tank for manoeuvres in shallow water at FHR. A technical overview of this facility can be found in (Van Kerkhove et al. 2009); its main dimensions are listed in Table 1.

Banks with varying characteristics are frequently built into the towing tank to investigate ship-bank interactions. The test results which will be used for the present paper are acquired in the frame of a project involving five different ship models moving at constant speed parallel to surface piercing banks with four different slopes (Figure 2). A limited selection of these model tests is made public as benchmark data in (Lataire et al. 2009). The total experimental program of 2009 contains more than 2 000 captive model tests, 570 of which were performed with the scale model of an inland vessel of CEMT (Conférence Européenne des Ministres de Transport) Class Va (Figure 1 and Table 2).

length over all	[m]	87.5
useful length	[m]	68.0
width	[m]	7.0
max. water depth	[m]	0.5

Table 1 Main dimensions of the towing tank at FHR

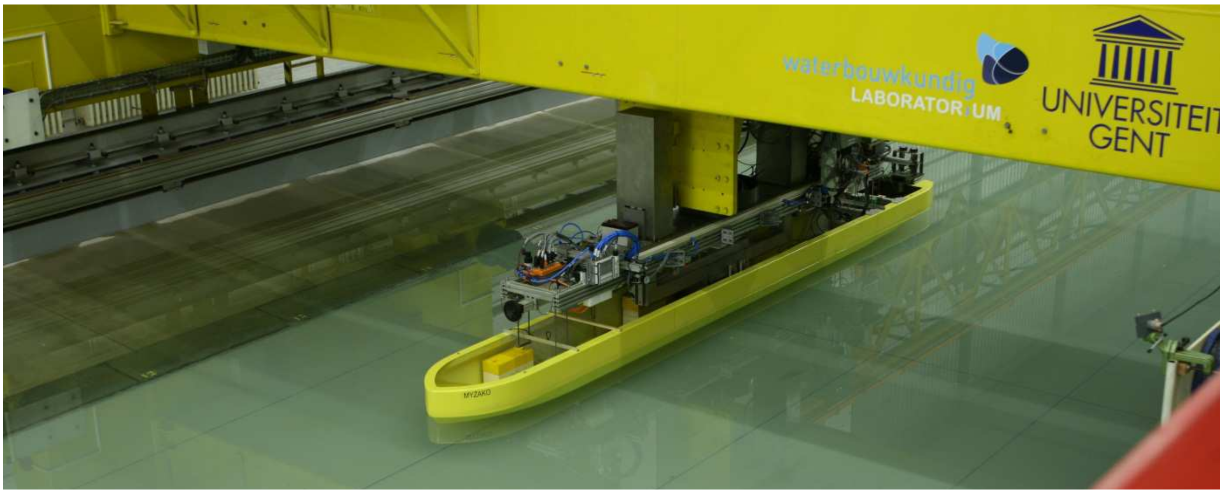

Figure 1 Ship model B01 towed along an installed sloped bank

			Inland Vessel B01	
scale factor	λ	[-]	1	25
Length between perpendiculars	L_{PP}	[m]	108.00	4.320
Length over all	L_{OA}	[m]	109.95	4.398
Breadth	B	[m]	11.45	0.458
Initial draft at the forward perpendicular	T_F	[m]	3.65	0.146
Initial draft at the aft perpendicular	T_A	[m]	3.65	0.146
Initial draft at the midship	T_M	[m]	3.65	0.146
Volume displacement	∇	[m³]	4096	0.262

Table 2 Main dimensions of the inland vessel

Different banks were installed in the towing tank to investigate the influence of the bank geometry on the forces and moments induced on the vessel, only tests in a steady state regime condition are considered. Therefore, the installed bank did not change in geometry for a significant amount of ship lengths (at least six ship lengths) before the ship model decelerates or another bank geometry starts. During these tests always two geometries are installed consecutively in the tank, the transition zone of one bank to another is constructed in such a way to create a smooth change in geometry, this is to avoid abrupt and long lasting transition effects.

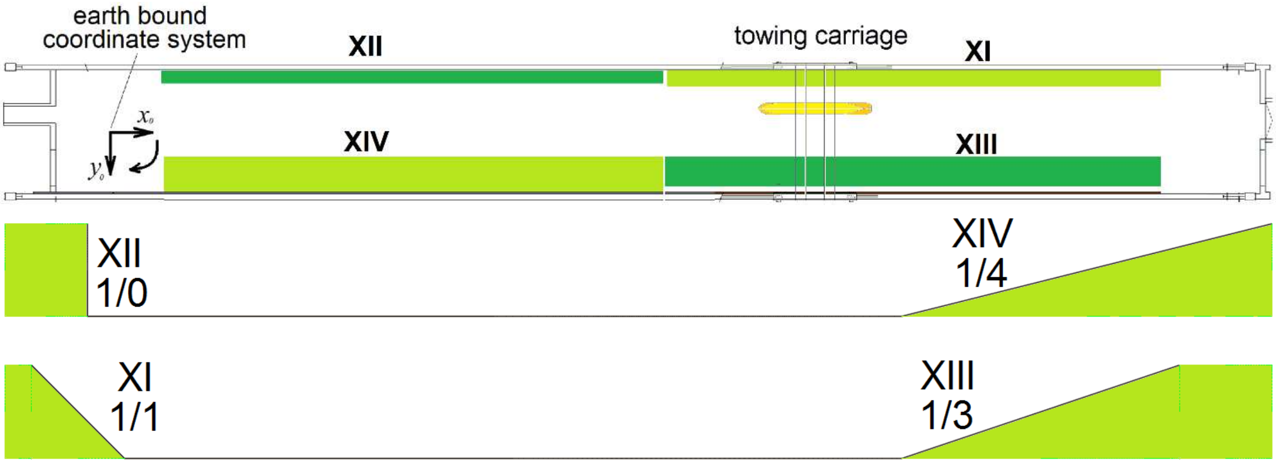

Figure 2 four different bank slopes as installed in the towing tank at FHR, plan view (top) and cross sections

All four installed banks have a constant slope from the bottom of the towing tank up to the highest water level tested. This slope is expressed as the ratio between the rise and run with a normalised rise (Figure 2 and Table 3).

Bank name	run/rise	W_h	Opposite bank run/rise
[-]	[-]	[m]	[-]
XI	1	4.200	3
XII	0	4.400	4
XIII	3	4.200	1
XIV	4	4.400	0

Table 3 Naming and dimensions of the sloped banks as tested at FHR

The tests are carried out at three different water depths: 120%, 135% and 300% of the draft (3.65m at full scale, Table 4). In this way, the range of water depths encountered by an inland vessel is more or less covered.

h/T [-]	h [m]
1.20	4.38
1.35	4.93
3.00	10.95

Table 4 Water depths of the test program scaled to full scale

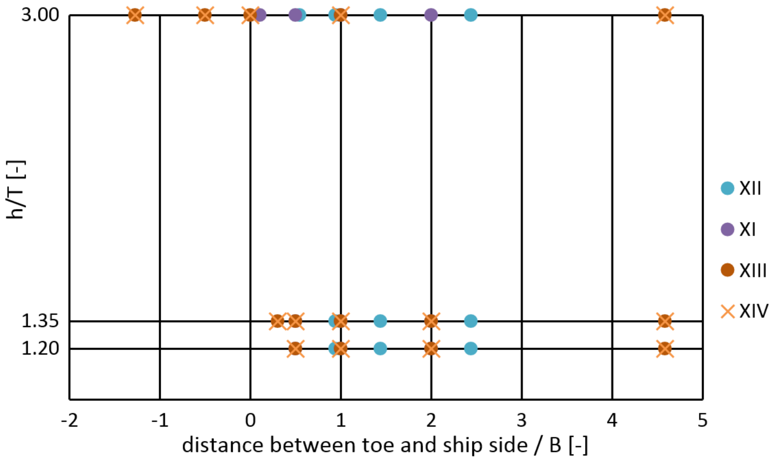

Figure 3 Lateral distance between toe of the sloped bank and ship side (made dimensionless with B) for the four tested banks at the three tested water depths

The lateral position of a ship model in a towing tank with banks installed can be defined in different ways. The most straightforward method is by referring to the earth bound coordinate system of the towing tank itself. In Figure 3 the distance between the ship side and the toe of the bank is plotted (made dimensionless by dividing by the ship's beam). In deep water (h/T=3.0) and with the more gentle sloped banks (XIII and XIV) tests were carried out with the ship sailing above the sloped bank (hence the negative values).

At all water depths the ship model was tested at forward speeds according to 6.5, 8.6, 10.8 and 13.0 km/h full scale. At the largest tested water depth, tests at 16.2 km/h were also added to the program. The ship model B01 was equipped with one propeller. During the test runs, two propeller rates were applied: zero propeller rate (n = 0 rpm) and a predefined value close to the self propulsion point for each speed (Figure 4).

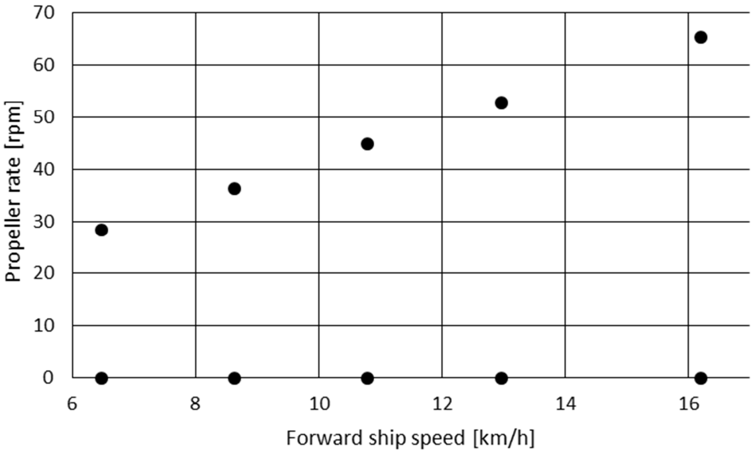

Figure 4 Propeller rate and forward speed combinations as tested

During captive manoeuvring tests, the ship model is imposed to follow a predetermined trajectory applied by the towing carriage. The ship model is free to heave and pitch but is rigidly connected to the planar motion mechanism according to the other degrees of freedom. The forces acting on the ship model, the rudder and the propeller are measured as well as the vertical positions of the hull (resulting in sinkage and trim), the propeller rate and the rudder angle. Other signals are sampled as well, e.g. wave gauges mounted at a fixed location in the tank.

3. SLOPE RATIO

The impact of the bank slope on the bank effects is illustrated by means of a selection of tests which are all carried out at a distance of half the ship's breadth between the ship's starboard side and toe of the bank (Figure 5). The bank slope clearly affects the remaining canal cross section between the ship's starboard side and the bank: the steeper the bank slope, the more constrained the considered fraction of the cross section. All tested water depths are considered, and all selected tests are carried out at 10.8 km/h (full scale) with a propeller rate near self-propulsion condition.

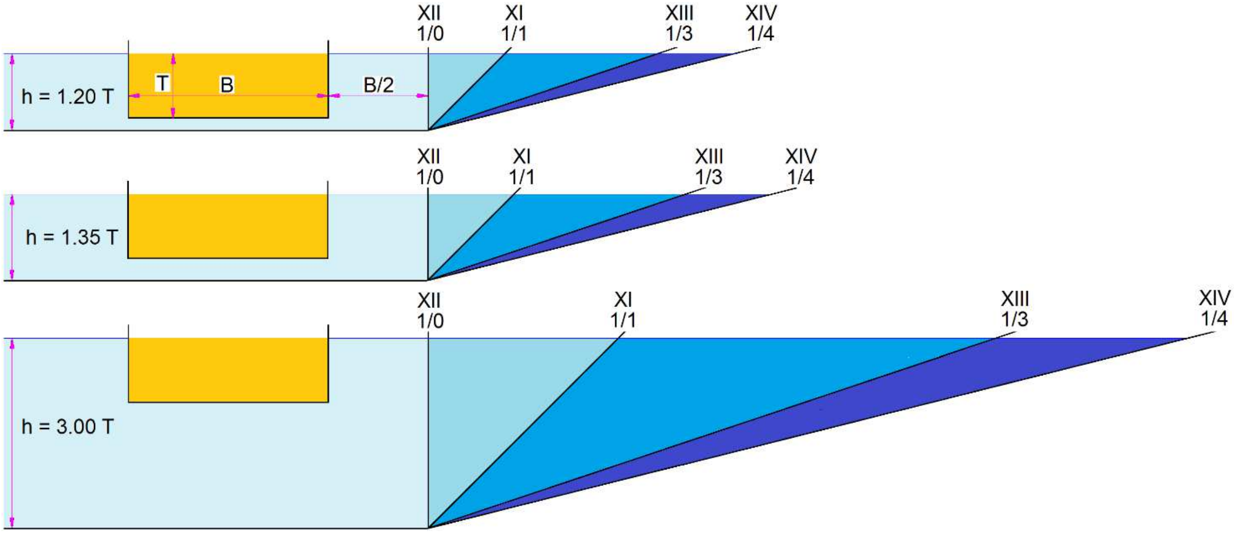

Figure 5 Cross section (on scale) of the selected tests with the same distance between toe of the slope and ship model at the three tested water depths

The bank induced forces in the horizontal plane can be decomposed in force components in the longitudinal (X_{BANK}) and lateral (Y_{BANK}) directions of the vessel and a yaw moment N_{BANK} around the vertical axis. The lateral force Y_{BANK} and yaw moment N_{BANK}, however, can also be decomposed in two lateral forces, a first one with point of application at the forward perpendicular Y_F and a second one applying at the aft perpendicular Y_A (Lataire 2014). In Figure 6 and Figure 7, the lateral forces Y_F and Y_A are plotted as functions of the run/rise ratio of the bank. The forces are normalized to the absolute value of the force measured along the vertical bank (run/rise = 0) at the lowest water level (h/T=1.20).

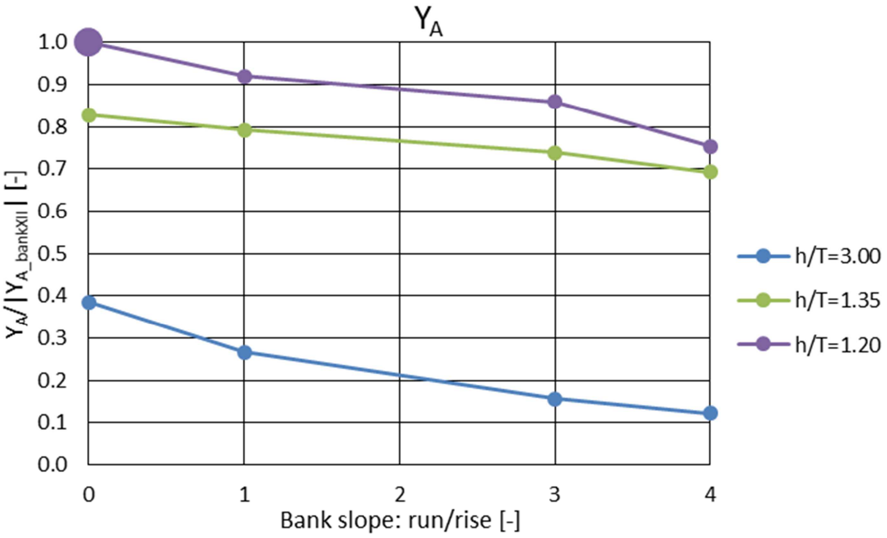

Figure 6 Non-dimensional force aft Y_A as a function of the run to rise ratio of the bank at a speed of 10.8 km/h, apropeller rate near self-propulsion (1122 rpm) and a distance between the ship's starboard side and the toe of the bank equal to half the ship's beam.

Based upon Figure 6 and Figure 7 several conclusions can be drawn. The lateral force at the aft perpendicular decreases when the slope of the bank decreases (less steep). This is ascribed to a lower return flow between ship and bank because the water has a larger area to spread this return flow and consequently a lower pressure drop will be the result. This pressure drop acts on the vessel as an attraction force Y_A directed towards the closest bank.

The lower the initial water level, the larger the magnitude of this attraction force. This is explained similarly; more space (water depth) results in a lower pressure drop along the hull.

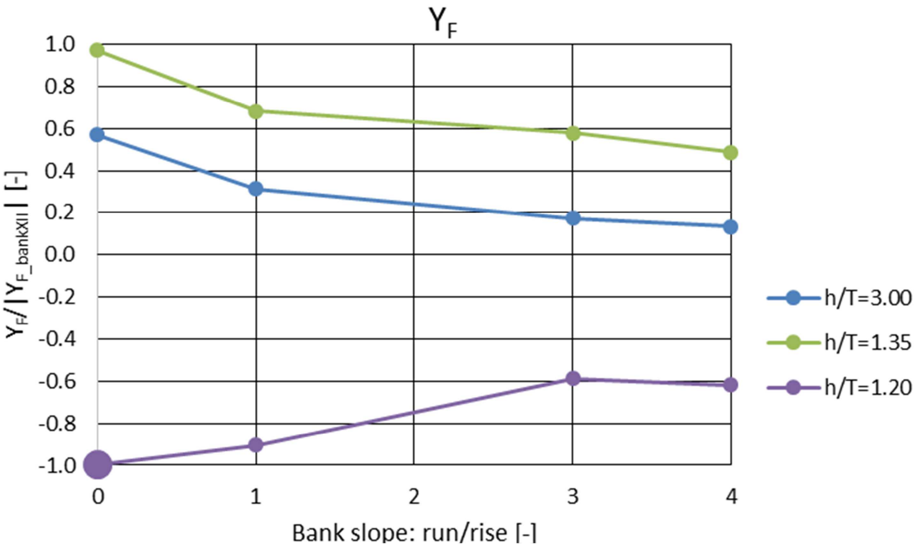

Figure 7 Y_F to a normalised run of the bank for one speed 10.8 km/h, one propeller action 1122 rpm and all distances to the toe of the bank equal (half the beam between closest ship side and toe)

In Figure 7 the lateral force with point of application at the forward perpendicular is plotted. When the vessel sails at a water depth of 300% and 135% of the draft, a positive attraction force is observed. If the vessel sails at even more shallow water (waterdepth of 120% of the initial draft), this attraction force becomes a repulsion force (away from the closest bank) with a magnitude similar to the tests at a water depth of 1.35 T (but with an opposite sign). In very shallow water a high pressure region at the forward part of the ship and between ship and bank results in this repulsion force while in deeper water this higher pressure is overruled by the velocity increase (and accompanying pressure drop) because of the return flow.

For all tests in Figure 6 and Figure 7 the magnitude of the force Y_A was larger than Y_F ($|Y_A|/|Y_F|>1$). Therefore, the overall lateral force Y_{BANK} will always be directed towards the closest bank (bank suction) and the yaw moment N_{BANK} will generate a bow-away moment. The bow-away moment in the most shallow water (h/T=1.20) will be significantly larger because the negative repulsion force at the forward perpendicular and positive attraction force at the aft perpendicular will both contribute to this bow-away moment.

4. REAL TIME SIMULATIONS

4.1 Research Project

The Deûle River is part of the CEMT class Va inland shipping network of Northern France. This network is, however, isolated from the Belgian, German and Dutch networks in the North and from the Seine River basin in the South because key links are only designed for CEMT class IV and smaller. The Deûle is one of these key links and is, together with the future canal Seine-Northern Europe, part of the Seine-Scheldt connection. This project is part of the Trans European Network – Transport development supported by the European Commission, within the subproject aiming to improve navigation conditions on the Seine-Scheldt connection.

For this study (2013-2015), which was performed by order of Voies Navigables de France, the Belgian consulting company IMDC (International Marine Dredging Consultants), the research institute Flanders Hydraulics Research and Ghent University joined their knowledge. IMDC brought its expertise in engineering projects, Flanders Hydraulics Research executed the real-time simulations on their two coupled simulators Lara and SIM225 and Ghent University provided expert feedback on the study.

4.2 Bank effects and ship-ship interaction model

As a typical example, the meeting of two vessels (both class Va, L_{OA}xBxT 110x11.45x3.00m^3) on the river Lys (water depth on this trajectory was 4.50m) is considered. This meeting was performed in a bend of the river, where the waterway at a depth of 3.00 m was about 40 m wide, while the total water depth had a value of 4.50 m. A bird’s eye view of the meeting situation is shown in Figure 8, both ships sail at a forward speed between 9 and 10 km/h (over the ground) during the meeting. At this location there is a current of 1.8 km/h, directed northerly.

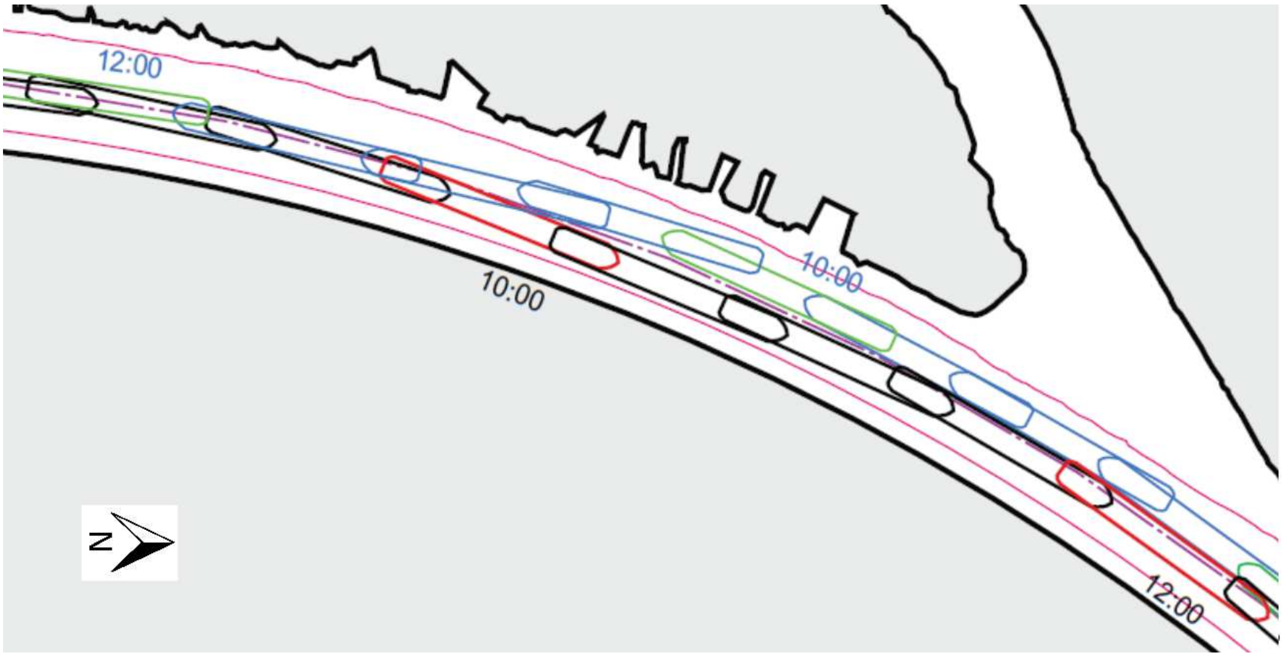

Figure 8 Bird's eye view of the meeting of two class Va vessels on a bend of the river Lys near Deûlémont.

During the meeting, both ships cannot remain at the centreline of the waterway, so that they are obliged to sail closer to one bank, resulting in the following hydrodynamic forces (Figure 9):

- An overall attraction force directed towards the closest bank;
- A bow-away moment pushing the bow of the vessel towards the centre of the waterway.

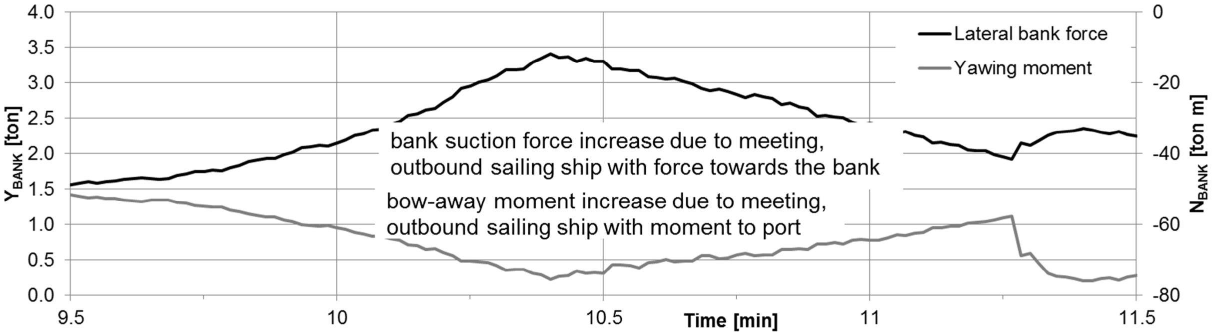

Figure 9 Modelled lateral attraction force (left axis) and bow-away moment (right axis) during the meeting in run 000 for the outbound class Va vessel on simulator Lara at FHR

The mathematical models for ship-ship interaction have been determined based on model tests with different ship types at different drafts, under keel clearances, meeting distances and operational parameters (ship's speed) in (Vantorre et al. 2002). This generic model is used for the prediction of the interaction forces and moment in the horizontal plane that have to be counteracted by using the rudder and engine (Figure 10).

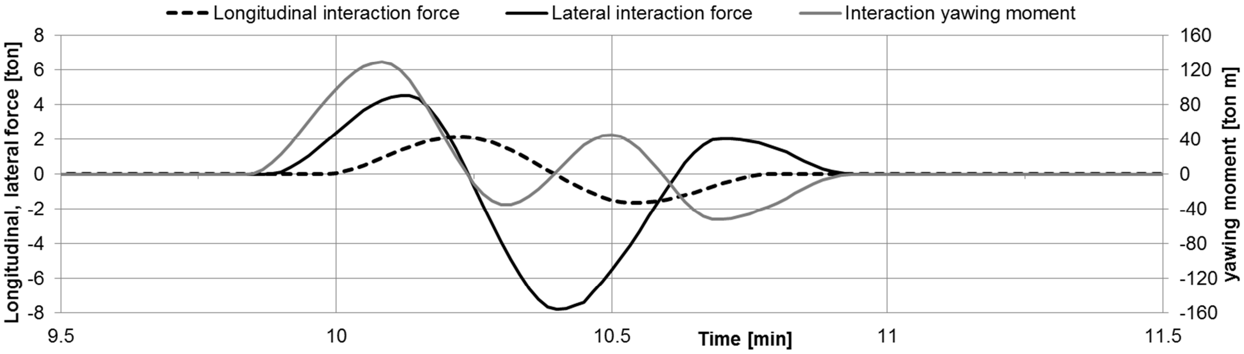

Figure 10 Ship-ship induced interaction forces (left axis) and yawing moment (right axis) during the meeting in run 000 for the outbound class Va vessel on simulator Lara at FHR

4.2 Validation

The mathematical models for the open water manoeuvring model, bank effects and ship-ship interaction have been validated by the skippers during the first simulation day on 16th of January 2014. Additionally the manoeuvring models of the class Va and IV vessels have already been used in different simulation studies and thus proven to be realistic.

5. CIRCULAR INLAND WATERWAYS

5.1 Cross section and navigation rectangle

The dimensioning of inland waterways in France is based on Circular 76-38 of March 1976, (Ministry of infrastructure and secretariat of state for transport 1976). Its purpose is to "…*define a certain number of classes of waterways and to fix the general characteristics that must be adopted in each class for the construction of new waterways or the improvement of existing waterways...*" In this circular, a navigation rectangle is defined. For a Class Va inland vessel (B x T 11.45 m x 3.50 m) this is a rectangle of 36.00 m wide (W_{nav}) and with a depth (h_{nav}) of T+1.00 m (green+orange area in Figure 11). Moreover, the cross section of the canal (orange+green+blue) must have an area of at least six times the midship area of the ship (orange), which implies a blockage ratio m which is less than 1/6.

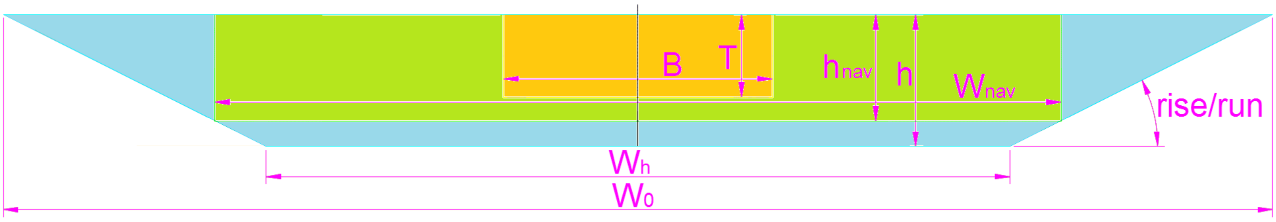

Figure 11 Cross section of the canal, navigation rectangle (green) and midship cross section (orange)

There exist different solutions for the geometry of the canal section to fulfil both conditions (a width W_{nav} at a water depth h_{nav} and a blockage ratio smaller than 1/6). For the same bank slope (rise to run ratio) the canal can be deepened to limit the overall width at the free surface (W_0) or the water depth is limited to h_{nav} which requires a larger width W_0. For run/rise ratios of 2 and 3 both solutions are worked out in Figure 12 and Table 5.

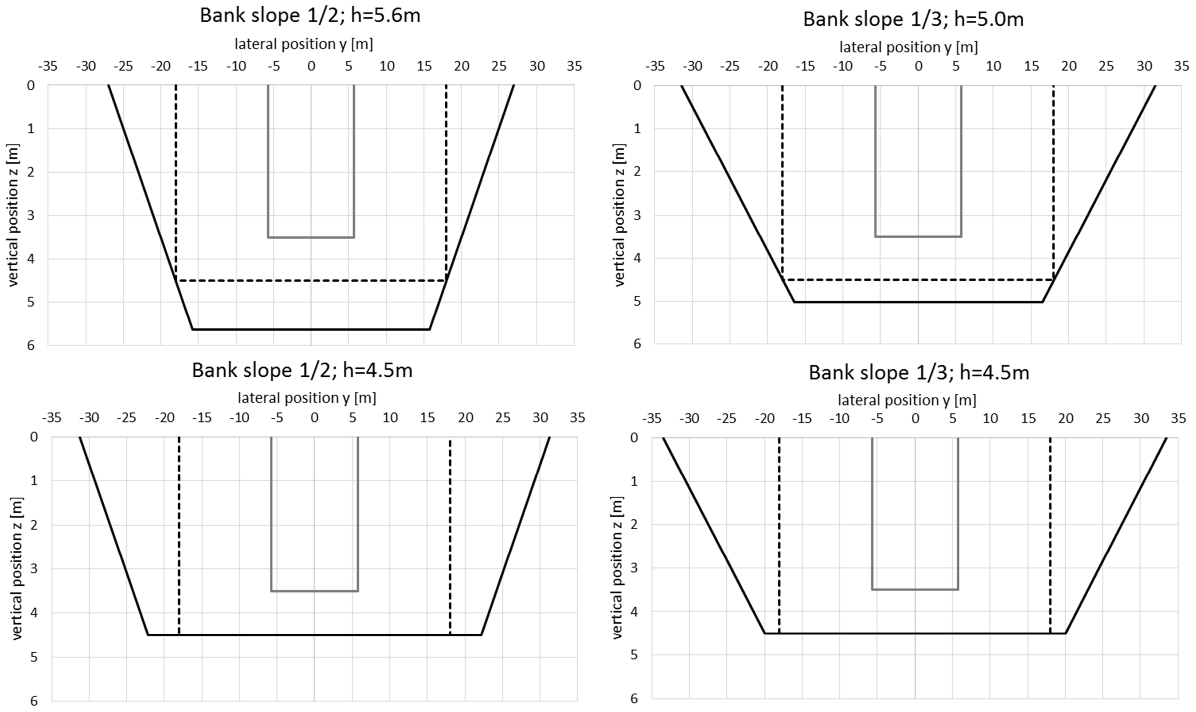

Figure 12 Four canal solutions for the same navigation rectangle and for a run/rise ratio of the banks of 2 and 3

name	[-]	Bank slope 1/2; h=5.6m	Bank slope 1/3; h=5.0m	Bank slope 1/2; h=4.5m	Bank slope 1/3; h=4.5m
run/rise	[-]	2	3	2	3
h	[m]	5.6	5.0	4.5	4.5
W_h	[m]	31.5	32.9	44.4	39.9
W_0	[m]	54.0	63.0	62.4	66.9
h/T	[-]	1.61	1.43	1.29	1.29

Table 5 Different canal solutions fulfilling the French Inland Waterways Circular for a CEMT Class Va vessel.

5.2 Comparison of the four cross sections

The water depth (or under keel clearance), the canal width and the slope of the bank will all have an influence on the bank effects on the inland vessel. Here the bank effects (longitudinal force X_{BANK}, lateral force Y_{BANK} and yaw moment N_{BANK}) are compared for a Class Va vessel sailing at ten equidistributed lateral positions. At position i=0, the ship is navigating on the centre line of the canal cross section, while at position i = 10, the ship's side is positioned above the toe of the sloped bank, see Figure 13

$$y_i = \frac{i}{10}\left(\frac{W_h}{2} - \frac{B}{2}\right) \qquad i = \{0, \dots, 10\} \tag{1}$$

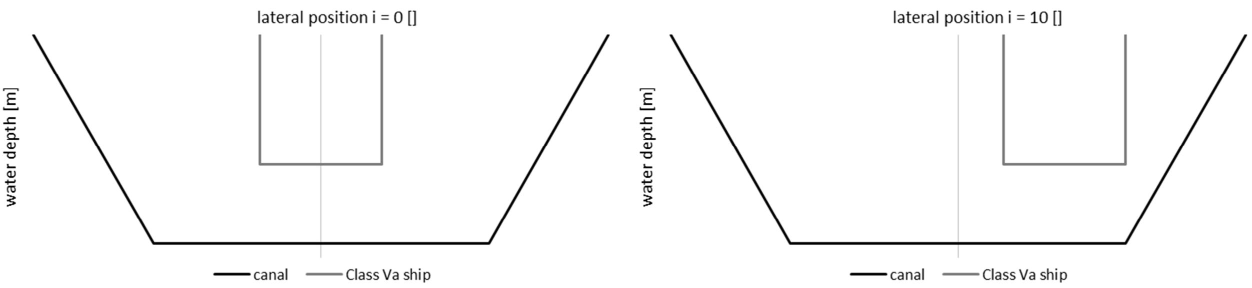

Figure 13 Inland vessel sailing on the centre line (left) and ship's side above the toe of the sloped bank (right)

In Figure 14 the increased resistance induced by bank effects is plotted for the 11 discrete positions in the four cross sections but made dimensionless with the same constant reference value. An increasing resistance induced by the presence of the banks is seen the closer the vessel sails to the bank with a non-zero value on the centre line. Furthermore the resistance increases with a decreasing water depth and with a steeper bank.

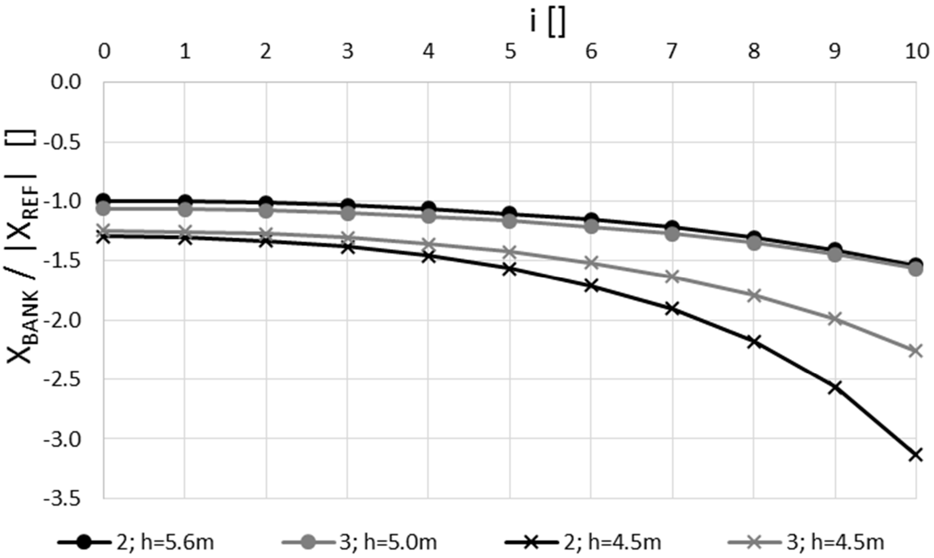

Figure 14 The increased resistance induced by the presence of banks

The lateral force Y_{BANK} for the four cross sections, again made dimensionless with a constant reference value Y_{REF} is plotted for the 11 different lateral positions. As expected, a zero lateral force on the centre line of the cross section is observed together with an increasing attraction force the closer the ship sails to the bank.

The difference in lateral force between cross section *Bank slope 1/2; h=5.6m* and *Bank slope 1/3; h=5.0m* are rather modest while the attraction force about doubles in cross section *Bank slope 1/2; h=4.5m.*

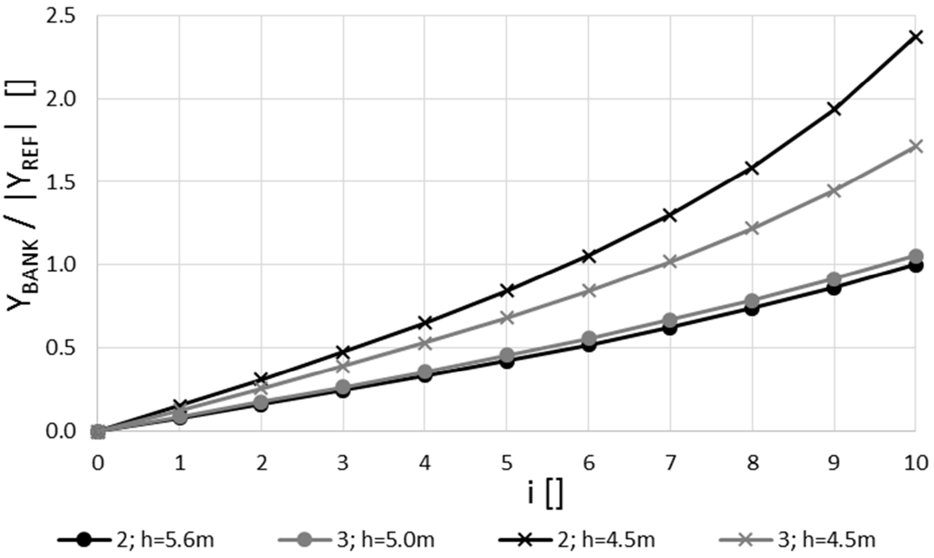

Figure 15 The lateral attraction force Y_{BANK} for the four cross sections under consideration

The yaw moment (directed bow away) is plotted in Figure 16 in the four cross sections. An increasing magnitude of this bow away moment (made dimensionless with the same constant value) starting on the centre line (zero value) up to the closest position (ship's side above the toe of the bank). Again the magnitude of the bank effects increase with decreasing water depth and increasing bank slope.

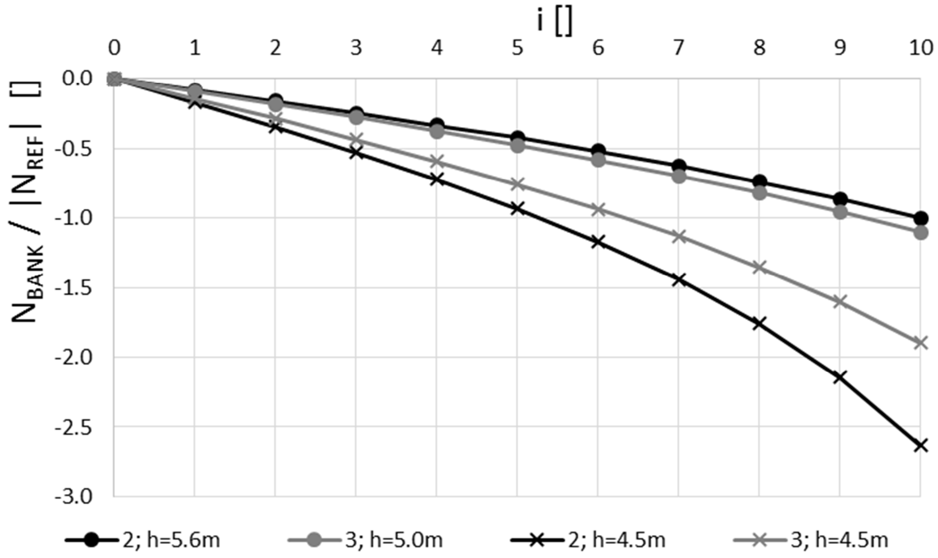

Figure 16 Bank effect induced bow away moment for the four different canal geometries

When the four different solutions for the same boundary conditions according to (Ministry of infrastructure and secretariat of state for transport 1976) are compared with respect to the bank induced forces, the same conclusion can be drawn. The closer the ship sails to (the toe of) the bank, the larger the magnitude of the force/moment will be. The cross section with the deepest water depth and 1/2 sloped banks consistently has the lowest magnitude for the same relative position in the cross section. The cross section with more gentle slopes of 1/3 and less water depth (but the same cross section area) generates 5-10% larger bank effects.

The cross sections with the lowest water depth (4.5m) induce significantly larger bank effects: About double for the lateral force and yaw moment for slopes of 1/3 and even more than double the magnitude for the steeper sloped banks of 1/2.

6. CONCLUSIONS

The mathematical model for bank effects as implemented in the inland navigation simulators of FHR and which is based upon extensive model tests show the significant influence of banks on the manoeuvrability of an inland vessel sailing on a manmade channel. According to French regulations, this channel must fulfil (among others) three conditions: a minimal water depth, a minimal width and a minimal cross section area. The exact geometry is free when these conditions are fulfilled. Therefore, different geometries are compared and the impact on the bank effects shown. Overall, it can be concluded that larger bank effects occur in more shallow water for the same cross section area. The magnitude of these bank effects can be more than double for different geometries according to exact the same boundary conditions and regulations.

NOMENCLATURE

∇	[m³]	volume displacement
B	[m]	ship's breadth
h	[m]	water depth
h_{nav}	[m]	depth of navigation rectangle
i	[-]	integer
L_{OA}	[m]	length over all

L_{PP}	[m]	length between perpendiculars
n	[rpm]	propeller rate
N_{BANK}	[N]	bank induced yaw moment
N_{REF}	[N]	reference yaw moment
T_A	[m]	draft at the aft perpendicular
T_F	[m]	draft at the forward perpendicular
T_M	[m]	draft amidships
W_0	[m]	width of the canal section at the free surface
W_h	[m]	width of the canal section at bottom level
W_{nav}	[m]	width of the navigation rectangle
X_{BANK}	[N]	bank induced longitudinal force
X_{REF}	[N]	reference longitudinal force
Y_A	[N]	bank induced lateral force at the aft perpendicular
Y_{BANK}	[N]	bank induced lateral force
Y_F	[N]	bank induced lateral force at the forward perpendicular
Y_{REF}	[N]	reference lateral force
y_i	[m]	lateral position
λ	[m]	scale factor

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