SYSTEMATIC MODEL TESTS ON SHIP – BANK INTERACTION EFFECTS

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SUMMARY

During the last decade ship sizes have been increasing but the fairways these ships are sailing are seldom expanded at the same rate. As a result the restricted dimensions of these fairways increasingly influence the vessel's hydrodynamics. The vicinity of banks induces forces and moments so a ship's bow will be pushed away from the closest bank, resistance and sinkage will change and a lateral force will act on her. All these hydrodynamic phenomena, so-called bank effects, adversely modify the ship's manoeuvring behaviour. At the *Towing Tank for Manoeuvres in Shallow Water* (*cooperation Flanders Hydraulics Research – Ghent University, Belgium*) an elaborated test program on bank effects has been carried out. In the presented paper a limited selection of measured model test data will be made available for validation of mathematical models, numerical calculations or CFD. Based upon the entire test program a mathematical model for predicting bank effects will be proposed and some applications of this mathematical model shown.

NOMENCLATURE

a	[m^{-1}]	*factor of the weight factor*
A_E	[m²]	*expanded area of the propeller*
A_0	[m]	*disc area of the propeller*
b	[m^{-1}]	*factor of the weight factor*
B	[m]	*beam of the ship*
C_B	[]	*block coefficient*
d	[m]	*hub diameter*
D	[m]	*propeller diameter*
d_{2b}	[]	*dimensionless distance to bank*
F_{NR}	[N]	*rudder normal force*
F_{TR}	[N]	*rudder tangential force*
Fr	[]	*Froude number (length between perpendiculars)*
Fr_h	[]	*Froude number (water depth)*
Fr_{VT}	[]	*Froude number (speed in propeller wake)*
Fr_{crit}	[]	*critical speed*
g	[m/s²]	*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*
P	[m]	*pitch*
Q_P	[Nmm]	*torque on the propeller shaft*
Q_R	[Nmm]	*torque on the rudder shaft*
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	[N]	*sway force*
$y_{0\alpha}$	[m]	*distance to start of the sloped bank*
y_{0O}	[m]	*distance to centre line of the ship*
y_{0max}	[m]	*half the width of the towing tank*
y_{infl}	[m]	*horizontal reach*
y_{sub}	[m]	*width of the submerged part of the bank*
$y_{T/2}$	[m]	*distance to bank at a water depth of T/2*
z_A	[m]	*sinkage aft*
z_F	[m]	*sinkage fore*
Z	[]	*number of propeller blades*
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/m³]	*density*
θ	[°]	*trim*
$\xi_{?n}$	[]	*coefficient of the mathematical model*

1. INTRODUCTION

An increase of the main dimensions of different ship types (container carriers, LNG-carriers, RoRo vessels) can be observed during the last decades but the dimensions of access channels, rivers, canals and ports called by these vessels often do not increase at the same rate. As a result, the behaviour of ships calling or leaving harbours will increasingly be influenced by waterways restrictions.

The asymmetric flow around a ship induced by the vicinity of banks causes pressure differences between her port and starboard sides. As a result, a lateral force will act on the ship, mostly directed towards the closest bank, as well as a yawing moment pushing her bow towards the centre of the channel. The proximity of banks increase the blockage, the ship's resistance as well as her sinkage. A reliable estimation of all these phenomena, known as bank effects, is important for determining the limiting conditions in which a ship can safely navigate a waterway.

The knowledge of these bank effects induced by a wide range of bank geometries is still very limited. Therefore a comprehensive research project has been carried out at Flanders Hydraulics Research (Flemish Government, Antwerp, Belgium) in cooperation with the Maritime Technology division of Ghent University.

The present paper intends to make available a selection of open data or test results that can be used for validation of mathematical simulation models, CFD calculations or

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other purposes. All measured forces, moments and motions will be made available for a limited set of model tests to be used as bench mark data. A second set of open data contains measured sinkages fore and aft of the towed model. For some tests of both sets the registration of three wave gauges will also be made available.

Furthermore the present paper will describe a mathematical model that has been developed based upon these model tests. This mathematical model calculates the longitudinal force, sway force, yaw moment and sinkages fore and aft of a ship sailing at a steady state condition along a randomly shaped bank. The model has been implemented in the ship manoeuvring simulators of Flanders Hydraulics Research. Finally some remarks of the pilots on the model are shown and investigated.

2. EXPERIMENTAL PROGRAM

2.1 TEST FACILITY

The results discussed and the open data delivered have been obtained by captive model testing in the *Towing tank for manoeuvres in shallow water* (*cooperation Flanders Hydraulics Research – Ghent University*).

This facility, with main dimensions 88 x 7 x 0.5 m³, is fully automated and allows execution of captive model tests 24 hours a day, 7 days a week, resulting into a capacity of up to 35 runs a day. As during most runs two consecutive bank configurations were installed in the towing tank, up to 70 test conditions a day could be investigated. Eventually more than 10,000 test conditions related to bank effects have been examined in 2006.

2.2 BANK GEOMETRIES

Seven different bank geometries have been installed in the towing tank. Two types of banks can be distinguished (see Figure 1):

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

Table 1: Overview of the tested banks

Name	h_0	α	$y_{0\alpha}$	y_{sub}
I	surface piercing	vertical wall	2.830m	-
II	surface piercing	1/5	0.530m	-
III	0.120m	1/5	0.530m	2.370m
IV	0.150m	1/5	0.530m	2.220m
V	surface piercing	1/8	0.530m	-
VI	0.150m	1/8	0.530m	1.770m
VII	surface piercing	1/3	2.230m	-

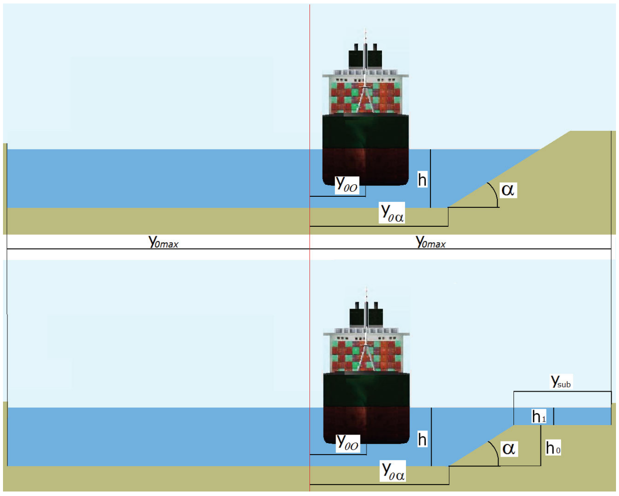

Figure 1: Surface piercing bank and bank with platform submergence

The characteristics of the installed banks are shown in Table 1 and Figure 1 with y_{0max} = 3.500m. 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* (Sternenschiereiland) in the outer harbour of Zeebrugge. A slope of 1/8 (V and VI) is very common for natural river banks, such as the Western Scheldt.

2.3 SHIP MODELS

Three ship models have been used during this test program. Systematic tests along the installed banks were carried out with a 8000 TEU container carrier and a LNG-carrier, while a smaller tanker model was used to investigate the maximal distance of influence between ship and bank. All open data are measurements of tests with the container carrier model at different loading conditions.

The body plan of the container carrier model is shown in Figure 2, while its main dimensions are listed in Table 2. This model has been tested extensively at two even keel conditions; a limited test program has been executed with the ship model in initially trimmed condition.

The LNG carrier and the container carrier are single screw ships. The main properties of the propeller of the container carrier are shown in Tables 3 and 4.

Table 2: Main dimensions of the ship models

		8000 TEU container carrier			LNG carrier	tanker
L_{OA}	[m]	4.332			4.000	2.310
B	[m]	0.530			0.594	0.295
T_F	[m]	0.149	0.180	0.161	0.157	0.178
T_A	[m]	0.149	0.180	0.180	0.157	0.178
C_B	[-]	0.65	0.66	0.65	0.77	0.80

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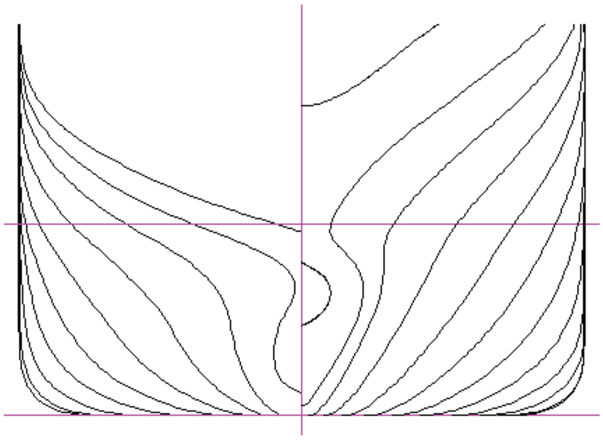

Figure 2: Body plan of the 8000 TEU container carrier

2.4 TEST CONDITIONS

For each loading condition of the container carrier model, tests have been carried out at three different water depth, so as to obtain under keel clearances (UKC) of 10%, 35% and 100% of draft. In this way, the UKC range encountered by a container carrier approaching or leaving the Flemish harbours is covered. The LNG-carrier is tested at 35% and 70% UKC which corresponds to the present practice at the harbour of Zeebrugge. Analogous to the container carrier the tanker is tested at 10%, 35% and 100% UKC.

The speed range in the regular test program varies between 0.343m/s to 0.916m/s for the container carrier and 0.369m/s up to 0.984m/s for the LNG carrier, so as to cover a speed range between 6 and 16 knots at full scale for both ship models.
The propeller rate is changed systematically from 0%, 40%, 60% up to 80% of the maximum propeller rate.
Tests are carried out for a wide range of lateral distances between ship and bank:

- as close as practically possible to the bank;
- with amidships above the toe of the sloped bank ($y_{0\alpha}$);
- with the ship's side above the toe of the sloped bank ($y_{0\alpha}$);
- 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 and by the wall of the towing tank beforehand are expected to counteract.

Table 3: Main properties of the propeller of the container carrier

Diameter	D	104	[mm]
Mean pitch ratio	P/D	1.00	[ ]
Blade area ratio	A_E/A_0	0.96	[ ]
Hub diameter ratio	d/D	0.19	[ ]
Number of blades	Z	6	[ ]
Rotation direction		Right	[ ]

2.5 CONVENTIONS AND REGISTRATIONS

After having covered a 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 results are obtained by averaging the measurements over this steady state condition.

The following coordinate systems are of interest:

- a rectangular, right handed earth bound coordinate system $O_0x_0y_0z_0$ (Figure 4). The $O_0x_0y_0$ plane is horizontal and coincides with the initial water plane at rest; the vertical $O_0x_0z_0$ plane is the longitudinal symmetry plane of the (empty) towing tank, with the vertical O_0z_0-axis directed downwards. The origin is located at the conventional home position of the towing carriage. All banks were built in at positive y_0 values;

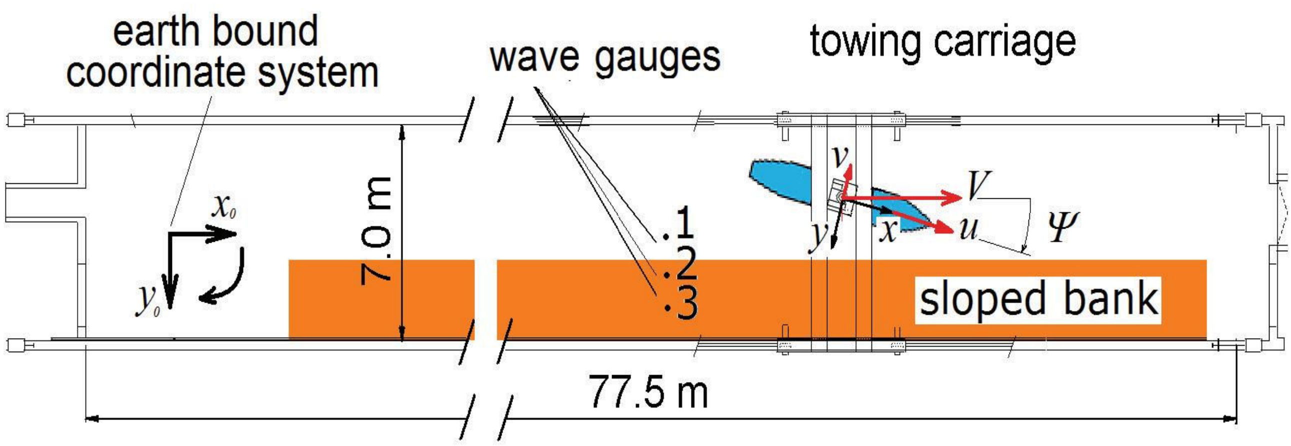

Figure 4: Position of the wave gauges and the coordinate systems

- a right handed, rectangular coordinate system *Oxyz* is attached to the vertical axis of the yawing table of the planar motion mechanism. When the latter is at rest at its home position, *Oxyz* coincides with the earth bound system. The ship model is mounted in such a way that the origin *O* is located at the midship section (½L_{PP} fore of APP), at the intersection of the longitudinal vertical symmetry plane and the waterline at rest. The longitudinal axis *Ox* is positive from stern to stem, the transversal axis *Oy* is positive towards starboard, and the vertical *Oz* axis is directed downwards. The yawing table imposes a heading angle ψ between the O_0x_0 axis and the *Ox* axis; a clockwise rotation is considered to be positive. The horizontal velocity vector $\vec{V}$ of the origin *O* is composed of the velocity components imposed by the longitudinal carriage (u_0) and the lateral carriage (v_0), the latter being zero during all tests considered in the present paper. $\vec{V}$ can be decomposed in components <u>*u* and *v* according to the axes *Ox* and *Oy*, respectively.</u>

During the captive model tests 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 following items have been measured during the tests.

- Hull: Longitudinal and lateral components of the horizontal forces acting between the ship model and the mechanism in two measuring posts located aft and fore in the ship model are registered and converted to a longitudinal force *X*, a lateral force *Y* and a yawing moment *N*, expressed in the *Oxyz* coordinate system. The roll moment *K*, preventing rotation around the *Ox*-axis, is measured separately as well. The vertical motion of the ship model is measured in four points (fore/aft, port/starboard) and converted into z_F and z_A, the vertical motion of the fore and aft perpendiculars, respectively, considered to positive in case of a downwards motion.

- Propeller: The thrust T_P is positive from stern to stem (as the propeller pushes the ship forward) and the propeller rate *n* is positive turning clockwise (for a right-handed propeller when looking forward). When the propeller generates a positive thrust having a positive propeller rate the torque Q_P on the propeller shaft is considered to be positive.

- Rudder (see Figure 7): The tangential force F_{TR} is positive from trailing towards the leading edge of the rudder, the normal force F_{NR} is positive towards the starboard side. The rudder angle δ is positive if resulting into a turning manoeuvre to port.

- Water surface level: For a selection of tests the wave pattern between the ship model and the bank were registered by three wave gauges installed at different lateral but at the same longitudinal position. A descending water level generates an increasing value of the wave gauge signals.

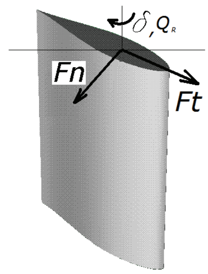

Figure 7: Orientation of normal and tangential forces on rudder and rudder angle and torque

Summarised, the following items are delivered:

Hull:

- Sinkage fore z_F [mm]
- Sinkage aft z_A [mm]
- 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 [Nmm]
- Propeller rpm n [rpm]

Rudder:

- Rudder normal force F_{NR} [N]
- Rudder tangential force F_{TR} [N]
- Rudder torque Q_R [Nmm]
- Rudder angle δ [deg]

More information on this test program is available in [1]. A selection of video footage can be seen at the website www.bankeffects.ugent.be.

3. OPEN DATA ON BANK EFFECTS

A set of measured data, free to use, is released with two different subsets. The first subset consists of measured sinkages (fore and aft) of the container carrier sailing along bank V at four different speeds and with four different distances between ship and bank. The second set contains ten tests and includes all measured forces, moments and motions. The results are obtained by tests carried out with the model of the container carrier at different initially even keel conditions. This second subset consists of tests with a wide range of speeds, bank geometries, drift angles, propeller rates etc.

3.1 FIRST SUBSET OPEN DATA

The container carrier model ballasted even keel with an initial draft fore and aft of 0.180m, is towed at zero drift angle, zero rudder angle and zero propeller rate at four constant forward speeds along bank V and at four lateral

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positions between ship and bank. The water depth *h* is 0.243m, resulting in an under keel clearance of 35% of draft. The four speeds are 0.458, 0.572, 0.687 and 0.801 m/s. The distances between the centre line of the ship and the Ox_0-axis y_{0O} (Figure 1) are:

- y_{0O} = -0.920 m: expected distance were the influence on sway force and yaw moment of the installed bank and the wall of the towing tank counteract;
- y_{0O} = 0.000 m: at the centre of the (empty) towing tank;
- y_{0O} = 0.2765 m: with the ship's starboard side above the toe of the sloped bank;
- y_{0O} = 0.490 m: with the centre line of the model above the toe of the sloped bank.

The resulting sinkages at the fore and aft perpendicular are given in Table 6. The test at 0.801 m/s and at the lateral position y_{0O} of 3.990 m was not possible to be carried out without grounding of the model.

Table 6: First subset open data: sinkage fore and aft.

	position in the cross section y_{0O} (see Fig. 1)								
speed	-0.920		0.000		0.265		0.490		[m]
[m/s]	z_F	z_A	z_F	z_A	z_F	z_A	z_F	z_A	
0.458	2.4	2.2	2.9	2.7	3.1	2.8	3.3	3.1	[mm]
0.572	4.5	4.0	4.8	4.4	5.4	5.0	5.6	5.2	[mm]
0.687	6.9	6.4	7.7	7.1	8.5	8.0	9.6	9.2	[mm]
0.801	9.6	10.8	10.4	14.1	10.4	16.1	-	-	[mm]

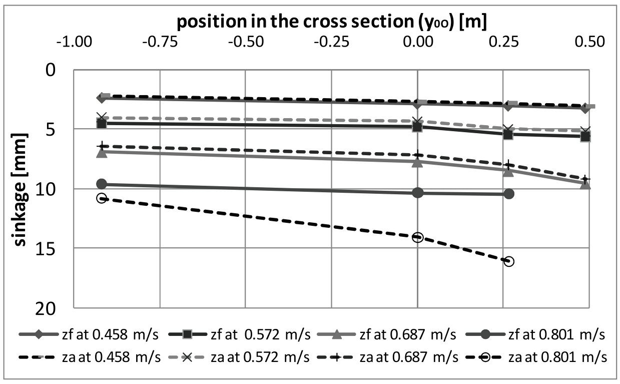

Figure 9: Measured sinkages fore and aft for four forward speeds and four distances between ship and bank.

Figure 9 shows the influence of forward speed and distance between ship and bank on the sinkage fore and aft of the container carrier.

3.2 SECOND SUBSET OF OPEN DATA

All data in this subset is obtained with model tests carried out with a model of a container carrier initially even keel ballasted but at different original drafts. This set contains a wide variation of the input parameters of the elaborated test program carried out at Flanders Hydraulics Research [1]. The input parameters of the ten tests (named A to J), as well as the test results, are summarised in Table 7.

For the tests B, C, E, F, I and J a registration of the water surface is made by three wave gauges at a fixed position in the towing tank. In all 6 cases the three wave gauges are installed at 19.00 m from the origin of the towing tank (O_0x_0 axis in figure 4). The lateral distances y_0 of the three wave gauges is summarised in Table 8.

Table 8: Lateral position y_0 of the three wave gauges

	Wave gauge 1	Wave gauge 2	Wave gauge 3
	[m]	[m]	[m]
B, C	1.080	1.480	2.315
E, I	1.440	1.780	2.680
F	1.910	2.440	2.970
J	1.450	1.850	2.315

The registration of the three wave gauges for the six tests is given in appendix A. On the abscissa the longitudinal distance between the midship's section of the container carrier and the wave gauges is plotted. The ordinate shows the water level relative to the still water level in the towing tank.

Digital information of the open data including a mesh of the hull, propeller, rudder and drawings of the test set up and wave gauges can be obtained via the authors or info@shallowwater.be

Table 7: Second subset of open data

name test	draft (even keel)	water depth	under keel clearance	forward component of speed vector	transversal component of speed vector	lateral position	heading angle	bank name	longitudinal force	transversal force	sinkage fore	sinkage aft	roll moment	yaw moment	propeller rate	propeller thrust	propeller torque	rudder angle	rudder normal force	rudder tangential force	torque on rudder shaft
	T	h	$\frac{h-T}{T}$	u	v	y_{0O}	ψ		X	Y	z_F	z_A	K	N	n	T_P	Q_P	δ	F_{NR}	F_{TR}	Q_R
[ ]	[m]	[m]	[%]	[m/s]	[m/s]	[m]	[°]	[ ]	[N]	[N]	[mm]	[mm]	[Nm]	[Nm]	[rpm]	[N]	[Nmm]	[°]	[N]	[N]	[Nmm]
A	0.180	0.360	100	0.684	-0.060	0.265	5.0	V	-4.13	5.14	5.1	3.7	-0.16	8.94	0	-1.10	-27	0	0.10	-0.05	0.75
B	0.180	0.198	10	0.343	0.000	0.265	0.0	IV	2.13	2.95	2.2	3.3	0.53	-4.99	540	4.37	70	0	0.22	0.01	-0.21
C	0.180	0.198	10	0.458	0.000	0.265	0.0	III	-2.62	-0.96	3.9	4.6	0.15	-4.30	0	-0.20	-3	0	0.00	0.00	0.12
D	0.149	0.297	100	0.687	0.000	1.340	0.0	V	-3.12	8.06	4.8	11.8	1.71	-16.41	540	3.30	54	0	0.13	0.34	3.37
E	0.180	0.243	35	0.687	0.000	0.530	180.0	VI	1.43	-5.42	7.6	9.5	-0.58	8.78	719	7.22	118	0	0.28	-1.12	3.44
F	0.180	0.360	100	0.801	0.000	1.435	0.0	VII	-5.36	1.65	6.6	5.4	0.05	-1.80	0	-0.93	0	0	0.07	-0.04	1.21
G	0.149	0.200	35	0.572	0.025	0.000	-2.5	II	2.76	-0.77	5.0	8.7	0.47	-10.41	719	7.55	120	0	0.41	-0.31	-0.94
H	0.149	0.163	10	0.458	0.000	1.965	0.0	I	-2.94	-2.55	2.8	5.0	0.18	-6.96	0	-0.37	7	0	0.01	0.01	-0.23
I	0.149	0.200	35	0.572	0.000	0.565	0.0	VI	-2.74	3.68	7.0	7.2	-0.74	-8.31	359	1.46	21	0	0.07	0.08	0.39
J	0.149	0.297	100	0.801	0.000	0.530	0.0	III	-1.75	2.26	5.8	8.8	0.21	-2.07	540	3.16	62	0	0.12	-0.21	2.26

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4. MATHEMATICAL MODEL

A mathematical model has been formulated for the sway force, the yaw moment, the longitudinal force and the sinkage induced by the vicinity of banks with arbitrary geometries This mathematical model is based upon all model tests carried out in the towing tank, the open data discussed in Section 3 are only a very limited selection of the tests used for this mathematical model.

Mathematical models for sloped and semi- submerged banks have been developed in the past by several authors (e.g. Norrbin [2], Dand. [3]). Norrbin [2] proposed a parameter y_B in the models for the sway force and yaw moment to determine the distance between a ship and a (sloped) bank. This parameter is based on the distances between the ship and a discrete point at a predefined water depth on the sloped bank. Therefore this method is very sensitive to the bank geometry at this and only at this discrete position.

These disadvantages are overcome by a new distance to bank parameter d_{2b} and an equivalent blockage parameter m_{eq}. Both parameters encompass the entire geometry of the bank. The mathematical model is briefly explained in this paper but originally and more elaborated in [1]

4.1 HORIZONTAL AND VERTICAL 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 a ship-bank distance can be defined as the boundary between open and confined water. This distance is defined as 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.

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.

For each combination of speed and water depth, the measured variables can be plotted as a function of the distance between the ship's centreline and the closest wall. 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 (▲);
- Close to the bank, a significant influence is generated (■);
- In between, the influence is measurable but not significant (◆).

This division in three ranges is carried out for all UKC – speed combinations. The results are summarised in one graph, see figure 12, 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.

$$Fr_h = \frac{V}{\sqrt{gh}} \tag{1}$$

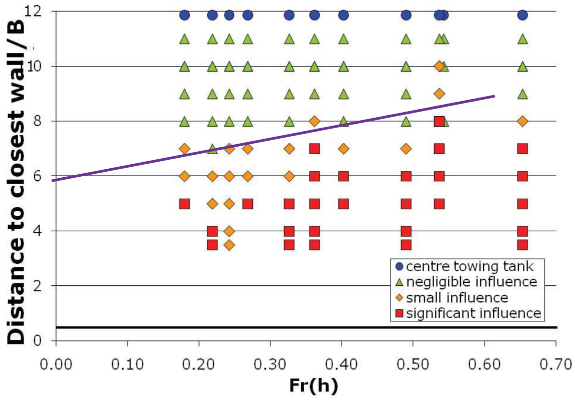

Figure 12: Horizontal reach and Fr(h) with the three influence regions

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

$$y_{\text{infl}} = B\left(5Fr_h + 5\right) \tag{2}$$

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

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 [4] defines $h = 3T$ or UKC = 200% as the separation between deep and restricted waters. No unambiguous definition of the water depth can be formulated when a ship sails above an irregular bathymetry; therefore 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.

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).

$$h_{eff} = h - z_{\max} \tag{3}$$

The effective under keel clearance UKC_{eff} is:

$$UKC_{eff} = \frac{T}{h_{eff} - T} \tag{4}$$

4.2 WEIGHT FACTOR AND WEIGHT DISTRIBUTION

The weight factor is a value between 0 and 1 indicating the influence of a water particle on the manoeuvrability of a ship. For a water particle close to the hull the value will tend 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 weight factor in the section taken by the ship is zero.

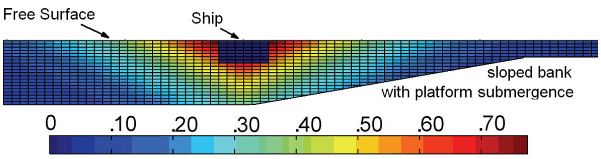

Figure 14: Graphical representation of the weight distribution

Analogous to Norrbin's factor [2] the weight distribution is defined as a decreasing exponential function. The expression of the weight distribution in the ship bound coordinate system is:

$$e^{-a|y|-b|z|} \tag{5}$$

The factor a is dependent on the horizontal reach y_{infl}:

$$a = \frac{3}{y_{\text{infl}}} \tag{6}$$

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

$$b = \frac{1}{3T} \tag{7}$$

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

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

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

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

Remark that the weight has a non-infinite solution at infinite. The weight of an infinite deep and infinite wide ocean is:

$$\begin{aligned}\chi_{ocean} &= 2\int_0^\infty\int_0^\infty e^{-(ay+bz)}dy\,dz \\ &= \frac{2}{ab} = 2y_{\text{infl}}T\end{aligned} \tag{10}$$

4.3 EQUIVALENT BLOCKAGE $m_{eq.}$

The amount of space a ship takes in the cross section of a fairway is indicated by the blockage. The blockage is conventionally defined as the ratio between the cross sectional areas of the ship and the fairway. In open water the blockage becomes zero. The blockage of a panamax in the Panama lock can reach 0.93.

This definition for the blockage is independent of the distance to the bank. No matter how close a ship sails along one bank, while the navigation area is unlimited at the other side, the blockage will be zero. 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 in [1]. This equivalent blockage is analogous to the conventional blockage but takes into account the weight distribution. The equivalent blockage is defined as:

$$m_{eq} = \frac{\chi_{ship}}{\chi_p+\chi_s} - \frac{\chi_{ship}}{\chi_{ocean}-\chi_{ship}} \tag{11}$$

The position and speed of the ship is taken into account in this equivalent blockage. The blockage m_{eq} will not be dependent on the canal cross section only. Furthermore, changing the configuration of a bank close to the ship will have a higher impact on the blockage m_{eq} than the same change in the bathymetry at a distance further away from the vessel. Finally this new blockage will be non-zero when sailing along a single bank and zero when sailing in unrestricted and deep water.

4.4 DISTANCE TO THE BANK d_{2b}

The distance between ship and bank is only unambiguously defined when sailing along a vertical bank at one side. In the past the distance between ship and bank at half the draft or at other 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 this distance between ship and bank.

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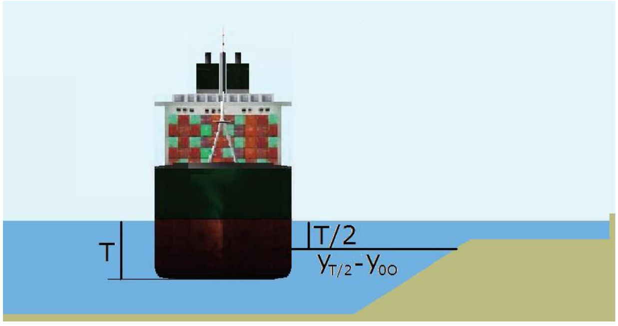

Figure 15: the distance between the centre of the ship and the bank at half the draft ($y_{T/2}$-y_{0O})

Figure 16 shows the relation between the distance between the centre of the ship and the bank at half the draft ($y_{T/2}$-y_{0O}, Figure 15) and the sway force for seven different bank geometries for the container carrier at 10 knots full scale, 100% under keel clearance and zero propeller rate.

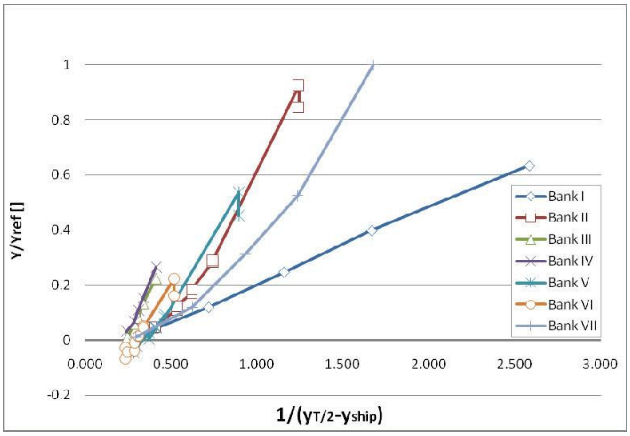

Figure 16: Sway force as a function of lateral distance between container ship's centre and bank at half draft for the container carrier (T=14.5m) for one speed with 100% UKC

The parameter originally proposed in [1] is more robust and sensitive to the entire bathymetry. This parameter is called *d2b* (distance to bank) and defined as:

$$\frac{1}{d2b} = \frac{1}{2}\left(\chi_{ocean} - \chi_{ship}\right)\left(\frac{1}{\chi_p} - \frac{1}{\chi_s}\right) \tag{12}$$

The expression for *d2b* 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 more sensitive for changes in the bank geometry close to the ship than at a distance further away. The influence of a submerged platform is taken into account in the parameter 1/d2b. Sailing along a surface piercing bank will induce a higher 1/d2b than sailing (in the same conditions) along a bank with the same slope but with a submerged platform. The width of this submerged platform y_{sub} is also taken into account. Widening a very wide submerged platform will almost have no influence on 1/d2b but widening a small submerged platform will, as long as the submerged platforms are within the horizontal reach.

The same sway forces shown in figure 16 are plotted in figure 17 as a function of 1/d2b. This figure 17 shows a satisfying linear relation between the parameter 1/d2b and the sway force induced by a wide variety of bank types. A wide range of tested banks; a vertical wall, steep sloped bank (1/3), gentle sloped banks (1/8), surface piercing and semi-submerged types of banks are included.

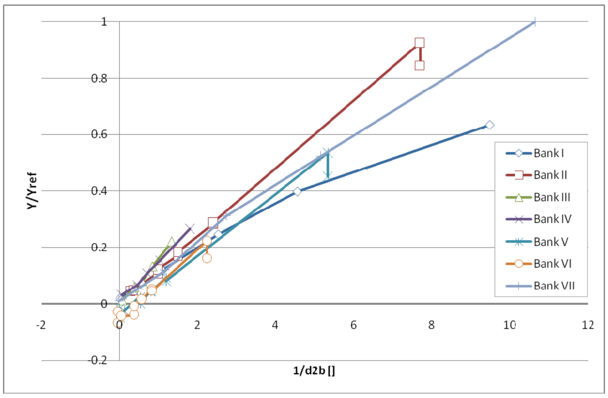

Figure 17: Exactly the same sway force as in Figure 16 as a function of 1/d2b

4.5 PROPULSION AND SPEED

As a result of a forward rotating propeller the flow velocity around the stern of the ship and the bow-away yawing moment will both increase. 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. Under specific conditions a propeller action in very shallow water (UKC <35%) will change a repulsion sway force to the closest bank into an attraction force directed away from the closest bank.

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

$$V_T = sign(T_P)\sqrt{\left|\frac{8T_P}{\rho\pi D^2}\right|} \tag{13}$$

This speed represents in a simplified way the axial speed in the flow field behind the propeller induced by the propeller. A fraction of this speed V_T is added to the forward speed of the vessel to take into account these propeller effects:

$$V_{eff} = V + \xi V_T \tag{14}$$

and made non-dimensional by the Froude number using the length between perpendiculars:

$$Fr_{eff} = \frac{V_{eff}}{\sqrt{gL_{PP}}} \tag{15}$$

4.6 SINKAGES, FORCES AND MOMENTS

The sinkage fore z_F and sinkage aft z_A are modelled 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 sinkage depends on the forward speed of the ship, the propeller rate and the entire bathymetry. The latter is taken into account in formula (16) by the equivalent blockage m_{eq}, while the forward speed of the ship and the propeller action are reflected in the effective Fr_{eff}.

$$z = T\, Fr_{eff}^2 \left(m_{eq} \left(\xi_{z1} Fr_{eff}^2 + \xi_{z2} \right) + \xi_{z3} Fr_{eff}^2 + \xi_{z4} \right) \tag{16}$$

When a ship sails on a canal or other restricted waterway it will experience a higher resistance than sailing in open water. The proposed mathematical model takes into account the increase of the resistance and the influence of hull, propeller, water depth and bank geometry. The effects of banks and water depth on the longitudinal force 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.

$$X_{total} = \frac{1}{2} \rho V^2 LT \left(\xi_{X1} + \xi_{X2} Fr^2 m_{eq}{}^2 \right) + (1 - \xi_{X3}) T_P \tag{17}$$

A ship sailing within the horizontal reach of a bank will be attracted to the closest bank when the under keel clearance exceeds a minimum value. When she sails in very shallow water she will be pushed away from the closest bank.

$$Y_{bank} = \frac{1}{2} \rho V_{effY}^2 LT \frac{1}{d2b} \cdot \left(\left(\xi_{Y1} Fr_{VT} + \xi_{Y2} \right) \frac{T}{h_{eff} - T} + \left(\xi_{Y3} Fr_{VT} + \xi_{Y4} \right) \right) \tag{18}$$

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

The measurements are fairly predicted for the container carrier using formula (18) but this formula should be improved for the LNG-carrier.

Contrary to the sway force the yaw moment is always directed so the ship's bow is pushed away from the closest bank, even at very shallow water conditions.

$$N_{bank} = \frac{1}{2} \rho V_{effN}{}^2 L^2 T \cdot \frac{1}{d2b} \frac{T}{h_{eff} - T} \left(\xi_{N1} + \xi_{N2} Fr_{effN} + \xi_{N3} Fr_{effN}{}^2 \right) \tag{19}$$

A higher than quadratic speed dependency was necessary in formula (19) to obtain satisfying results. This 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 but significant improvements can be made in the future.

4.7 RESTRICTIONS ON THE MATHEMATICAL MODEL

The mathematical model proposed in this paper is valid for a wide range of conditions but some attention have to be made at specific situations. These restriction are explained in [1] and here repeated.

Unfortunately a ship can run aground or crash into a bank. The mathematical model presented is not valid for such extreme conditions. Furthermore it does not cope with very high blockages such as in a narrow lock or extremely close to a quay wall. The minimal tested ratio between the weight at port or starboard side (χ_p, χ_s) and half of the weight of the ship ($\frac{1}{2}\chi_{ship}$) is 0.90; therefore the validity of the model is limited by:

$$\frac{\chi_{p/s}}{\chi_{ship}} > 0.45 \tag{20}$$

The mathematical model is based upon model tests which are carried out with forward ship speed and non-negative propeller rates (quadrant I). The formulae are therefore only tested and validated for ships sailing under these circumstances.

The model was not satisfying for tests carried out at speeds close to the critical speed as defined by Schijf [5].

$$Fr_{crit} = \left(2 \sin\left(\frac{\arcsin(1-m)}{3} \right) \right)^{3/2} \tag{21}$$

In formula (21) the conventional 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. A

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mathematical model coping with supercritical speeds is out of the original scope of this research. The proposed mathematical model is therefore only valid when sailing slower than 84% of the critical speed.

$$Fr_h < 0.84 Fr_{crit} \qquad (22)$$

5. APPLICATION OF THE MODEL

The mathematical model for bank effects described in Section 4 has been implemented in the ship manoeuvring simulators of Flanders Hydraulics Research. For different research projects series of voyages have been made with this updated model. One of the research projects dealt with the meeting of two large container carriers (Lpp 381.0m, B 51.6, T 15.0m) on the river Scheldt, a fictitious situation nowadays. During one particular voyage very significant bank effects were experienced on the vessel sailing to Antwerp between buoy 87A and buoy 89 (Figure 18).

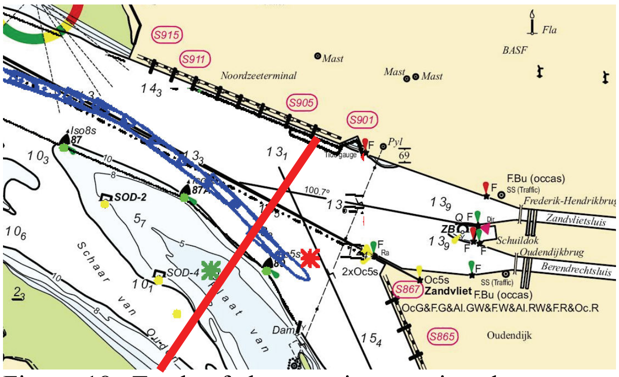

Figure 18: Track of the container carrier close to one bank.

The position of the cross section of the fairway is given in figure, the cross section and the position of the container carrier is shown in Figure 19.

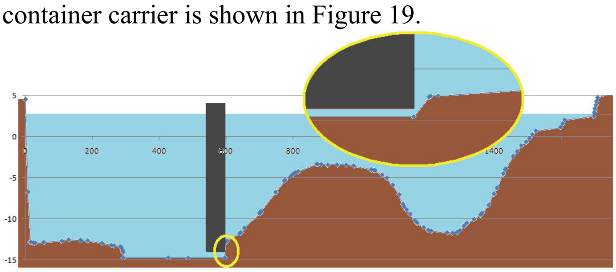

Figure 19: Cross section of the fairway

When the container carrier sailed at the point of the cross section (12.2 minutes after the start of the exercise) the bank effects peaked to values Y_{bank}=212ton and N_{bank} 113K tonm. The sinkage nor the longitudinal force peaks at this point. The peak in the lateral force and yaw moment results in drastic bank effects which badly influenced the manoeuvrability of the vessel. The yaw moment at this point was evaluated by the pilots as overestimated. On the other hand at that point the container carrier was sailing at 10 knots, very close to a bank, with a high thrust (propeller rate 68 rpm, resulting in a higher effective speed) and an effective UKC of only 5% which is a rather extreme situation.

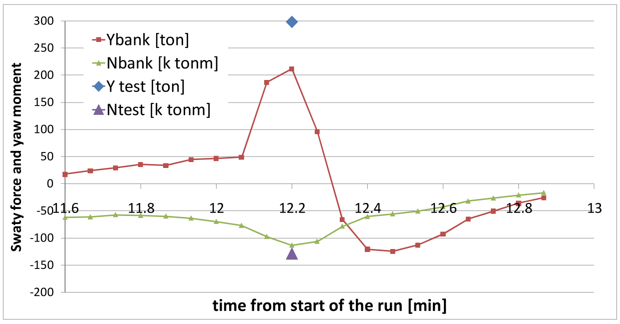

Figure 20: Time history of Y_{bank} and N_{bank} during the simulation run and the Y_{bank} and N_{bank} measured during model tests.

In figure 20 sway force and yaw moment as measured during a model test which was very similar (Bank VI, UKC 10%, speed 10 knots, propeller rate 60% of sea full and with the ship's side at the toe of the sloped bank) is added to the graph.

The lack of correspondence between the experience of the pilots and the results obtained by this model only suggests more research is required on the topic. Not only towing tank tests or numerical calculations can be of high value for the prediction of these effects but an objective validation of the forces and moments based on full scale measurements will help in evaluating the mathematical model for simulation purposes.

6. CONCLUSIONS

The manoeuvrability of a sailing vessel is influenced by the proximity of banks. In 2006 an extensive research program on bank effects is carried out and for a limited amount of tests the results, free to use, are given in the presented paper.

Based upon the model tests of the research program a mathematical model taking into account irregular bank geometries is proposed. Finally this model is implemented in the ship manoeuvring simulator and the bank effects are analysed and detailed during a specific simulation.

7. ACKNOWLEDGEMENTS

The research project "*Determination of Bank Effects*" is funded by the Flemish Government, Department Mobility and Public Works, and executed in 2005 – 2007 by Flanders Hydraulics Research (Antwerp, Belgium) who commissioned the Maritime Technology Division of Ghent University to supply scientific support. Special thanks go out to ir. Erik Laforce for the initiation of this research project.

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9. AUTHORS BIOGRAPHY

Evert Lataire is currently assistant at the division of Maritime Technology at Ghent University and responsible for limited teaching tasks. He is making a PhD on the topic of bank effects mainly based upon model tests. His previous experience includes research on ship manoeuvring simulators and model tests with ship to ship interaction.

Marc Vantorre holds the current position of senior full professor of marine hydrodynamics at Ghent University, where he is head of the Maritime Technology Division. His research, in close co-operation with Flanders Hydraulics Research, Antwerp, mainly focuses on ship hydrodynamics in shallow and restricted waters, including captive model testing, simulation and access channel policy.

Katrien Eloot obtained a Master's degree in Naval Architecture from Ghent University Belgium in 1995. She worked as an academic assistant at the university from 1995 until 2000. There she started her principal research concerning mathematical modelling of ship manoeuvres in shallow water and captive model testing. In 2001 she entered Flanders Hydraulics Research, a laboratory of the Flemish Government. As coordinator of the nautical research group she carries out research contracts on real-time and fast-time manoeuvring simulation for the public and the private sector.

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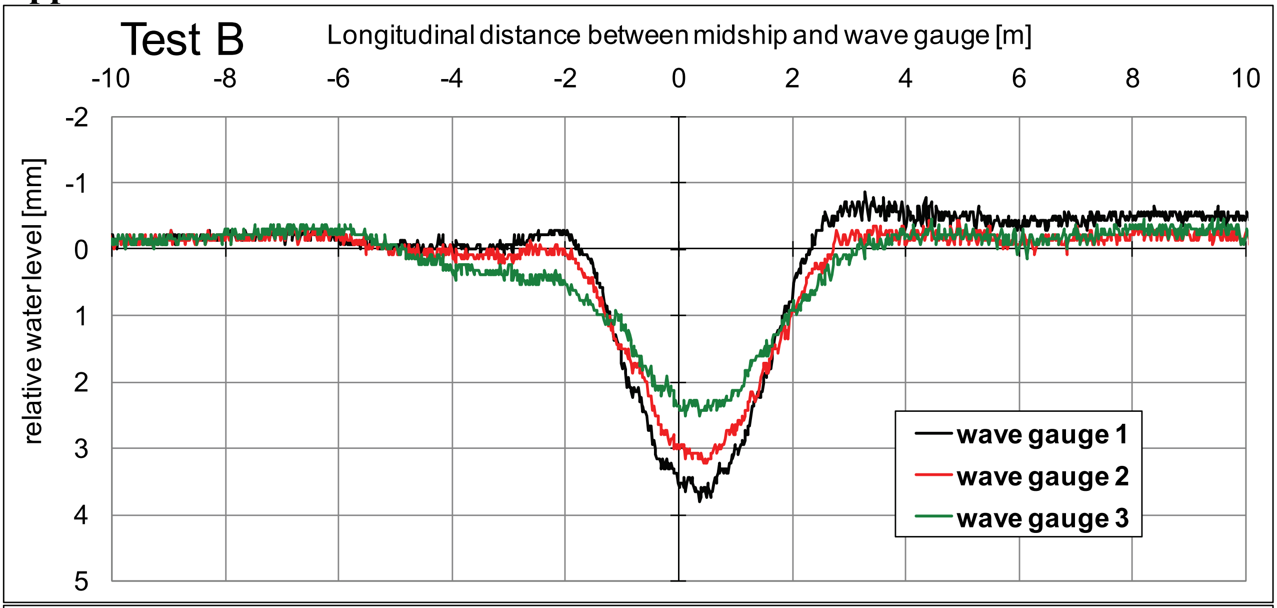
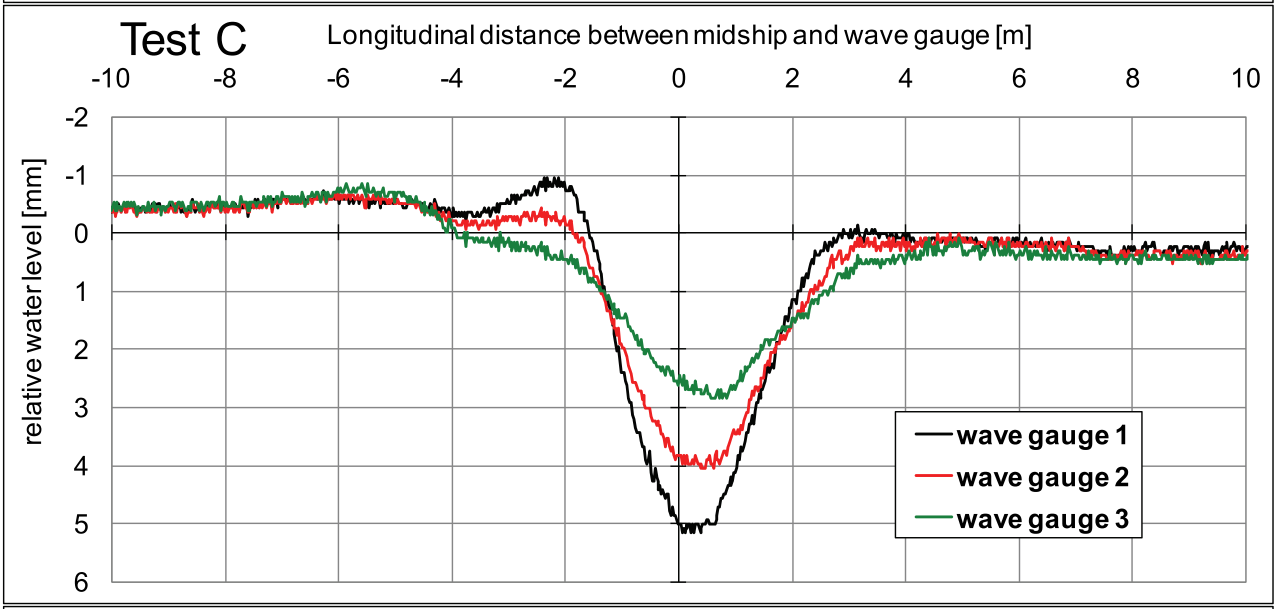
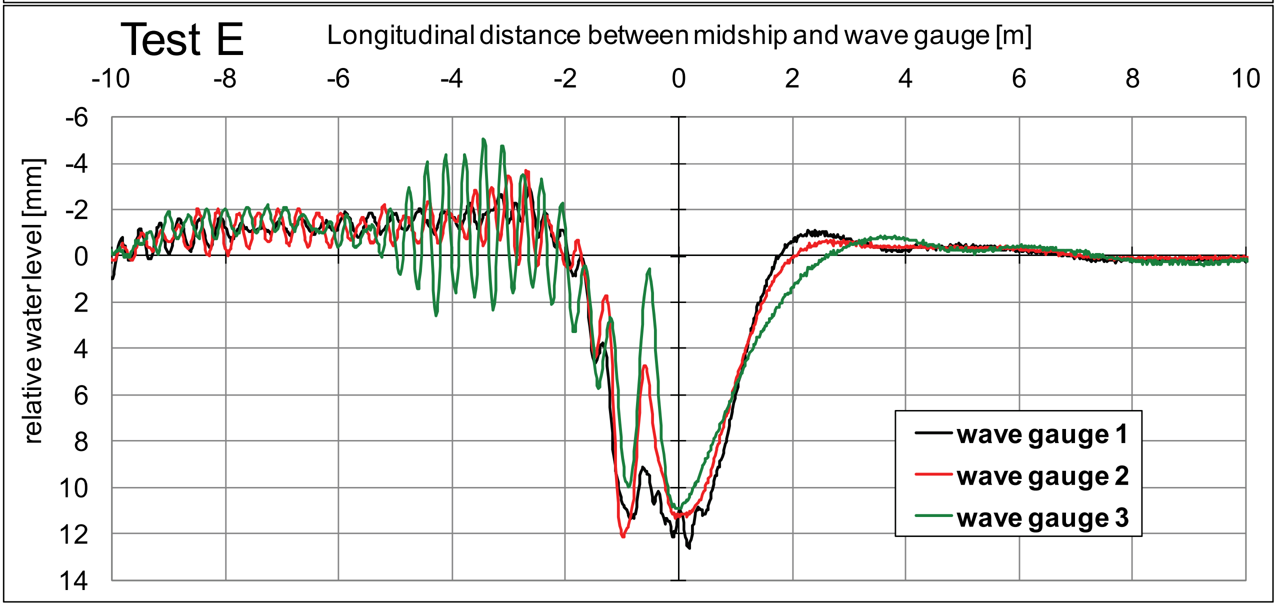
Appendix A:



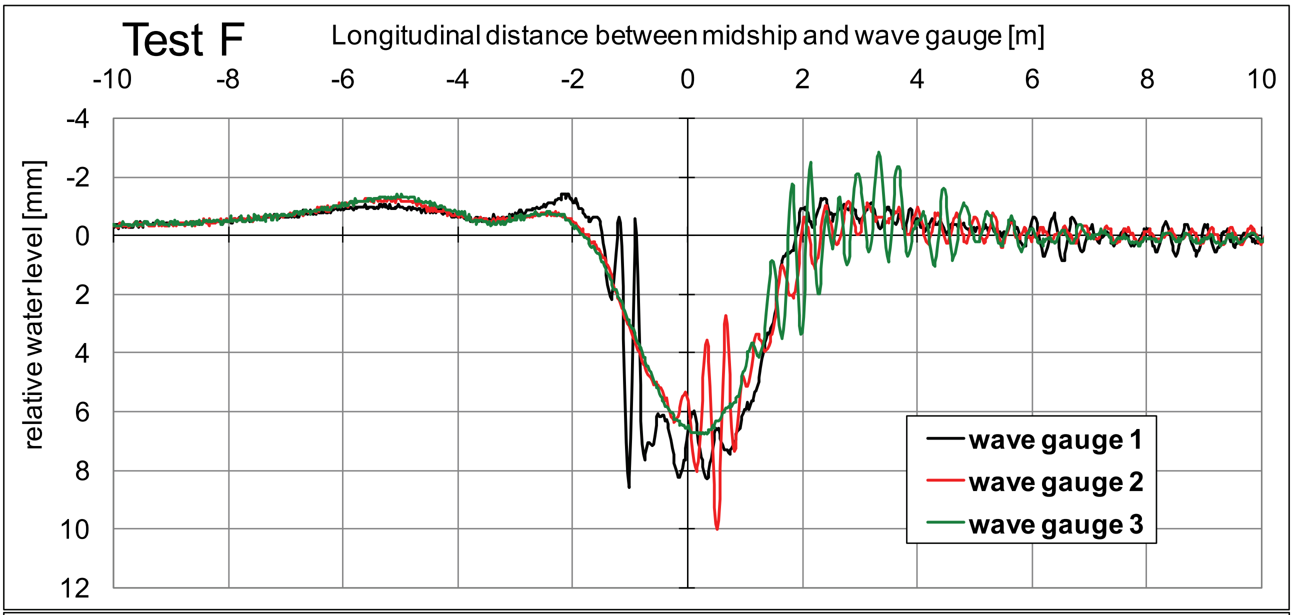
Test B
Longitudinal distance between midship and wave gauge [m]
relative water level [mm]
wave gauge 1
wave gauge 2
wave gauge 3

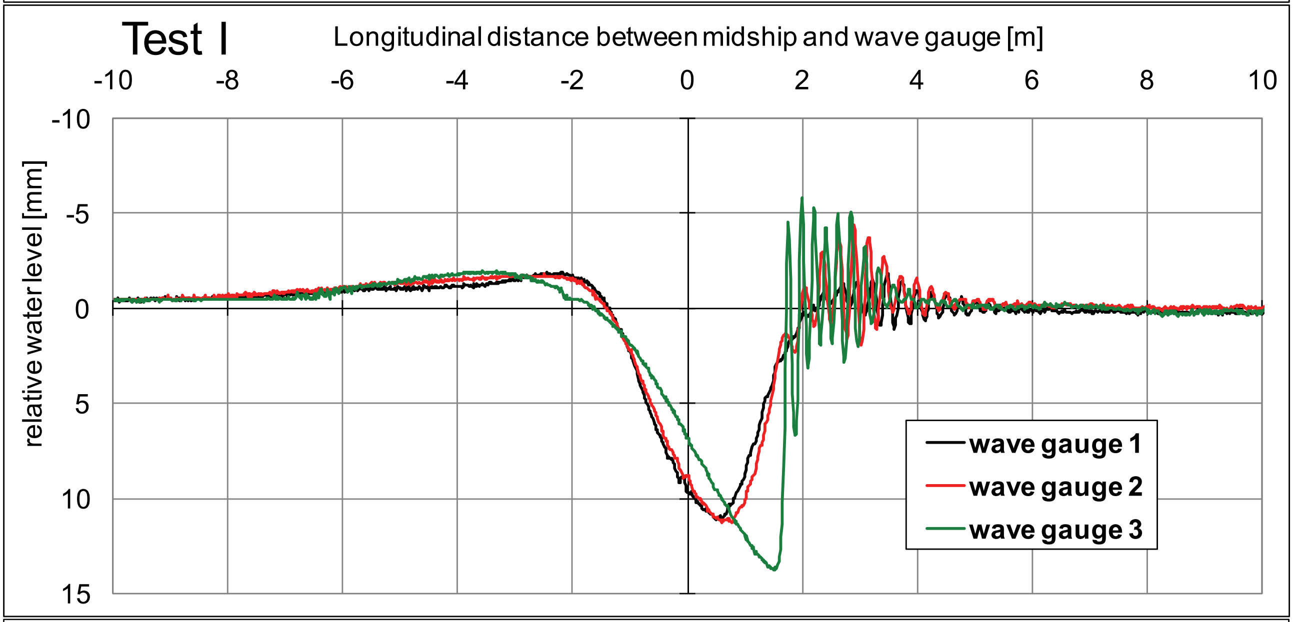


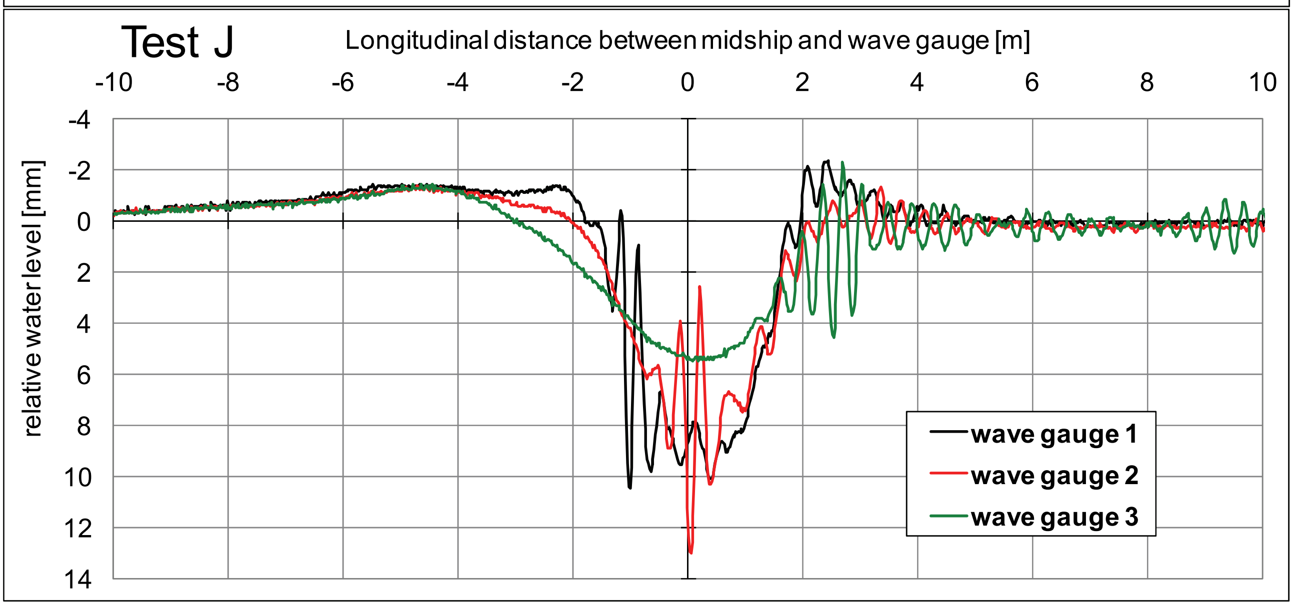
Test C
Longitudinal distance between midship and wave gauge [m]
relative water level [mm]
wave gauge 1
wave gauge 2
wave gauge 3



Test E
Longitudinal distance between midship and wave gauge [m]
relative water level [mm]
wave gauge 1
wave gauge 2
wave gauge 3







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