# Ship behaviour in Shallow and Confined Water:

# an Overview of Hydrodynamic Effects through EFD

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## *ABSTRACT*

*Due to the scale enlargement in the maritime fleet the accessibility of existing harbours worldwide is getting more and more complex. To reduce infrastructural and operational costs for the adaptation of these harbours the knowledge of ship behaviour in horizontally and vertically restricted channels and waterways helps in designing a cost effective access channel. Ship manoeuvrability is changing considerably if the vertical and lateral clearance is decreasing. To be able to estimate the hydrodynamic forces occurring in shallow and confined water Flanders Hydraulics Research, a laboratory of the Flemish Government, has invested in several experimental research programs with especially ship models of merchant vessels. The parametric investigation of hydrodynamic effects through experimental fluid dynamics is illustrated for ship manoeuvrability in shallow water, ship-bank interaction, ship-to-ship interaction and the concept of nautical bottom. These effects are applied in a support tool (Protoel) for the evaluation of the admittance policy to the Flemish harbours and are being translated to the even more challenging behaviour of inland vessels.*

## 1.0 SCALE ENLARGEMENT AND THE EFFECT ON SHIP BEHAVIOUR

### 1.1 Introduction

The maritime world has significantly changed during the last decades. While twenty years ago Ultra Large ships as ULCC took only a minor percentage of the total maritime fleet, ship sizes have been growing for all ship types. Even Ultra Large Container Ships of over 366 m of length and LNG carriers of 300 m and more are becoming common in ports around the world. Situated in the northern part of Belgium, the Flemish harbours belong to the European and worldwide maritime transport network. All of them, the more modest coastal harbour at Ostend, the ever growing port of Ghent along a restricted canal and the most important worldwide operating ports of Zeebrugge at the coastline and Antwerp at the Scheldt estuary, are continuously challenged by the increasing ship dimensions. An increased tonnage requires more efficient hinterland connections; therefore, the inland waterways are under investigation to make them accessible for the larger inland vessels of CEMT classes Va and Vb. Scale enlargement in existing waterways is thus not only restricted to the maritime fleet. Even estuary vessels are operating along the coastline to link the maritime and inland transport modes.

### 1.2 Shallow and confined water in the Belgian context

The access channels to the Flemish harbours are characterised by vertical and horizontal restrictions. The under keel clearances (UKC) as a percentage of the ship's draft are situated in the range of 50 to 10 percent for most fairways although in low speed access areas e.g. nearby or in the port of Antwerp and in the canal Ghent-Terneuzen even lower UKC values are under investigation or accepted. In the canal Ghent-Terneuzen the gross UKC may indeed not be lower than 1 m so that for a canal water depth of 13.5 m a maximum vessel's draft of 12.5 m is reached (Figure 1). This low UKC in an even horizontally restricted canal can only be achieved if the vessel's speed is limited to avoid bottom touch and unacceptable bank effects. To give an idea of the channel sections found in Flemish maritime access channels Figure 2 shows a section in the Bend of Bath. Although the Western Scheldt is open for two way traffic for the largest ships coming to the port of Antwerp due to the constrictions e.g. at the section shown in Figure 2 meeting of large ships is avoided at this section in real life. This section is also situated in a bend so that turning of a ship increases her swept path according to the imposed drift angle. A virtual passage of two 55 m beam vessels is drawn on Figure 2 where a water level of 5 m (high water) is supposed. The bank clearance of the inbound ship is 1.5 times the ship's beam while the passing distance between both ships is chosen in the same way. Figure 2 shows clearly that this virtual two-way configuration is even on a straight section characterised by important horizontal and vertical restrictions. On inland canals and rivers these horizontal restrictions are mostly even more extreme with channel sections as shown in Figure 3 for the Upper-Sea Scheldt.

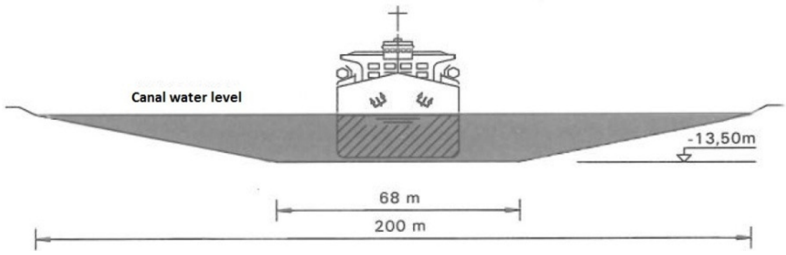



**Figure 1: Section on the Belgian territory of the Canal Ghent - Terneuzen**

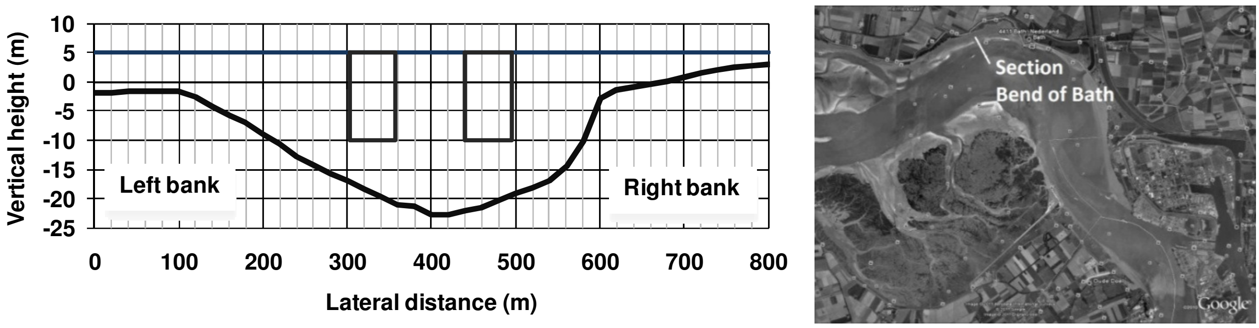



**Figure 2: Section on the Western Scheldt (Bend of Bath) and virtual passage of two ultra large ships with beam 55 m**

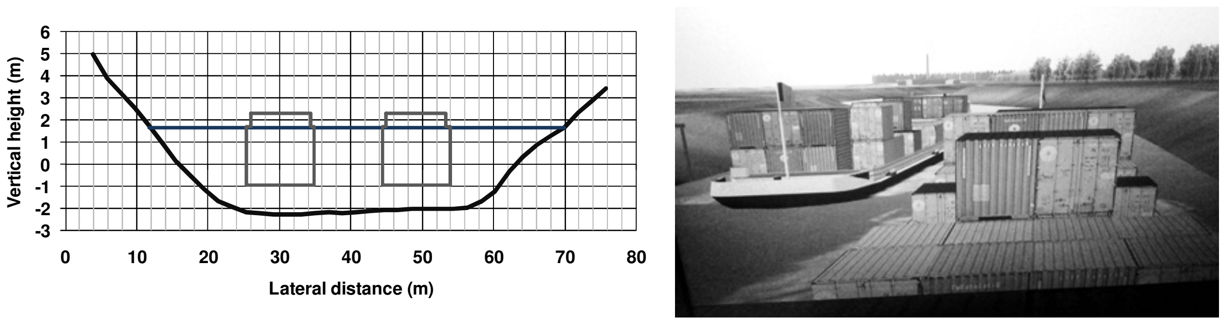



**Figure 3: Passage of two class IV inland vessels on a section of the Upper-Sea Scheldt (scheme and simulation)**

Due to the limited UKC values for deep-drafted ships, continuous bottom survey and maintenance dredging works are of great importance for the accessibility of the harbours, particularly in the Scheldt estuary and the Belgian coastal zone which, due to the important tidal range and corresponding currents, is sensitive to sedimentation and erosion. In some areas, sedimentation occurs as a deposit of fine bottom material causing a mud layer on the solid bottom. While the top of this mud layer may be fluid (‘black water’), the density and the rheologic properties (viscosity, yield stress) of the layer gradually increase with depth. Due to the low density (1.03-1.30 ton/m³) and, hence, the high water content of this layer, it is difficult and inefficient to remove the mud by dredging techniques, especially in a port as Zeebrugge where the layer may reach a thickness of 3 to 4 m in the zone between the breakwaters. In navigation areas subject to sedimentation, the nautical bottom concept has been introduced, so that the upper part of the mud layer is incorporated in the under keel clearance. As a result, the vertical clearance between a ship’s keel and the mud layer may become very small or even negative. It is clear that, although contact with the fluid mud layer does not cause any damage, ship behaviour is affected to a great extent by the presence of a fluid layer between the water column and the bottom.

To be able to examine ship hydrodynamics in these shallow and confined channels the Towing Tank for Manoeuvres in Shallow Water has been installed in Flanders Hydraulics Research (FHR) in 1992 and is since then operated in co-operation with the Maritime Technology Division of Ghent University (UGent). Among all methodologies Experimental Fluid Dynamics (EFD) based on model tests remain the main methodology for parameterisation of ship behaviour in shallow and confined water. Although the power of Computational Fluid Dynamics (CFD) in ship hydrodynamics issues is ever growing, the results of EFD will be essential during the following decades in validating and confirming the pros and cons of both experimental and numerical methods in complex hydrodynamic research.

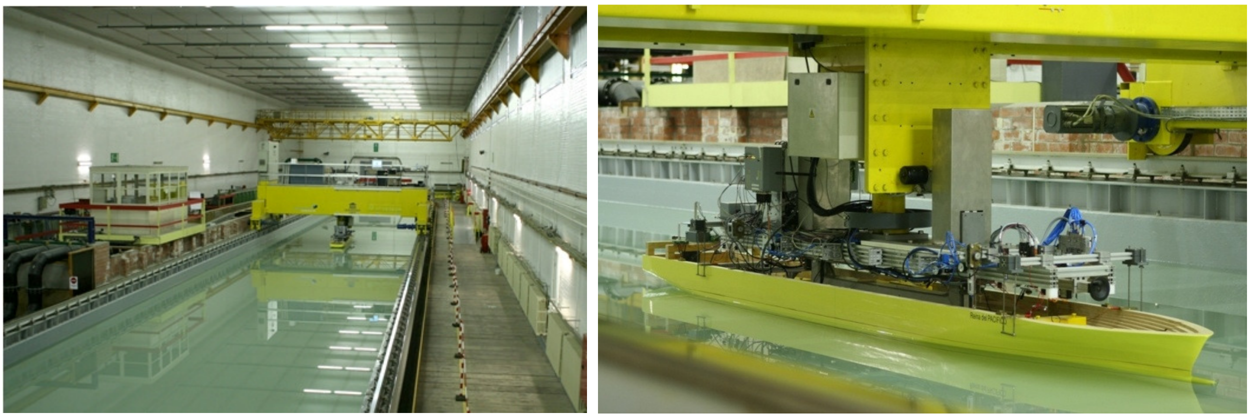


**Figure 4: Towing Tank for Manoeuvres in Shallow Water**

The keynote paper discusses hydrodynamic effects acting on a vessel in shallow and confined water resulting from thousands of model tests executed in the towing tank of FHR. These effects are also summarised on the website of the Knowledge Centre Manoeuvring in Shallow and Confined Water, www.shallowwater.be, established in May 2008 to consolidate, extend and disseminate knowledge on the behaviour of ships in shallow and confined water. An overview of the discussed topics is:

- ship manoeuvring in open and shallow water
- bank effects
- ship-to-ship interaction
- nautical bottom
- admittance policy
- inland navigation

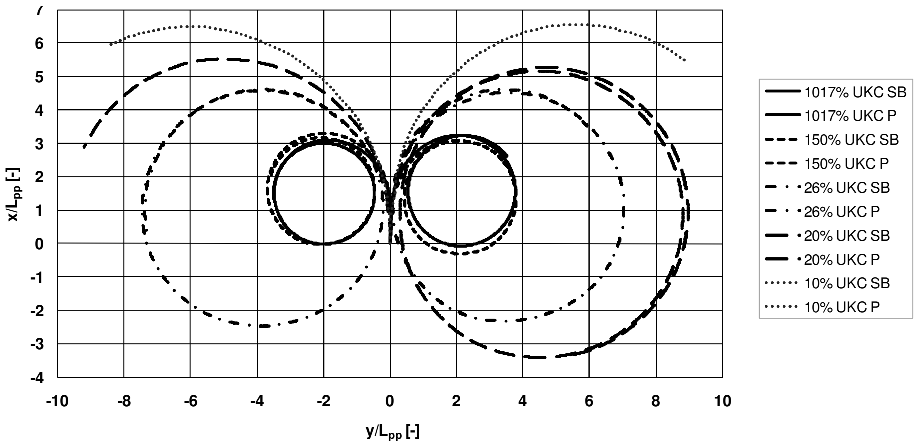
## 2.0 SHIP MANOEUVRING IN SHALLOW WATER

The prediction of ship manoeuvrability based on mathematical models started in the middle of last century at several institutes all over the world. At that time decades of research work had been carried out to understand the resistance and propulsive characteristics of existing and new building ships. Proceeding from this subject a need was growing not only to examine the straight ahead motion of a ship but especially to have tools to predict the manoeuvring performance. In a more recent past, going back to the1980s, the '*concept of modularity based on a separate representation of elements of the manoeuvring model*' [1] was fully recognised by Ankudinov and led to the development of modular mathematical models. The MMG model developed within the Mathematical Model Workgroup of the Manoeuvrability Subcommittee of the Japan Towing Tank Committee [2], is the most well-known and widespread modular model for ship manoeuvring. In Hamburg (HSVA) Oltmann and Sharma developed a mathematical model suitable for the digital simulation of combined engine and rudder manoeuvres for a wide range of surface ships and introduced the four-quadrant concept for the four operating modes of a manoeuvring vessel – forward motion, stopping, astern motion and stopping from astern motion [3]. Their work was inspired by the low speed manoeuvring models developed by Hydronautics Research Inc. [4]. For the prediction of ship manoeuvrability in especially shallow water the introduction of look-up tables by DMI in Denmark, now Force Technology, proved to be innovative and has been used by FHR and UGent for the development of a new type of mathematical manoeuvring models.

Since the installation of the towing tank at FHR in 1992 mathematical manoeuvring models have been developed for different ship types based on captive model tests (3 or 4 DOF). Vertical motions due to waves have also been examined but no 6 DOF model is still available as the behaviour of (large) sea-going ships in the access channels to the Flemish harbours are rarely influenced by waves and the focus of training and research still lies on ship manoeuvring in shallow and confined water.

The ship behaviour predicted by the manoeuvring models is validated using free-running model tests and full-scale measurements. Indeed, since 2009 a free-running device is added to the carriage at FHR so that standard manoeuvring tests, like acceleration, crash stops and zigzag tests, can be executed in a rather narrow towing tank. Nevertheless, to complete this information with model tests in a manoeuvring basin a project was ordered and fulfilled in the basin of the Bulgarian Ship Hydrodynamics Centre where two container ships, a car-carrier, a RoRo and a LNG-carrier were examined on their manoeuvrability using standard manoeuvring tests in deep and shallow water. The main reason for this extensive validation is the increasing influence of the chosen test parameters during captive model tests on the derived mathematical models when the under keel clearance is decreasing. This influence is extensively described in [5] where hydrodynamic coefficients of a full (the Esso Osaka) and a slender ship (an 6000 TEU container ship) are compared for different test types and varying test parameters. Additionally, it is expected that the influence of scale effects on the derived coefficients differ for deep and shallow water.

As an example standard manoeuvres derived from mathematical models based on captive model tests are compared to the same manoeuvres executed during free-running tests with a 1/75 scale model of a 6000 TEU container ship. In Figure 5 the free-running trajectories are shown together with the non-dimensional tactical diameter $T/L_{PP}$ from full scale simulation models in tabular form. While the full scale simulation models give larger tactical diameters for a turn to starboard, the free-running trajectories are opposite. Therefore, the tactical diameters for all UKCs are smaller for the free-running turning circles to starboard compared to the results from the mathematical models. For the turn to port the difference is opposite and quantitatively larger. Nevertheless, the increase of the tactical diameter with decreasing UKC is predicted by the simulation models with enough accuracy.




| UKC (%) | $T/L_{PP}$ SB | $T/L_{PP}$ P |
|---|---|---|
| 150 | | |
| 32 | 9.1 | 7.0 |
| 26 | 8.4 | 7.2 |
| 15 | 10.5 | 8.6 |
| 10 | 13.6 | 12.4 |

**Figure 5: Free-running turning circle model tests with a 6000 TEU container ship in deep and shallow water compared with the tactical diameter prediction (table) from captive model tests**

In Figure 6 an example is given of the influence of the test frequency and the test type on the added mass due to sway and on the velocity dependent yawing moment with drift angle relationship. The test frequency has a clear influence on the added mass derived from captive model tests if the UKC is 50% of the ship's draft or lower. For deep water this influence is negligible for the full form ship models E and A. The influence of the test frequency of PMM tests is also seen for the velocity dependent yawing moment but the difference between oblique towing and PMM tests is even larger. As lower absolute values are measured during PMM tests the destabilising yawing moment N'(β) could be underestimated based on harmonic PMM tests compared to oblique towing tests so that the simulation models in Figure 5 predict the manoeuvrability of a container ship that is more course stable than seen during free-running tests.

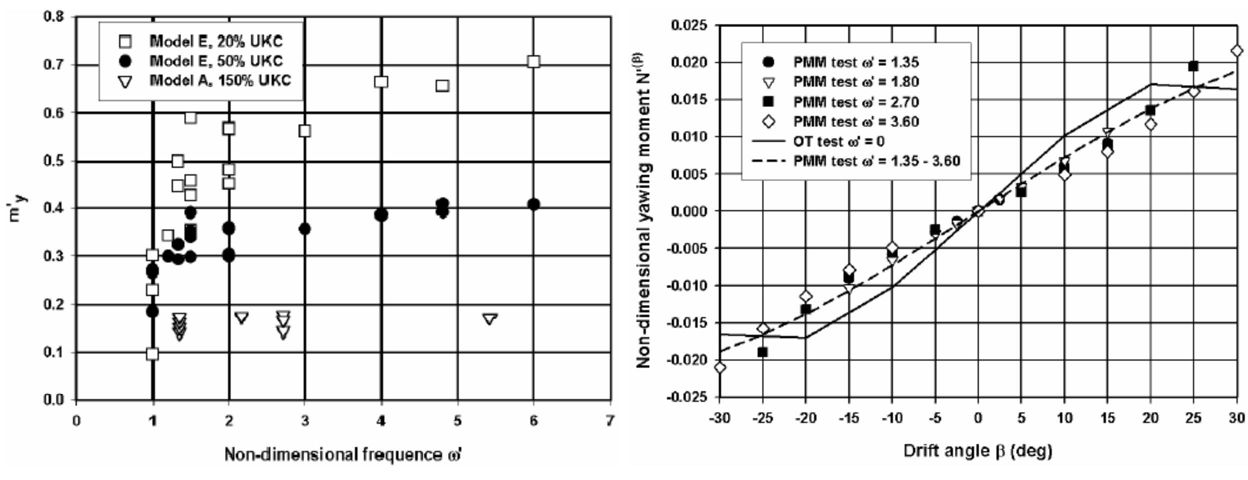



**Figure 6: Influence of test parameter (test frequency) and test type (PMM or Oblique Towing) on added mass due to sway $m'_y$ (for reference non-dimensional ship's mass is 0.27) and destabilising yawing moment $N'^{(\beta)}$ for full form ship models**

The SIMMAN workshop, established by the Manoeuvring Committee of the International Towing Tank Conference (ITTC) and first organised in 2008 [6], is linked to the difficulties reported in this paper concerning model test based predictions in deep and shallow water. The purpose of the workshop is to benchmark the prediction capabilities of different ship manoeuvring simulation methods including systems and CFD based methods. After focussing on deep water in 2008, a new workshop will be organised in 2013 for which FHR delivered among other institutes captive and free-running model test results with the benchmark ships KCS (container ship) and KVLCC2 (crude carrier) in shallow water.

# 3.0 SHIP BEHAVIOUR DUE TO BANK EFFECTS

Ships sailing in horizontally restricted channels like harbours, access channels to these harbours, the Panama and Suez canal, the North Sea and much more other navigation areas worldwide must be operated in such a way that pilots and captains have still enough ship manoeuvrability left to counteract the hydrodynamic effects due to banks mostly occurring during ships' passages. Many accidents occur when a ship has to move to one bank to clear the way for another meeting or overtaking ship. Other causes of this movement outside the channel's centreline can be wind or current. The asymmetrical flow around a vessel nearby a bank leads to pressure variations between the starboard and port sides resulting into a lateral force mostly directed towards the closest bank and a bow-away moment. The ship's resistance and squat (sinkage and trim) are increased.

In the nineteen seventies with the arrival of very large crude carriers in the maritime fleet Norrbin [7] executed captive force measurements and free-response trajectory tests with a tanker model along different banks with the aim to develop analytical models for the lateral force and yawing moment induced by banks. In [8] Norrbin stated that if the channel banks are not vertical walls but sloping beaches the definition of the bank distance parameter is less obvious. Which vertical reference height has to be taken for the ship (distance at keel line, waterline or halved draft, distance from ship's centreline to the toe of the bank) to measure the distances between ship and banks? Can a clear relationship be found between an effective bank distance parameter and the induced forces and moment? The analytical models of Norrbin, only based on one ship model, are often used in ship manoeuvring simulation thanks to their straight-forward formulations and the easy determination of the bank distance parameter. Ch'ng, Doctors and Renilson [9] extended and improved Norrbin's research based on model tests with different ship types and developed generalised mathematical models with ship geometry parameters included.

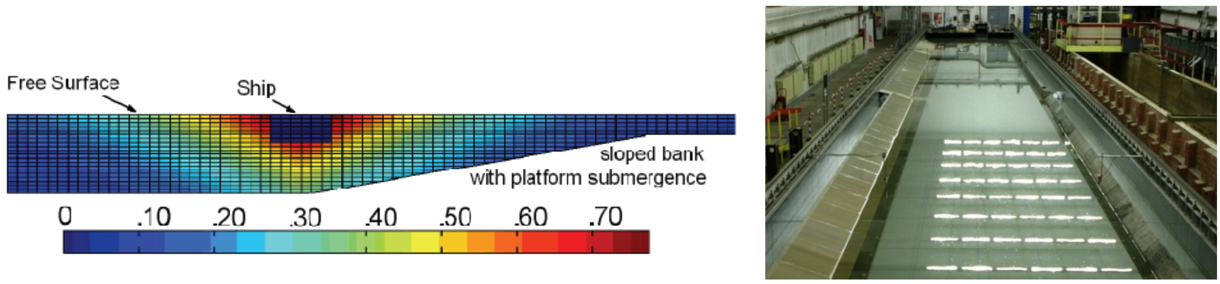



Figure 7: Graphical presentation of weight distribution (left) and four bank types in the towing tank (vertical wall, slope 1/1, 1/3 and 1/4)

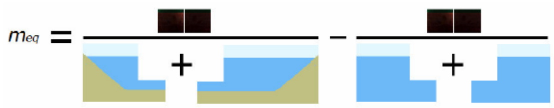
Extensive research at FHR and UGent has nevertheless shown that formulations based on bank distance parameters using discrete points have shortcomings for a real channel bank. Since 2004 FHR and UGent have been testing seven different ship types (two container ships, LNG carrier, KVLCC2, Wigley hull, RoRo and class Va inland vessel) along submerged and surface-piercing banks with varying slopes and water depths. Bank clearances, ship speeds (with and without drift) and propeller rates have been varied as well. This investigation has shown that an effective bank distance parameter at a discrete point of a real channel section as developed by Norrbin cannot fully describe the bank effects induced by the entire channel geometry. To take into account the modified water surface (definition of an effective water depth $h_{eff}$ – mean water depth less maximum sinkage - and an effective $UKC_{eff}$) and water flow around the ship in a real channel a new distance to bank parameter $d_{2b}$ and an equivalent blockage parameter $m_{eq}$ were defined in [10]. In Figure 7 a graphical presentation is given of the weight distribution (with a weight factor between 0 and 1) which indicates the influence of a water particle on the manoeuvrability of a ship.

The weight distribution in the ship bound coordinate system is defined analogous to Norrbin's factor [7]:

$$e^{-a|y|-b|z|}$$

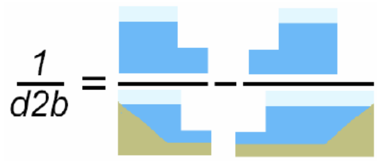
The equivalent blockage $m_{eq}$ is analogous to the 'classic' blockage - the ratio of the cross sectional areas $\chi$ of the ship and the fairway – but it takes into account the weight distribution as:

$$m_{eq} = \frac{\chi_{ship}}{\chi_{port} + \chi_{starboard}} - \frac{\chi_{ship}}{\chi_{ocean} - \chi_{ship}}$$




An new bank distance parameter is then defined as the 'distance to bank' or d2b:

$$\frac{1}{d2b} = \frac{1}{2}(\chi_{ocean} - \chi_{ship})\left(\frac{1}{\chi_{port}} - \frac{1}{\chi_{starboard}}\right)$$




In Figure 8 a comparison is made between the lateral force induced by bank effects related to two different bank distance parameters, $y_{B3}$ and $1/d_{2b}$. The parameter $y_{B3}$ is defined by Ch'ng in [9] as the ship-bank distance measured at half draft:

$$y_{B3} = \frac{B}{2}\left(\frac{1}{y_{port3}} + \frac{1}{y_{stb3}}\right)$$

with $y_{port3}$ the distance from the ship's centreline to the bank at port side and $y_{stb3}$ the distance from the ship's centreline to the bank at starboard side, both distances measured at half draft.

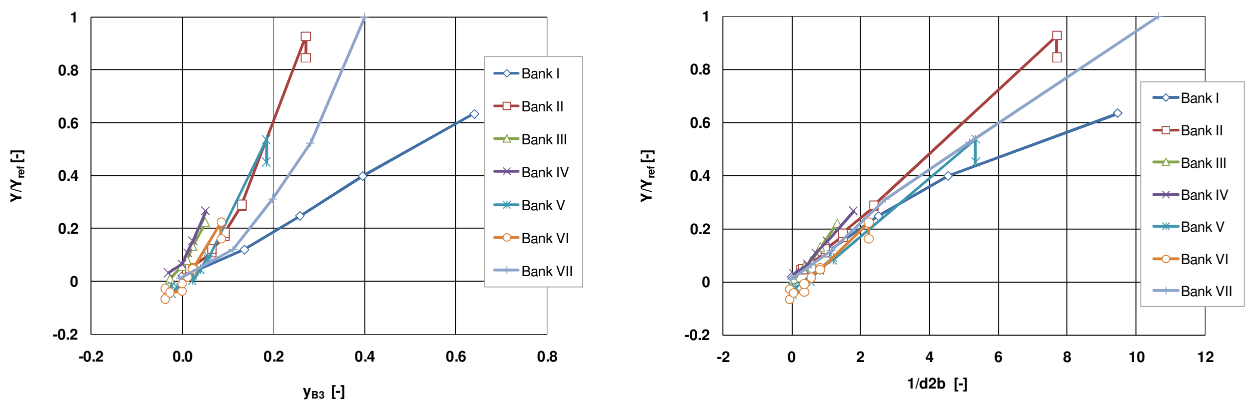



Figure 8: Comparison of the relationship of two different bank distance parameters with non-dimensional lateral force for a container carrier at 10 knots, 100% UKC (no propeller)

The measured lateral forces for an 8000 TEU container ship model passing different bank types at different clearances and 10 knots full scale speed show a better relationship based on $1/d_{2b}$ than on the bank distance parameter $y_{B3}$. In Figure 9 the lateral forces due to bank effects as function of $1/d_{2b}$ are shown for the KVLCC2 at a draft of 20.8 m full scale, 50% UKC and sailing at a full scale speed of 10 knots alongside four types of bank – bank XI with slope 1/1, bank XII a vertical wall, bank XIII with slope

1/3 and bank XIV with slope 1/4. For higher $1/d_{2b}$ values the expected linear relationship between force and bank distance parameter is hard to be found and an optimisation of this parameter for extreme situations where the ship is sailing very close to or above the bank, could still be proposed.

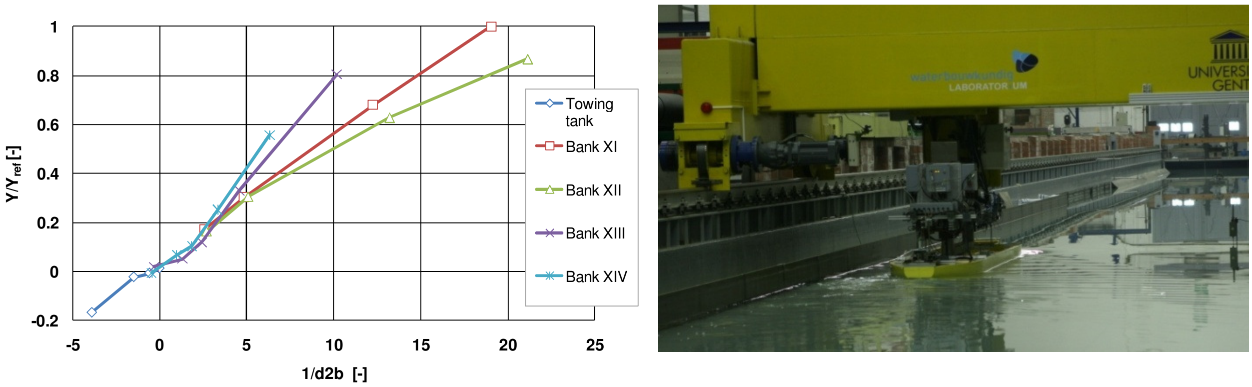
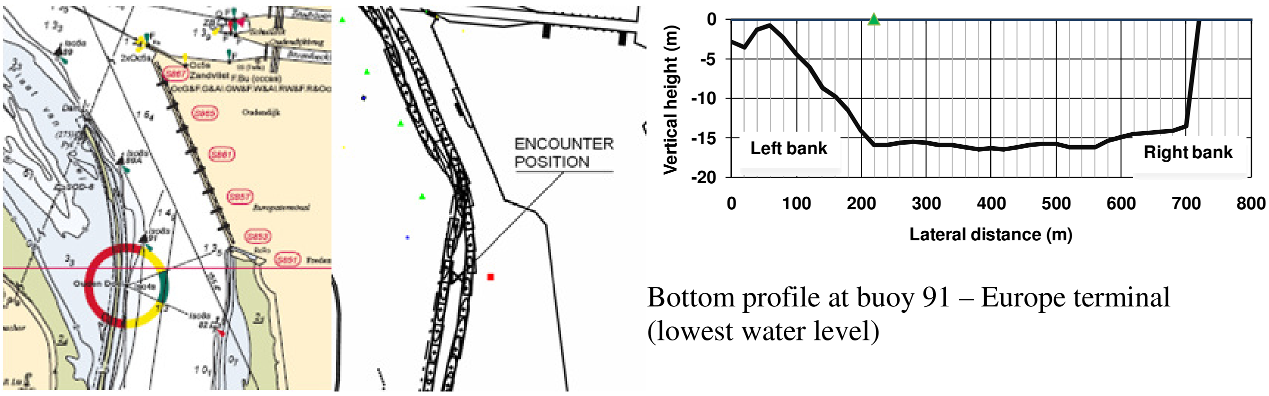



**Figure 9: Relationship between 1/d2b and non-dimensional lateral force for KVLCC2 at 10 knots, 50% UKC (no propeller)**

The mathematical models developed based on the test results with the 8000 TEU container ship model have been extensively used in an accessibility simulation study for ultra large container ships sailing to the port of Antwerp. The ship length and draft were varied between 350 and 400 m, respectively 42.8 and 56.4 m, and meetings were simulated at the smallest river sections of the Western Scheldt (Bend of Bath to Deurganck dock). In Figure 10 the passage of the inbound sailing ship nearby buoy 91 is disturbed by the bank effect that counteracts the ship's turn to starboard. Based on the results of these simulations meetings in the vicinity of buoy 91 are discouraged by the pilots and can only happen at least two ship lengths further southwards.




Bottom profile at buoy 91 – Europe terminal (lowest water level)

**Figure 10: Bank effect during a simulated encounter at the river Scheldt**

## 4.0 SHIP BEHAVIOUR DURING SHIP-TO-SHIP INTERACTION

Dense traffic situations, cargo transfer and ship's operations in harbours are characterised by frequent ship-to-ship interactions. In May 2011 the Knowledge Centre organised together with MARINTEK, NTNU and RINA a conference with main topic ship-to-ship interaction [11]. Based on the summary in these proceedings it is clear that interaction scenarios are much wider than meeting and overtaking manoeuvres and may involve several of the following:

- moored ships alongside quays;
- ships anchored or moored to buoys;
- ships meeting / passing on parallel / oblique / curved / steered paths;
- interaction with more than one ship or marine structure;
- ship-to-ship interaction during lightering operations;
- ship-to-ship interaction during tug assistance.

These topics are worldwide examined using different modelling techniques as theoretical calculations, potential flow or more in general numerical codes, EFD and CFD. Due to the increased hydrodynamic effect in vertically and horizontally restricted water FHR and UGent has chosen for three different systematic test programs executed in the towing tank since 2000 (Figure 11). These programs have led to an enormous amount of parameter variations per research topic:

- *encountering and overtaking manoeuvres [12]*: during these captive model tests with one ship attached to the main carriage and the other to an auxiliary beam along the tank wall, four ship models with model characteristics as shown in Table 1 have been tested on parallel courses during three interaction modes: encountering, overtaking and overtaken. Ship C is a bulk carrier, ship E and H are tankers and ship D a container ship. Ship C, D and E have approximately same lengths but varying breadth while the dimensions of model H are overall smaller. The reference draft $T_{ref}$ is used in the mathematical models described in [12] but more drafts are examined to investigate the influence of the loading condition. All tests were executed at the model self propulsion point. The clearance between both ship models during the tests varied between 0.25 and 2 times the smallest of both ship beams. The ships' speeds varied from 0 to 0.95 m/s on model scale or 0 to 15 knots at full scale so that even the interaction with moored ships (zero speed) were examined. The under keel clearance was varied between 10 and 70% of the draft.

| Ship | | C | D | E | H |
|---|---|---|---|---|---|
| $L_{pp}$ | m | 3.984 | 3.864 | 3.824 | 2.210 |
| B | m | 0.504 | 0.550 | 0.624 | 0.296 |
| $T_{ref}$ | m | 0.180 | 0.180 | 0.207 | 0.178 |
| $C_B$ (at $T_{ref}$) | - | 0.843 | 0.588 | 0.816 | 0.830 |
| T | m | 0.155 – 0.200 | 0.155 – 0.200 | 0.136 – 0.256 | 0.125 – 0.178 |

**Table 1: Ship model characteristics**

- *lightering operation between the KVLCC2 (STBL or ship to be lightered) and an Aframax tanker (SS or service ship) [13]*: this test program is executed at FHR in the framework of Work package 3 of the project "KMB Investigating hydrodynamic aspect and control systems for ship-to-ship operations". This project is co-ordinated by MARINTEK (Trondheim, Norway) and financially supported by the Research Council of Norway. The Aframax tanker was connected to the Planar motion mechanism of the carriage while the KVLCC2 was connected through a secondary beam added to the main carriage of the towing tank to be able to perform ship-to-ship interaction tests for ships with a zero longitudinal speed difference. These tests can be considered as a special case of the tests described in [12] as overtaking and overtaken manoeuvres are coming together.

  The test parameters of the steady state tests have been modified as shown in Table 2. Dynamic tests (harmonic sway, yaw and rudder angle tests) have been executed as well. Open STS data have been published in [14].

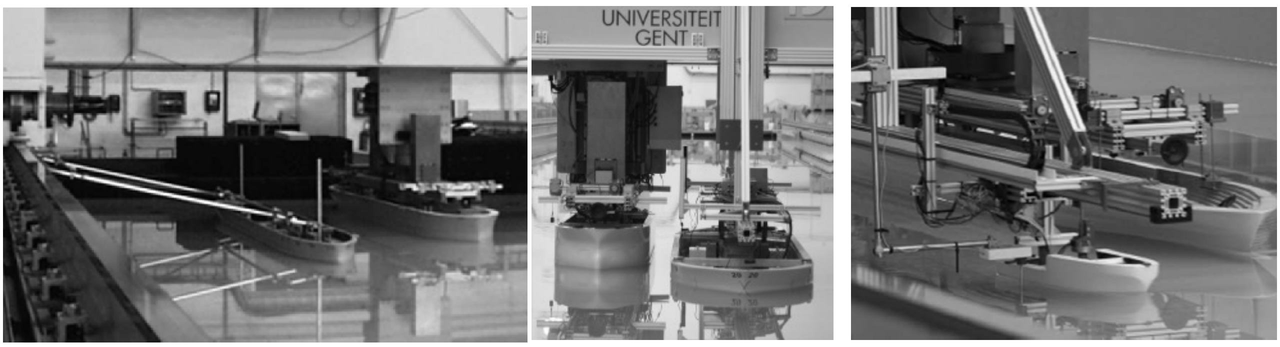
| h | $T_{STBL}$ | $n_{STBL}$ | V | $T_{SS}$ | $\psi_{SS}$ | $n_{SS}$ | δy | δx |
|---|---|---|---|---|---|---|---|---|
| [m] | [m] | [-] | [kts] | [m] | [deg] | [-] | [m] | [m] |
| $h_{max}$ | 20.8 | selfprop | 2.0 | 7.5 | 180 | Slow | 4 | 0 |
| 1.35 $T_{STBL}$ | 12.8 | | 4.0 | 15 | 179 | Half | 10 | L/2 |
| | | | 5.0 | | 178 | selfprop | 25 | -L/2 |
| | | | 6.0 | | 177 | | 50 | |
| | | | | | 175 | | 100 | |

**Table 2: Test matrix of steady state lightering tests (full scale)**

- *interaction between a tug and a container ship [15]:* in consequence of an accident with an Azimuth Stern Drive tug operating at the bow of a container ship the Towage and Salvage Union (URS) in Antwerp ordered a model test program that as a Master thesis project of Delft University of Technology helped in increasing the knowledge of the hydrodynamic interaction effects acting on a tug in the vicinity of another ship to be assisted. A comparable test set-up was used for tug and container ship as for the lightering tests. The container ship attached at the PMM carriage and the tug at an auxiliary frame of the main carriage maintained in this set-up the same speed during the whole test. Different speeds, longitudinal and lateral separation distances and drift angles are examined according to Table 3.

| | |
|---|---|
| Forward speed [knots], full scale | 5, 6, 7, 8, 9 |
| Longitudinal separation $x'_{rel}$ [-], from amidships of container vessel to centre of gravity of tug (non-dimensional value based on length of tug) | 0.73, 1.25, 1.77, 2.29, 2.82, 3.33, 3.88, 4.41, 4.93 |
| Transverse separation $y'_{rel}$ [-], from centreline to centreline (non-dimensional value based on breadth of tug) | 2.6, 3.3, 4.0, 4.4, 5.3 |
| Drift angle [°], negative angle bow-in since tug model is situated on starboard in the towing tank | -10, -5, 0, 5, 10 |

**Table 3: Test matrix for tug-container vessel interaction**




Overtaking and encountering [12] Lightering [14] Tug-ship interaction [15]

**Figure 11: Three model test programs for ship-to-ship interaction executed at FHR**

These three test programs have led to different mathematical models predicting the forces and moment in the horizontal plane and the modified squat due to interaction. A unified model for all these test cases and thus all interactions in real life is hard to be found. The hydrodynamic change in pressure field around the ship hulls is so diverse that dedicated interaction models will still remain and will be used for specific simulation purposes.

The mathematical prediction models developed in [12] have been used for the evaluation of the accessibility of ultra large container ships to the port of Antwerp, as reported in chapter 3.0 too. Although no tests between two interacting container ships have been executed, thanks to the generalization of the models based on a displacement ratio parameter, the resulting hydrodynamic effects based on these models were validated positively by pilots. Remarks still remain if the ship length ratio differs considerably from 1 which means that the passing ships have totally different ship lengths and for low UKC. For the latter remark subjective validation by pilots for avoidable situations in real life must be interpreted appropriately.

Many authors have developed prediction models or estimate the time-dependent forces and modified squat based on numerical codes or CFD as is also illustrated in [11]. Collaboration in SIMMAN's vein with different methodical combinations will help in understanding the complex water flows around interacting vessels. In 2011 a JIP, called ROPES, has started under the leadership of Maritime Research Institute Netherlands (MARIN), with the aim to develop a computer tool to predict the effects of passing ships on moored ships. FHR will execute model tests in the framework of this project.

## 5.0 NAUTICAL BOTTOM CONCEPT

Due to the presence of fluid mud layers on the bottom of navigation areas, the nautical bottom concept is introduced in several harbours and access channels. PIANC [16] defined the term *nautical bottom as the level where physical characteristics of the bottom reach a critical limit beyond which contact with a ship's keel causes either damage or unacceptable effects on controllability and manoeuvrability*. The application range of this definition is quite general, and is not limited to muddy bottoms. In case of a hard (e.g. rocky) bottom, contact with the bottom level will cause damage, while contact with a muddy bottom will rather result into an unacceptable ship behaviour.

Although navigation above/through muddy bottoms has been common practice in several harbours worldwide for many years, the concept of nautical bottom was introduced in the 1970s and 80s for deep-drafted vessels in a number of harbours in the Netherlands (Rotterdam), France, Germany and Belgium (Zeebrugge). The practical application of the definition in muddy areas requires a multidisciplinary approach, involving measuring/survey techniques, dredging techniques, understanding of the physical mud characteristics and – as mentioned explicitly in the definition – knowledge on the effects of the presence of mud layers on the behaviour of a ship. The role of EFD in this respect could be questioned: while even in pure water, viscous effects cannot be assessed correctly by tests with ship models due to the impossibility of fulfilling Reynolds' Law, scale model tests with ships navigating above or through a muddy bottom are even more challenging. Furthermore, it is impossible to create a test environment in which a mud layer with depth dependent density and rheology is simulated at reduced scale. Model tests are therefore only feasible in a simplified model of the navigation environment, in which the mud layer is represented by a homogeneous layer with constant density and rheological properties, using a fluid that is preferably immiscible with water to be able to perform systematic test series. In spite of these simplifications, towing tank tests have contributed considerably to the knowledge on the hydrodynamics of ships in muddy areas. Only in a limited number of research institutes such model tests have been carried out: MARIN [17], Sogreah [18], Flanders Hydraulics Research [19], [20] and BAW Hamburg [21].

The model test series in the shallow water towing tank at FHR (Figure 12) can be considered as the most comprehensive test program. A complete mathematical model for manoeuvring simulation has been developed for a container carrier navigating above and through simulated mud layers, with systematic variation on layer thickness, mud density, mud viscosity and under keel clearance; in total 78 parameter combinations were tested. All these models were implemented into the Zeebrugge harbour layout at the full mission bridge simulator at FHR, which allowed the coastal pilots to evaluate which situations could be considered as feasible and in which situations the manoeuvre would be unacceptable from the point of safety, duration, tug assistance, etc. Besides a qualitative judgment of the experienced group of pilots, the tracks were analysed and the runs were evaluated based on several criteria: controllability of the ship controlled by own means (minimum speed, course keeping) and required tug assistance.

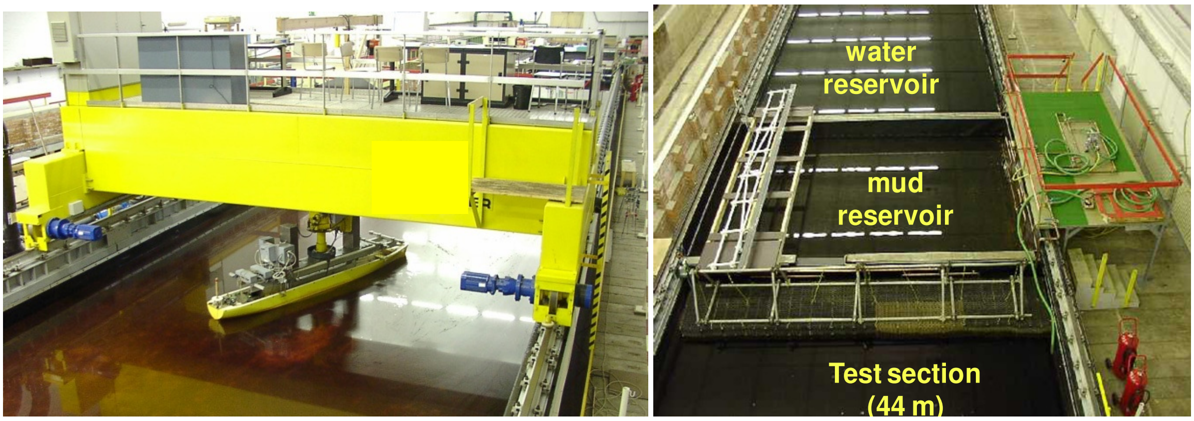



**Figure 12: Towing tank for manoeuvres in shallow water: captive model test setup with mud bottoms simulated by a chlorinated paraffins – petrol mixture, requiring environmental measures**

As a result of the project, it was decided to modify the local criterion to determine the nautical bottom from a density level of 1.15 t/m³ to 1.20 t/m³. It was also accepted that deep-drafted container vessels could safely navigate through fluid mud layers, provided that sufficient tug assistance is available: for a container carrier of 300 m of length, a penetration of 7% of the draft is acceptable if the ship is assisted by two tugs of 45 ton bollard pull each. It is clear that these results depend very much on the local situation and the manoeuvres that have to be carried out.

According to the pilots, the behaviour of the virtual ship during simulations was sufficiently realistic for assessing the real manoeuvres, in spite of the fact that the mathematical models are based on model tests in a simplified environment with unrealistic scaling of viscous effects. This can be explained by considering the two main causes of the effects of the presence of mud layers on ship manoeuvrability. Firstly, the pressure field generated by a moving vessel causes a wave pattern in the water–mud interface, which affects the flow around the ship, even if no contact occurs with the mud layer. This internal wave pattern depends greatly on mud density. Secondly, the rheology of mud and water may be very different. Besides non-Newtonian, mud is also thixotropic, which implies that the deformation due to shear stress depends on the history of the material. Rheology mainly affects the ship’s behaviour in case of contact with the mud layer. If the mud layers considered have low rheological characteristics and can be considered as a Newtonian fluid, the first effect, ruled by Froude Law, is dominant and can be realistically simulated by model tests. However, in situations where the ship’s keel touches more viscous, non-Newtonian fluids, especially if the fluid characteristics show vertical variations, EFD is not the most appropriate means of investigating ship-mud interaction.

Presently the research at FHR on this topic focuses on determining a more suitable parameter for measuring the nautical bottom. As indicated above, in Zeebrugge – as in most other waterways where the nautical bottom concept is applied – the survey makes use of a critical density value, although density is not the most appropriate parameter to assess the “fluidity” of a mud layer. Density has been selected mainly because reliable and efficient in situ survey techniques have been developed, while this is not the case yet for mud rheology. On the other hand, the contact forces between a ship's keel and a mud layer will be dominated by mud rheology, so that – again referring to the PIANC definition – a suitable parameter for the nautical bottom should be linked to a (combination of) rheological characteristics. Two main aspects are involved: how does a ship 'feel' the mud, i.e. which relationship exists between mud characteristics and forces exerted on the ship, and, secondly, how can relevant characteristics be measured in situ, following a reliable and generally accepted protocol? Therefore, a Sediment Test Tank (STT, Figure 13) has been constructed at FHR and filled with Zeebrugge mud to execute controlled comparison measurements to evaluate available rheology based survey instruments in a mud layer with vertical rheological variations. To give an answer to the first question, a research project is in preparation involving CFD techniques to get more insight into mud-ship interaction, supported by validation tests in the STT.

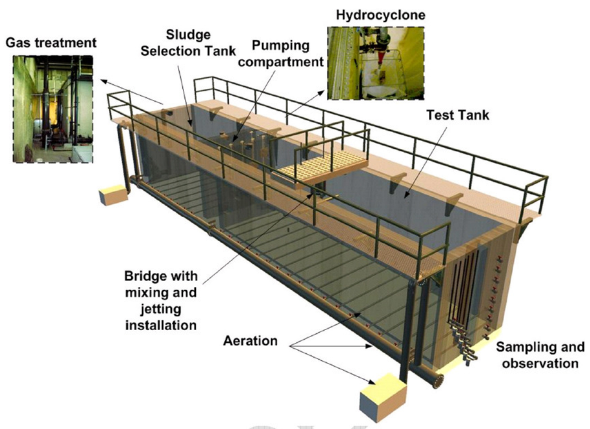



**Figure 13: Sediment Test Tank at Flanders Hydraulics Research**

## 6.0 ADMITTANCE POLICY FOR THE MARITIME FLEET

Access channels to harbours are often subject to tide, so that arrival and departure of ships may be limited to a certain window. This window is mainly determined by the variations of the water level and is therefore of particular importance for deep-drafted vessels, but also other parameters such as lateral and longitudinal current components, or penetration of the keel into soft mud layers may be limiting factors.

At present, the determination of tidal windows is based on a minimum value for the gross under keel clearance, expressed as a percentage of the ship's draft. This minimum value depends on the channel, taking account of the wave climate and the ships' speed range (Figure 14):

- 15.0% for the coastal channels Scheur West, Scheur East and Wielingen;
- 12.5% for Pas van het Zand and Western Scheldt (Dutch part);
- 10.0% for the Scheldt river on Belgian territory and for the Zeebrugge outer harbour area, i.e. within the breakwaters;
- 1.0 m for the Sea Canal from Terneuzen to Ghent.

In addition, ships do not enter the harbour of Zeebrugge if the cross current in the approach channel exceeds 2 knots (1.5 knots for arriving LNG-carriers), or if the keel penetrates more than 7% of the draft into the fluid mud.

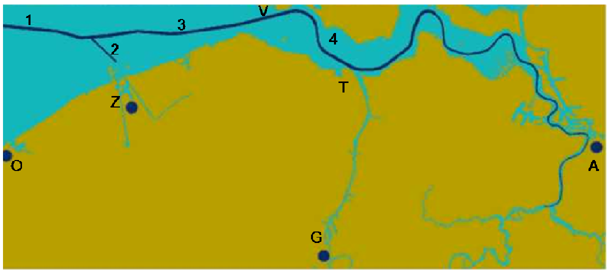



**Figure 14. (left) Access channels: 1: Scheur West, 2: Pas van het Zand, 3: Scheur East, 4: West Scheldt. Harbours: A: Antwerp/Antwerpen (B), G: Ghent/Gent (B), O: Ostend /Oostende (B), T: Terneuzen (NL), V: Flushing/Vlissingen (NL), Z: Zeebrugge (B) (www.maritiemetoegang.be); (right). Wave response test on a model of an ultra large container carrier at FHR**

The present access policy accounts for water level fluctuations due to tidal action and for the ship's draft, but does not make any distinction regarding other ship characteristics, weather conditions or wave climate. In order to optimize the access policy, a decision supporting tool named ProToel for determining tidal windows for deep-drafted vessels arriving at or departing from the Belgian harbours, based on both deterministic and probabilistic criteria, has been developed, [22], [23]. In a deterministic mode, the gross under keel clearance (UKC), relative to both the nautical bottom and the top of fluid mud layers, and the magnitude of current components are taken into account. In case probabilistic considerations are accounted for, a positive advise will only be given if the probability of bottom touch during the voyage – due to squat and response to waves – does not exceed a selected maximum value. The following input data are taken into consideration: ship characteristics, waterway characteristics, trajectory, nautical bottom level, top mud level, speed over ground and through the water, tidal elevation, directional wave spectra, current, departure time.

ProToel can either be used for supporting short term decisions for a particular ship, or for long term estimations for the maximum allowable draft. ProToel is presently in an evaluation phase for supporting decisions taken by the Flemish Pilotage and Shipping Assistance in a short term approach for ships arriving at and departing from the harbour of Zeebrugge. For the harbour of Antwerp, to be reached by sea channels and the river Scheldt, the program can also be used as an approach policy supporting tool for long term considerations; extensions to support short term decisions are considered.

Based on a specified route and departure time, the ProToel program calculates the UKCs and bottom touch probabilities for a specific ship following the route with a chosen speed along the trajectory. The route is split into several intervals. In each interval, the UKCs are calculated based on bottom depth, up-to-date current and tide data and the speed dependent squat. The bottom touch probability is calculated from the directional wave spectrum for that time, location and the motion characteristics of the ship. A typical output is shown in Figure 15.

ProToel requires the availability of a number of databases:

- a ship database with dynamic response characteristics and squat data for a large range of ship dimensions and types, valid for a realistic range of forward speeds, drafts and water depths;
- a database of trajectories and trajectory points, containing recent soundings of the (nautical) bottom and, where applicable, the mud-water interface;

- forecasts or measurements of hydro-meteorological data for a number of locations as a function of time: tidal elevation, current speed and direction, directional wave spectra, water density.

The last two types of databases requires a close co-operation with the Flemish Hydrography (Agency for Maritime and Coastal Services of the Flemish Government), which co-ordinates the surveys of the access channels, and runs the Oceanographic Meteorological Station (OMS), a hydro/meteo forecast centre located in Ostend, and the monitoring network 'Flemish Banks' in the Belgian part on the North Sea and along the coast. The ship data bank consists of squat and dynamic response data on a large number of slender and full hull forms. The content of this data bank is based on seakeeping tests carried out with five ship models in the towing tank at FHR and additional numerical calculations. The database covers a large number of draft – water depth combinations, and also contains data for a variation of metacentric heights. Although 2D (strip theories) and 3D boundary element methods are in general quite reliable for calculating linear ship motions due to waves, it was preferred to verify the results experimentally. As a matter of fact, the required accuracy is relatively high taking account of the rather limited under keel clearance. While most applications in full sea focuse on wave lengths which are about equal to the ship length, this application concentrates on rather short wave lengths, in combination with limited depth to draft ratios.

Squat data are also based on tank tests, and can be directly obtained from the data base by interpolation; for container vessels, the sinkage fore and aft can also be calculated by means of model test based empiric formulae that also take account of the lateral channel dimensions [24]. The validation of modelled squat values are under investigation by full scale measurements with a GPS based equipment (see chapter 7) during voyages of large (container) ships to the Flemish harbours.

**ship hull:** W100 **trajectory:** KWB_-_Z-All_K120_(S1)
**maximal draft [m]:** 15.5 **date of departure:** 01/08/2008 CET
**GM [m]:** 0.0 **waves considered:** true

| location | | limit | 8:15 CET | 8:30 CET |
|---|---|---|---|---|
| Kwintebank | location reached at [CET] | | 08:24 | 08:39 |
| | tide in Zeebrugge [m LAT] | | 0.70 | 0.70 |
| PvhZ-SZ | location reached at [CET] | | 09:40 | 09:55 |
| | tide in Bol van Heist [m LAT] | | 1.29 | 1.44 |
| PvhZ-Strekdammen | location reached at [CET] | | 09:55 | 10:10 |
| | tide in Zeebrugge [m LAT] | | 1.37 | 1.49 |
| Zeebrugge A2 K120 | location reached at [CET] | | 10:12 | 10:27 |
| | tide in Zeebrugge [m LAT] | | 1.52 | 1.58 |
| Kwintebank-Scheur | min gross UKC to nautical bottom [%] | 15.00 | 11.77 | 12.07 |
| | min gross UKC to nautical bottom [m] | 2.32 | 1.82 | 1.87 |
| | point on trajectory | | 200 | 500 |
| Scheur_West | min gross UKC to nautical bottom [%] | 15.00 | 12.96 | 13.95 |
| | min gross UKC to nautical bottom [m] | 2.32 | 2.01 | 2.16 |
| | point on trajectory | | 110 | 110 |
| Pas_van_het_Zand | min gross UKC to nautical bottom [%] | 12.50 | 14.12 | 15.07 |
| | min gross UKC to nautical bottom [m] | 1.94 | 2.19 | 2.34 |
| | point on trajectory | | 7 | 7 |
| | min gross UKC to top mud [%] | -7.00 | 14.12 | 15.07 |
| | min gross UKC to top mud [m] | -1.08 | 2.19 | 2.34 |
| | point on trajectory | | 7 | 7 |
| Zeebrugge_Ingang | min gross UKC to nautical bottom [%] | 12.50 | 14.84 | 15.61 |
| | min gross UKC to nautical bottom [m] | 1.94 | 2.30 | 2.42 |
| | point on trajectory | | 0 | 0 |
| | min gross UKC to top mud [%] | -7.00 | 14.84 | 15.61 |
| | min gross UKC to top mud [m] | -1.08 | 2.30 | 2.42 |
| | point on trajectory | | 0 | 0 |
| | max current speed [knts] | 2.00 | 1.41 | 1.31 |
| | point on trajectory | | 0 | 0 |
| Zeebrugge | min gross UKC to nautical bottom [%] | 10.00 | 10.86 | 11.29 |
| | min gross UKC to nautical bottom [m] | 1.55 | 1.68 | 1.75 |
| | point on trajectory | | 600 | 600 |
| | min gross UKC to top mud [%] | -7.00 | -7.21 | -6.40 |
| | min gross UKC to top mud [m] | -1.08 | -1.12 | -0.99 |
| | point on trajectory | | 601 | 610 |
| Zeebrugge_Kaai | min gross UKC to nautical bottom [%] | 10.00 | 11.29 | 11.67 |
| | min gross UKC to nautical bottom [m] | 1.55 | 1.75 | 1.81 |
| | point on trajectory | | 615 | 615 |
| | min gross UKC to top mud [%] | -7.00 | -6.77 | -6.40 |
| | min gross UKC to top mud [m] | -1.08 | -1.05 | -0.99 |
| | point on trajectory | | 615 | 615 |
| probability of bottom touch | | 1.00E-2 | 1.00E0 | 1.00E0 |

**Figure 15. Extract from a ProToel virtual example output file, showing waypoints and criteria as a function of departure time**

# 7.0 INLAND NAVIGATION

As stated in the introduction the design of inland waterways differ from the design of channels for maritime transport. First of all the vessel speed of inland vessels is much lower than the service and manoeuvring speed of sea-going vessels. Inland motor ships and push boats have high rudder efficiency thanks to the propeller-rudder configuration and the large rudder angles. Contrary to these advantageous aspects for ship manoeuvring, the horizontal and vertical restrictions are much larger for the inland transport mode compared to the maritime transport.

The Upper-Seascheldt, the most upward part of the tidal river Scheldt (Figure 16), is accessible for a class IV inland vessel (length: 85 m, beam: 9.5 m, design draft: 2.65 m) from Antwerp (boundary at Schelle in Figure 16) to Merelbeke (more than 70 km of distance). Exceptional permissions are given for larger vessels. Most laden inland vessels leave Antwerp one hour before high water so that the vessel can follow the tidal wave and has enough keel clearance left when approaching the locks in Merelbeke through a dredged and with concrete plates protected canal from Melle to Merelbeke. If the departure time in Antwerp has been delayed or the passage time on the river has been prolonged, the vessel enter the canal with an under keel clearance of less than half a meter (19% UKC) while a reasonable speed has to be maintained to reach the lock in due time.

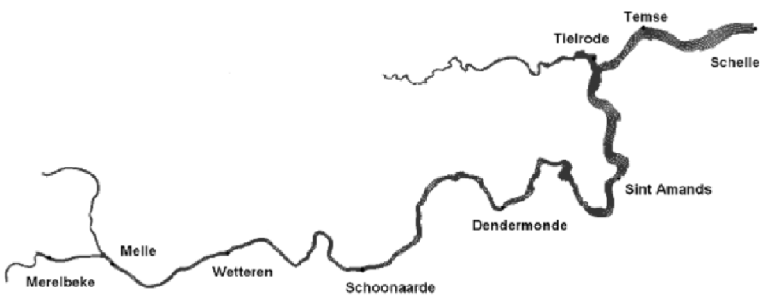


**Figure 16: Upper-Sea Scheldt, tidal river for class IV inland vessels**

To offer a realistic simulation environment and take into account the scale enlargement also find in the inland transport, a model of a class Va inland vessel has been examined in open, vertically restricted water and alongside the bank configurations reported in Figure 9. The 1/25 scale model of the inland container vessel (length: 110 m, beam: 11.45 m, design draft: 3.65 m) was equipped with a ducted propeller (5 blades, left-handed) and two coupled rudders (max. rudder angle 75/58 deg) and tested at different drafts (3.65 and 2.85 m) and in different water depths (200, 35, 20, 10% UKC, Figure 17). Open water tests have been executed with the ducted propeller and the rudders. The modelling of the single propeller - twin rudder system was a real challenge as the inflow to the rudders is strongly dependent on the propeller action (Figure 17), the ship motion and the twin rudder interaction.

The model velocities tested in the towing tank had to be adjusted compared to the real velocities of a class Va vessel to take into account the hydrodynamic restrictions of the towing tank based on blockage – speed relation. Model speeds higher than 0.9 m/s (16.2 km/h full scale) are within the critical speed range for the model test setup at FHR. The wave profile of a 0.72 m/s (13km/h full scale) model test is shown in Figure 17. A large decrease of the waterline in the vicinity of the ship model midship can be recognised. In addition the ship resistance and the angle between the Kelvin wave pattern and the ship's longitudinal axis are increasing considerably.

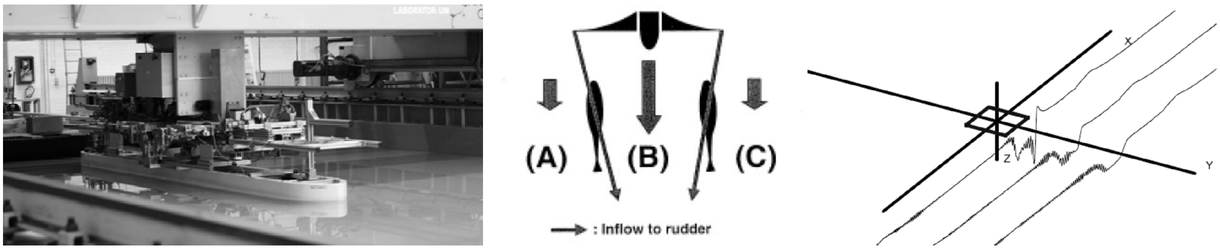



**Figure 17: Class Va ship model in the towing tank at FHR: inflow to the single propeller-twin rudder arrangement [25] and measured wave profile at three distances from the model tested at a draft of 3.65 m, 35% UKC and 13 km/h full scale**

Validation of the mathematical models was based on a comparison between measurement and model of additional multi-modal tests (one or more test parameters are harmonically varied), on standard manoeuvres measured during free-running model tests, full scale measurements during trial voyages and finally on feedback of a skipper executing real-time simulations on the inland simulator LARA (Figure 18).

**Figure 18: Full scale measurement equipment at a class IV inland vessel and inland simulator LARA**

Measured lateral forces at fore and aft gauges during bank interaction tests reveal additional challenges in modelling bank effects for the inland transport [26]. Contrary to the more or less linear relationship between the total lateral force ($Y = Y_{fore} + Y_{aft}$) and the bank distance parameter $1/d_{2b}$ reported in chapter 3, in Figure 19 this lateral force is non-linear and vary differently depending on the under keel clearance. A large difference is seen between 200 and 35% UKC on one side and 20% UKC on the other so that special attention should be paid to ship behaviour predictions of vessels at under keel clearances of approximately 20% of the ship's draft and lower. A better understanding of the flow field around the ship model can be obtained if the measured lateral forces at fore and aft gauges are considered as in Figure 20. Although the propeller is not working the lateral force $Y_{aft}$ increases non-linearly with increasing inverse of $d_{2b}$ for all tested water depths. The lateral force $Y_{fore}$ increases as well with increasing $1/d_{2b}$ if the UKC is 35% or higher but becomes negative (bank repulsion) for a restricted UKC of 20%. This change in sign will result in a very large bow-away yawing moment in very restricted water.

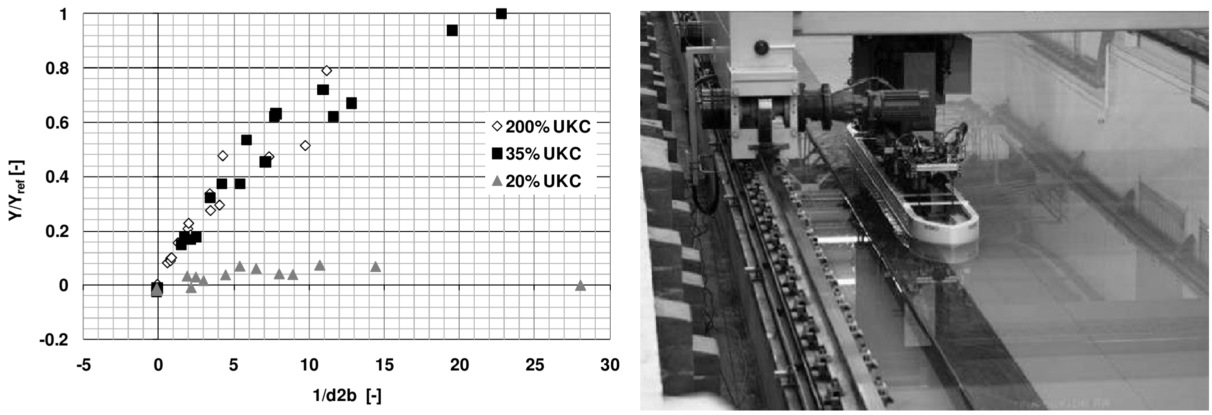



**Figure 19: Lateral force due to bank effects (Bank XI to bank XIV) as function of $1/d_{2b}$ for a speed of 10.8 km/h full scale and deep (200% UKC) to shallow water (35% and 20% UKC), no propeller**

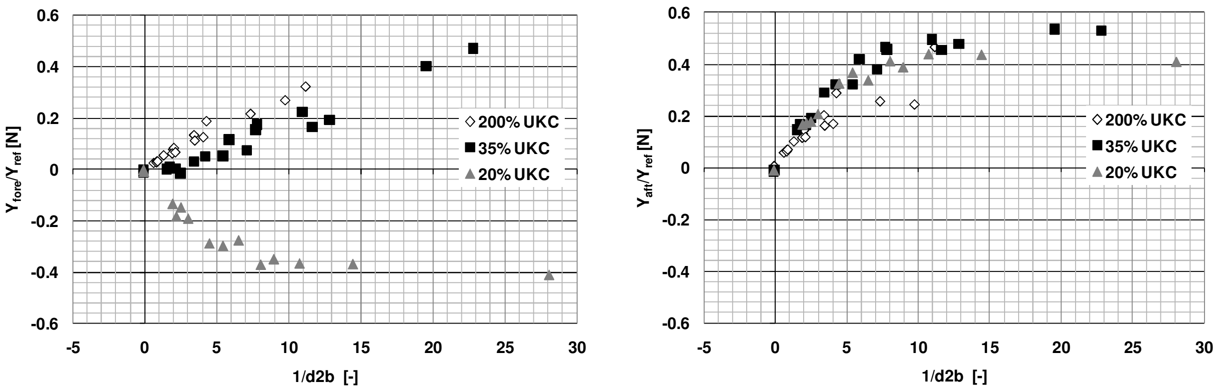



**Figure 20: Lateral force measured at fore and aft gauges of ship model for the same test conditions as in Figure 19, no propeller**

As design guidelines for inland waterways cannot always be met for the adaptation of existing waterways in protected areas, in-depth research based on EFD and real-time simulations will help in defining the limits. Future research for inland navigation will have to focus on the prediction of the manoeuvring behaviour of push convoys and estuary ships in open and confined water and the interaction between inland ships.

## 8.0 SUMMARY

The prediction of ship behaviour in shallow and confined water is discussed based on a summary of extensive model test programs executed in the Towing Tank for Manoeuvres in Shallow Water (Antwerp, cooperation FHR – Ghent University). Ship manoeuvrability is reducing considerably if the under keel clearance is decreasing below 50% of the ship’s draft. Taking into account the available water depth in the access channels and rivers to the Flemish harbours, water depth to draft ratios h/T between 1.5 and 1.1 are being studied and even lower values or negative UKCs compared to the water-mud interface are considered. The hydrodynamic effect due to ship-bank or ship-ship interaction reduces the ship manoeuvrability additionally. The test parameters summary and the test results show the complexity of modelling these hydrodynamic effects in shallow water. Intensified research is still needed and synergy between different modelling techniques - EFD, CFD and numerical methods – could help in understanding the hydrodynamic background of the forces and their modelling.

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