THE NAUTICAL BOTTOM CONCEPT IN THE HARBOUR OF ZEEBRUGGE

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ABSTRACT

In order to keep navigation safe, ships need a minimum under keel clearance; therefore, an unambiguous definition and a reliable survey technique for the depth of navigation areas are required. However, in harbours and access channels covered with a soft mud layer the bottom is hard to define, while the common measuring techniques such as echo-sounding do not lead to satisfactory results. Therefore the nautical bottom concept was introduced by PIANC (1997) 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". An overview is given of an experimental program that had been setup to assess the controllability of ships in muddy areas. Based on the results of this research project, a revision of the definition of the nautical bottom in the harbour of Zeebrugge was suggested.

SOMMAIRE

Comme la sécurité de navigation dépend incontestablement du pied de pilote, la disponibilité d'une technique de mesure fiable pour déterminer la profondeur des voies navigables est indispensable. Pour autant les techniques communes, comme *l'echosounding* ne résultent pas en données satisfaisantes quand le fond est couvert d'une couche de vase. Ainsi le concept du fond nautique a été introduit par PIANC (1997) comme "le niveau où les caractéristiques physiques du fond atteignent une limite critique, au-delà de laquelle tout contact avec la quille d'un navire cause des avaries ou des effets inacceptables au niveau de la contrôlabilité et de la manœuvrabilité du navire." L'article présent offre un résumé d'une recherche expérimentale sur la contrôlabilité des navires dans les secteurs vaseux. Les résultats de ce programme de recherche ont mené à une révision de la définition du fond nautique au port de Zeebrugge.

KEYWORDS: nautical bottom, mud layer, towing tank, simulator, mathematical model, manoeuvring

1. INTRODUCTION

The ever increasing scale of vessels allows ship owners to reduce their expenses. On the other hand larger ships have to manoeuvre in areas where opportunities for expansion are limited, as it is the case for harbours and channels. Particularly the under keel clearance of the ships with larger draughts is critical for safe navigation. From this point of view it is important to have a reliable indication of the available depth at any time. Common techniques for depth measurements such as echo sounding have already proven their efficiency, but cannot be used in every circumstance. The use of echo sounding results especially inadequate in areas where the bottom is covered with a soft fluid mud layer. In this case a high frequency echo reflects on the water-mud interface, while a low frequency echo penetrates fairly deeper into the mud.

This difference in reflection depth can reach values up to several metres, and is due to the variation of the composition and the properties of the mud layer with increasing depth. The upper part of the mud layer is rather fluid, while the material at a larger depth will be denser and more viscous. If the results of the high frequency echo are used, the bottom will be defined at the water-mud interface. However, the upper part of the mud will intuitively not damage the ship as a rocky bottom would. In case the lower frequency echo is used, the bottom is delineated at a deeper position in the mud layer, a location which seems to be different with each measurement and therefore not reliable. If the ship's keel touches this denser mud the controllability of the ship may be affected.

These considerations resulted in the nautical bottom concept which has been defined by PIANC in 1997 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". This nautical bottom concept has already been introduced in various harbours which suffer from sedimentation and the formation of fluid mud layers. The composition of the mud depends of many factors, but usually the density has been used to denote the critical limit, because of the difficulty to measure other (e.g. rheological) parameters in a continuous way (Van Craenenbroeck K., 1998)

In the case of the harbour of Zeebrugge, measurements of the rheology profile in the 1980s showed that a considerable increase of the rheological properties occurred at a density level which was always above 1.15 ton/m^3. This so-called rheological jump was considered as the nautical bottom, so that the 1.15 density-level was accepted to be a safe criterion, however, more recent measurements showed however that the position of the rheological jump had shifted to a higher density. Consequently an increase of the critical density could be justified; on the other hand, due to the thickness of the mud layer an adaptation of the criterion would often result into a considerable penetration of the keel of deep drafted vessels into the mud layer. The question was raised whether this could lead to adverse effects on the manoeuvring behaviour of the ships.

Additional knowledge on ship behaviour in those conditions was required, because only a few research institutes have investigated ship behaviour in muddy areas: MARIN, Wageningen (Sellmeijer, 1983); Sogreah, Grenoble (Brossard, 1990); Flanders Hydraulics Research, Antwerp (Van Craenenbroeck, 1991; Vantorre, 1991). Moreover those experimental programs had not the coverage that was needed to predict the manoeuvrability of large drafted vessels in harbour conditions, especially not for ships navigating with a considerable negative under keel clearance referred to the mud-water interface. An extensive research program (2001-2004) has therefore been carried out at Flanders Hydraulics Research, Antwerp, with the scientific support of the Maritime Technology division of Ghent University. The results lead to the determination of an upper limit for the nautical bottom from a nautical viewpoint and to guidelines for the pilots concerning ship handling in muddy areas.

2. EXPERIMENTAL SETUP

2.1 Facilities

Flanders Hydraulics Research is the hydraulic research station of the Ministry of Flanders, Belgium and is particularly concerned with investigation of ship hydrodynamics in relation with the concept, adaptation and operation of navigation areas.

To simulate the manoeuvring behaviour two full bridge ship-manoeuvring simulators have been installed for research and training: SIM225 with a visual system of 225 degrees view, to be combined with a horizontal or vertical tilt of the image, and SIM360+ with 360 degrees and lateral view of the ship's hull, see Figure 2. During the presented research project, SIM225 has been used for simulation runs. Both simulators consist of a mock-up of a ship's navigation bridge with telegraph, rudder, radar, etc. Communication equipment is available and tug assistance is also simulated. The position, course and speed of the vessel are calculated by a mathematical model that determines the horizontal forces and moment acting on the ship at each time step.

In order to provide the mathematical model of the simulator with realistic data, especially in the (very) shallow water range, the availability of experimental facilities was considered as a requirement. At present these facilities consist of a shallow water towing tank (88 m * 7 m * 0.6 m), equipped with a planar motion carriage, a wave generator and an auxiliary carriage for ship-ship interaction tests, see Figure 1. Thanks to computerised control and data-acquisition, the facilities are operated in a fully automatic mode.

Figure 1 – Shallow water towing tank

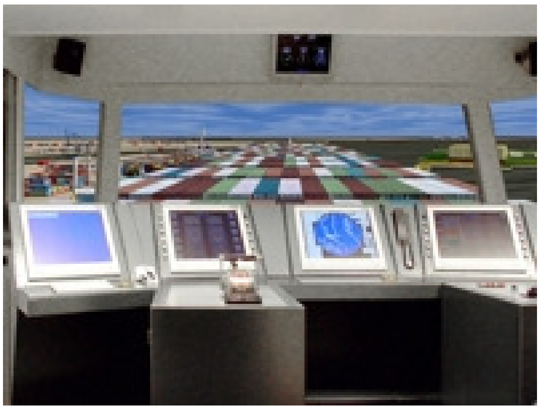


Figure 2 – Bridge of SIM360+

2.2 Experimental conditions

The use of natural mud to perform model tests was discarded as it took to long for the mud to settle down to its initial position after a run in the towing tank was performed. As the natural mud was not sufficiently controllable, an artificial mixture, consisting of two types of chlorinated paraffin and petroleum, has been used. In total seven mud layers of a different viscosity and density have been utilized to carry out captive manoeuvring runs at different under keel clearances, see Table 1. The different relative positions of ship and mud layer are also shown comprehensively in Figure 3. The selected density-viscosity combinations were based on measurements of density and rheology profiles carried out in the outer harbour of Zeebrugge in 1997-98. A mud layer configuration is defined by two characters: a letter (b,…,h) denoting the material characteristics and a figure (1, 2, 3) representing the layer thickness. Tests carried out above a solid bottom are referred to as "S".

The letters D, U (container carriers) and E (tanker) in Table 1 denominate the ship models that have been used. More details can be found in Table 2. Most runs have been carried out making use of model D of a 6000 TEU container carrier, because of the importance of container traffic for the harbour of Zeebrugge. Further results in this paper will therefore focus on this ship. For model D, the gross under keel clearance (ukc) relative to the tank bottom was varied between 7 and 32% of draft, yielding -12 to +21% ukc relative to the mud-water interface. Throughout this paper, the interface water-mud will be used as a reference for expressing the under keel clearance, unless specified otherwise.

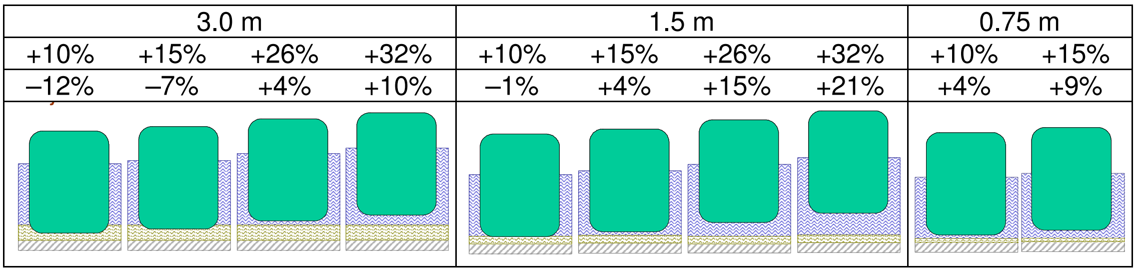


Figure 3 – Tested combinations of mud layer thickness (1st row),
under keel clearance to solid bottom (2nd row)
and to mud-water interface (3rd row).

Table 1. Bottom conditions and tested models.

Mud type	Density (ton/m³)	Dynamic viscosity (Pa s)	Layer thickness 0.75 m "1"	1.50 m "2"	3.00 m "3"
"d"	1.10	0.03	D/E	D/E	D/E/U
"c"	1.15	0.06	D	D	D
"b"	1.18	0.10	D	D	D
"f"	1.20	0.11	-	D	-
"h"	1.21	0.19	D/E	D/E	D
"e"	1.26	0.29	-	D	-
"g"	1.25	0.46	-	D/E	D/E
"S"		solid bottom			

Table 2. Ship models.

Model	D	E	U
Scale	1/75	1/75	1/80
L_{PP} (m)	289.8	286.8	331.8
B (m)	40.25	46.77	42.82
T (m)	13.50	15.50	14.54
C_B	0.59	0.82	0.65
A_R (m²)	60.96	98.34	83.13
# blades	5	5	6
D_P (m)	8.145	7.733	8.46
P/D_P (-)	0.97	0.65	1.00
AEP (-)	0.8	0.62	0.96

For each bottom condition a wide range of parameters had been varied in order to be able to build a mathematical model that could cover harbour manoeuvring. Following data were measured: longitudinal and lateral force components fore and aft, vertical motion (four measuring posts: fore/aft, port/starboard), rudder parameters (normal and tangential forces, torque, angle), propeller parameters (torque, thrust, rpm). In particular cases, vertical motions of the mud-water and water-air interfaces were registered as well, see Figure 4.

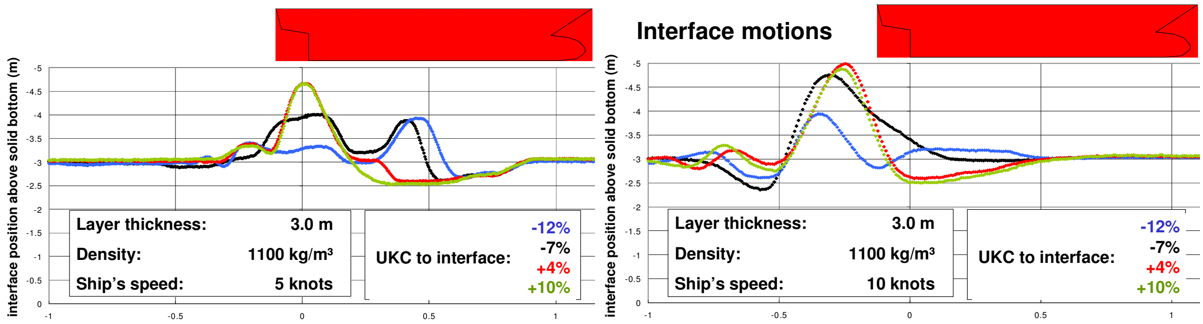


Figure 4 – Undulations of the interface: influence of speed and under keel clearance.

3. MATHEMATICAL MODELS

A comprehensive mathematical model for the forces acting on the ship in the horizontal plane has been developed for each condition of Table 1 and is valid for a wide range of forward and lateral speeds, yaw rates, rudder angles and propeller loadings (four-quadrant propeller action, 360 deg drift and yaw angle). The mathematical models are of the modular type, so that the force and moment components are expressed as a sum of hydrodynamic reactions on the hull, and terms induced by the propeller and rudder action:

$$F = F_H + F_P + F_R \tag{1}$$

It was decided to formulate force components by determining functions of non-dimensional parameters in a tabular form, rather than attempting to define analytical expressions. More information on the mathematical model can be found in (Delefortrie G. et al, 2005).

4. SIMULATION RUNS

4.1 Programme

In April 2004 a first series of simulation runs above muddy bottoms, with constant characteristics throughout the harbour, has been carried out with the cooperation of the Zeebrugge pilots (Flemish pilotage). The three main purposes of this simulation programme were:

- ✓ Validation of the mathematical model. Each pilot started with a run above solid bottom or above a low density mud layer to get used to the simulator environment and to assess the validity of the mathematical model.
- ✓ Defining the nautical bottom. The behaviour of the ship has been evaluated with the keel touching mud layers of different density and viscosity to define the limit of controllability.
- ✓ Assessing the navigability of ships penetrating mud layers. Adopting a larger critical limit will lead to contact between the ship's keel and mud layers of a lower density.

For each condition up to four trajectories, see Figure 5, were carried out. Moderate wind conditions were selected for increasing the realism of the situation without disturbing the actual manoeuvre (SW 4 BF). Currents occurring at low tide, characterised by considerable cross-currents in the access channel beyond the breakwaters, were also taken into account. The pilots had two tugs of 45 ton bollard pull that could provide assistance. In some runs more tug assistance and/or a more severe wind condition were given.

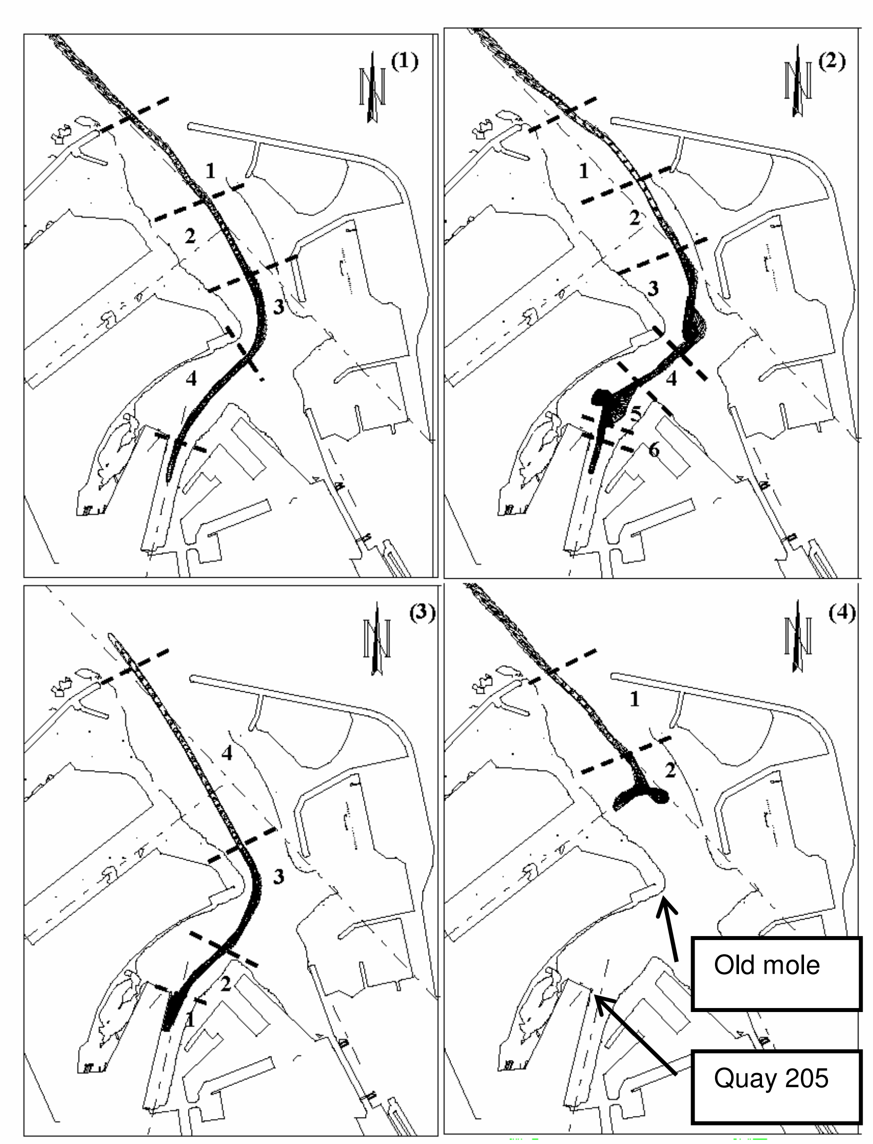


Figure 5 - Harbour of Zeebrugge. Real time simulations: trajectories and sub-trajectories.

4.2 Pilots evaluation

After each run pilots were asked to fill in a questionnaire. The analysis of their evaluation is shown in Figure 6. Runs where the keel touches a mud layer of a density of 1.20 ton/m³ or more were always assessed as dangerous, especially with severe wind conditions. The main reasons therefore were insufficient speed when leaving the harbour and lack of tug assistance. In some cases, as for navigation with small positive under keel clearances above the water-mud interface, the course stability was no longer sufficient. According to the nautical bottom concept, a critical density of 1.20 kg/m³ seemed acceptable; however the penetration depth in mud layers of a lower density should also be restricted, depending on the available tug assistance.

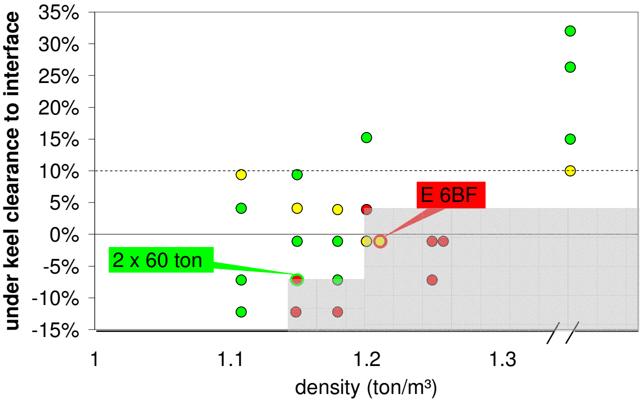


Figure 6 – Harbour of Zeebrugge. Global analysis of runs with ship D based on the pilots findings. (green = safe; yellow = difficult; red = dangerous; grey zone = unacceptable)

4.3 Analysis of simulation runs

The evaluation of the pilots gives a good insight in the mud conditions were controllability problems can occur, but is not free of subjectivity. A quantitative analysis can be made based on the following criteria:

- Speed: is the speed the departing vessel reaches sufficient to counteract the tidal currents outside the harbour breakwaters? A speed of 10 knots was considered to be safe; leaving the harbour at 8 knots is still possible, but difficult.
- Course stability: has the ship sufficient stability when navigating by her own means, i.e. without tug assistance? A suitable criterion appears to be the standard deviation of the yaw rate. An unstable ship will have a high standard deviation; values of 6°/min or more were assessed as unacceptable.
- Controllability: with the ship's own means and the provided tug assistance, is the ship still manoeuvrable? This criterion can be evaluated by introducing a so-called control power concept.

4.3.1 Analysis of control power

Analysis of the control power is based on the impulse of steering force and moment, which are defined as follows:

$$I_Y = I_{YT} + I_{YR} = \sum_i \int S_i dt + \int |Y_R| dt \tag{2}$$

$$I_N = I_{NT} + I_{NR} = \sum_i \int S_i x_i dt + \int |N_R| dt \tag{3}$$

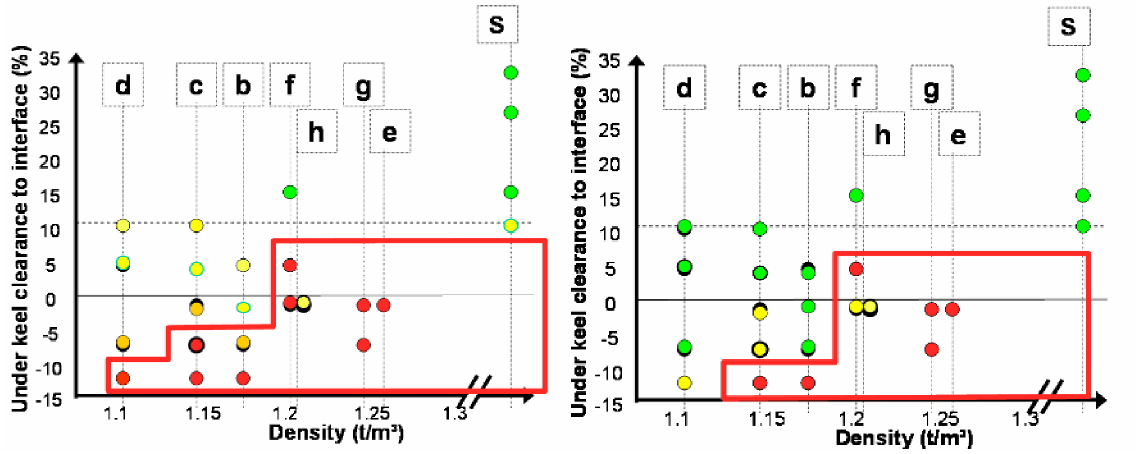
S_i being the force exerted by tug number i, applying at a longitudinal position x_i of the ship. The rudder yields a force Y_R and a moment N_R on the ship. Formulae (2) and (3) take into account which force has to be applied for how long in order to carry out the manoeuvre. The smaller the value of the impulse functions the higher the controllability of the ship is. Expression (4) also allows assessing the controllability of the ship with different tug assistance (BP ton bollard pull) than the provided one (45 ton bollard pull).

$$I_{Y,\max}^{(\mathrm{BP\ ton})} = I_{Y,\max}^{(45\ \mathrm{ton})} \left(\frac{I_{YR}}{I_Y} + \frac{BP}{45} \frac{I_{YT}}{I_Y} \right) \tag{4}$$

4.3.2 Results

Figure 7 shows the overall results of the analysis. The density value of 1.20 ton/m^3 appears to be confirmed as a critical limit for the nautical bottom; on the other hand, in comparison with the pilots' evaluation the restriction of keel penetration into the mud layer is more severe:

- With two tugs of 45 ton bollard pull the penetration depth is limited to -5% for mud layers of 1.15 ton/m^3 and to -7% for mud layers of a lower density.
- This constraint is less severe when two tugs of 60 ton bollard pull are provided. In this case navigating at -7% in mud of 1.15 ton/m^3 is still acceptable - and in fact this restriction can be totally ascribed to the speed criterion - and in less dense mud layers an under keel clearance of even -12% is still possible.



a – Tug assistance: 2 x 45 ton bollard pull. b – Tug assistance: 2 x 60 ton bollard pull

Figure 7 - Harbour of Zeebrugge. Global analysis of runs with ship D.
(green = safe; yellow = difficult; red = dangerous; red zone = unacceptable)

As can be seen on Figure 7a, even when the ship's keel is not in contact with the mud layer the controllability is challenging. This is most likely on account of the undulations that are generated in the water-mud interface when a ship passes by. Those undulations, illustrated in Figure 4, increase in amplitude and move more aft with increasing speed and decreasing mud density. In most cases the maximal amplitude is reached near the propeller and rudder, disturbing the water inflow to the ship's controls and therefore decreasing the vessel's manoeuvrability.

4.4 Analysis of sub-trajectories

Figure 5 also shows the division of the trajectories into sub-trajectories, which have been analysed separately in order to find out which sub-trajectories were critical. In the following paragraphs the most critical sub-trajectories are discussed, more information can be found in (Delefortrie G. et al, 2006).

4.4.1 Analysis of departure

4.4.1.1 Sub-trajectory 3.1: unberthing

Unberthing is a typical tug assisted manoeuvre. The impulse of steering force during the departure is shown in Figure 8. Some simulation runs, in which pilots mentioned the lack of tug power, have been marked. A clear limit can be drawn based on the pilots' comments. With expression (4) this limit can be extrapolated to limits for different tug assistance. Note that two tugs of 60 ton bollard pull will be sufficient in all tested conditions, unless there is strong east wind. The influence of the wind and the tug power available is very important. Two tugs of 30 ton bollard pull are insufficient once the under keel clearance referred to the water mud interface is 5% or lower.

4.4.1.2 Sub-trajectory 3.3: rounding old mole

During this turning manoeuvre the integral of the steering moment will be more important, see Figure 9. Manoeuvres that pilots found difficult are marked and are characterised by a high value for the integral of the steering moment. Some differences between the pilots' evaluation and the steering impulse can be observed:

- The run with 10% under keel clearance above mud c.
  The available tug assistance was assessed by the pilot to be insufficient, but the manoeuvre was completed in a record time, which resulted into a smaller impulse. The manoeuvre can therefore be categorised as acceptable.
- The run with -1% under keel clearance in mud c.
  A large integral of steering is needed to complete the in this condition, although the pilots found the tug capacity sufficient.

The influence of tug power is smaller than when leaving the quay, as the own controls of the ship have a larger share in the total control power. Two tugs of 60 ton bollard pull are sufficient to carry out the manoeuvre above any bottom condition, while it is not advisable to touch the mud layer when only two tugs of 30 ton bollard pull are available.

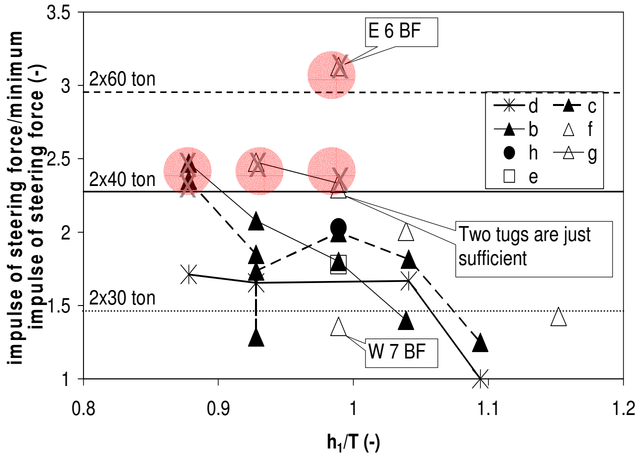


Figure 8 – Harbour of Zeebrugge: impulse of steering force of the ship's when leaving quay 205 (trajectory 3, sub-trajectory 1) during real-time simulation with ship D.

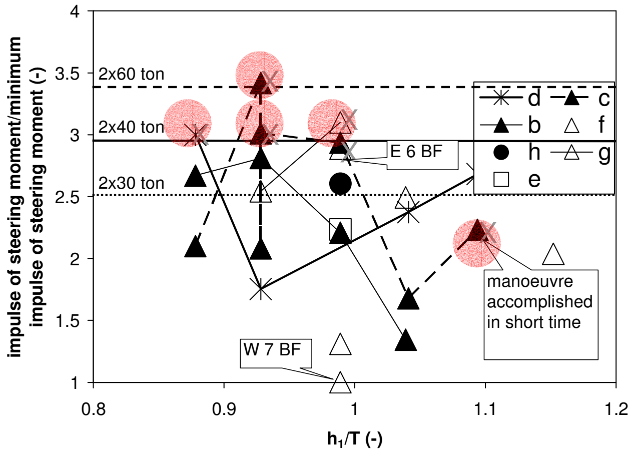


Figure 9 – Harbour of Zeebrugge: impulse of steering moment of the ship's when turning around the old port entrance (trajectory 3, sub-trajectory 3) during real-time simulation with ship D.

4.4.2 Analysis of arrival

4.4.2.1 Sub-trajectories 1.4 and 2.5: berthing at quay 205

Due to lack of time, berthing manoeuvres at arrival (trajectory 1 or 2) have not been fully executed. On the other hand as wind plays an important role, and as the dominant SW wind hinders the berthing more than the departure, the limit of steering impulse will be more severe. If two tugs were just sufficient for departure, the available power will be too small for a normal berthing manoeuvre.

4.4.2.2 Sub-trajectories 1.3 and 2.3: Rounding old mole

The limit of the integral of the steering moment, Figure 10, with assistance of two tugs of 40 ton bollard pull is basically the same as with departure. The limits of two tugs of 60 or 30 ton bollard pull are different, as this time the share of own controls is smaller. Pilots mentioned insufficient tug assistance for four runs, which are struck out on the graph. The ship had nevertheless sufficient control power in two of the mentioned runs.

The manoeuvre can always be carried out with two tugs of 60 ton bollard pull; although in some cases the limit is reached. With two tugs of 30 ton bollard pull the manoeuvre is already risky at 10% under keel clearance above a solid bottom.

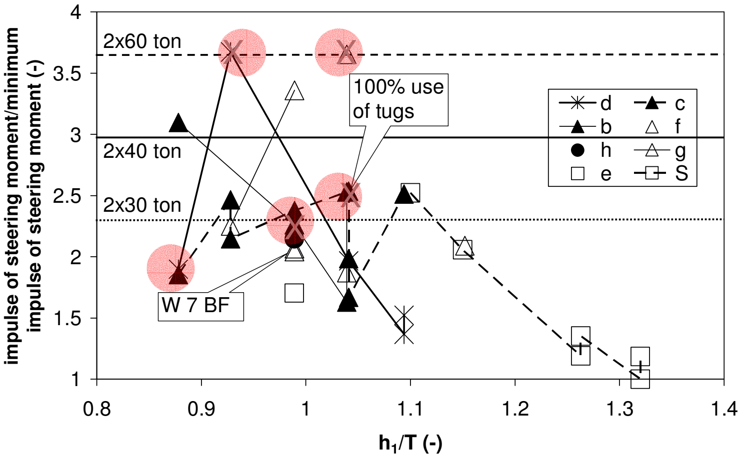


Figure 10 – Harbour of Zeebrugge: impulse of steering moment of the ship's when turning around the old port entrance (trajectories 1 and 2, subtrajectory 3) during real-time simulation with ship D.

5. APPLICATION OF THE NEW CRITICAL LIMIT

5.1 Constraints

The results of the simulation runs with the Zeebrugge pilots permitted the redefinition of the nautical bottom to a higher critical density limit, but a number of additional requirements have to be met as well:

- The under keel clearance to the 1.20 ton/m³ density level has to be 10% of draught;
- Penetration of the keel into the mud is restricted, depending on the available tug assistance and mud density;
- Pilots must be aware of the position of the water-mud interface, in order to anticipate modified ship behaviour due to the undulations interfering with the vessel's propeller and rudder.

Hence, pilots need to have charts with the positions of the water-mud interface (high-frequency echo), the 1.20 ton/m³ density level and an intermediate density level, for instance 1.15 ton/m³, to have an idea of the penetration depth.

5.2 Guidance

Since the formation of mud layers is a non-stationary process, periodical survey of the mud layers is required. With the different constraints applying on the navigation in muddy areas it results difficult to carry out the necessary calculations in order to know whether the manoeuvre can be carried out safely or not. So software has been developed, which allows the calculation of the limit conditions, such as the maximal draught, given the density profile. Some fictitious examples for the harbour of Zeebrugge are shown in Figures 11 and 12.

a – Tug assistance: 2 x 45 ton bollard pull. b – Tug assistance: 2 x 60 ton bollard pull.

Figure 11 – Central part of the harbour of Zeebrugge. Ship D.
Maximal acceptable draft (m) at low tide with moderate wind conditions.

6. ADDITIONAL DEVELOPMENTS

6.1 Mathematical models

As previously stated, a mathematical model has been developed for each single bottom condition. As a consequence simulation runs were carried out with a constant bottom condition for the entire harbour area. Currently a force-interpolation model is being developed, dividing the harbour in quadrangles with each a single bottom condition, allowing simulation runs in more realistic bottom conditions. A next step in the modelling will be the development of a mathematical model, permitting transitions between several types of muddy bottoms, to further increase the realism of the simulations.

6.2 Simulation runs

Additional simulation runs are planned in 2006 implementing the division of the harbour in quadrangles, see 6.1. In order to improve the decision scheme the pilots take as a guideline, runs will be carried out with a variety of wind conditions and tug assistance, concentrating on the possible conditions that can occur in real circumstances. The involvement of a large group of pilots is important, as the human factor plays an important role in the simulation results.

6.3 Full scale validation

Detailed registrations of manoeuvres carried out with deep-drafted vessels at low tide are planned to validate the concept. The observations will allow a validation of the mathematical models that are based on model tests carried out in a simplified environment.

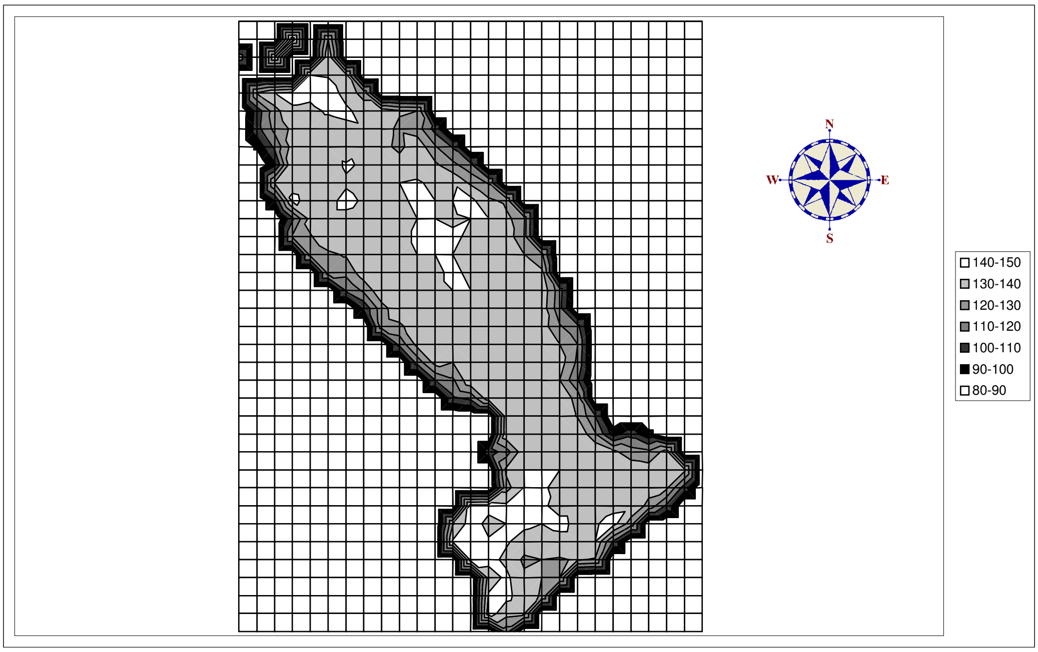


Figure 12 – Maximum allowable draft (in dm) in the outer harbour with tug assistance of 2 * 60 ton bollard pull.

7. CONCLUSIONS

A research project based on captive ship model tests, mathematical modelling and real-time simulation runs has resulted into an upper limit for the nautical bottom from a nautical viewpoint. The results have offered insight in the manoeuvring behaviour of deep drafted container vessels calling at a harbour with muddy bottom conditions and to guidelines for the pilots. Environmental conditions, such as tidal currents and wind, and the available tug assistance are of particular importance; additional simulation runs are therefore planned to fine-tune the operational limits.

It should be emphasized that these specific conclusions are only valid for deep-drafted container carriers arriving at or departing from Zeebrugge harbour, as the mud layer characteristics, the environmental conditions (e.g. current) and harbour layout are typical for this area.

On the other hand, a similar methodology can be applied for assessing the limits for navigation in other harbours and waterways suffering from fluid mud deposits, provided that the local conditions (bottom, ship type, …) are covered by the experimental database and, therefore, the mathematical model. The present approach offers an important advantage: the new criterion for the nautical bottom is not merely based on one single physical property of the mud layer, but has been determined taking into account all significant factors such as harbour layout, bottom characteristics, ship behaviour, environmental conditions (current, wind), available tug assistance and human control.

8. ACKNOWLEDGEMENTS

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