Revision of the nautical bottom concept in Zeebrugge based on the manoeuvrability of deep-drafted container ships

G. Delefortrie[1], M. Vantorre[2], and E. Laforce[3]

Abstract: In the harbour of Zeebrugge, Belgium, the bottom is covered with a mud layer with physical characteristics (density, viscosity, yield stress) gradually increasing with depth. The bottom is difficult to define with echo-sounding, so that the nautical bottom concept has been introduced: 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 (PIANC, 1997). The upper mud layer can be considered as black water while at a lower level a transition between loose and solid mud occurs. In Zeebrugge, in-situ measurements in the 1980s revealed that this transition corresponded with a density of 1.15 ton/m³ or higher; this density was selected as the critical limit.

More recent measurements showed an increase of the layer thickness and a shift of the rheological transition level to higher densities. An adaptation of the density criterion would offer the advantage of an optimisation of the maintenance dredging efforts without affecting the accessibility of the harbour. However, contact between the mud and the keel of deep-drafted ships would be unavoidable, so that additional research on the controllability of vessels navigating above or through mud layers was required.

An extensive research program, consisting of captive model tests and full bridge manoeuvring simulations with a 6000 TEU container carrier was carried out at Flanders Hydraulics Research, Antwerp, scientifically supported by Ghent University, on behalf of the Maritime Access Department (Ministry of Flanders) and TV Noordzee & Kust (Ostend). During the simulations, Zeebrugge pilots experienced that a ship in contact with lower density mud layers is still controllable. Eventually a new critical density of 1.20 ton/m³ can be adopted. Nevertheless sufficient tug capacity must be available to guarantee safe and economic manoeuvres.

Keywords: mud, manoeuvrability, simulation

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NOMENCLATURE

AEP	expanded blade area ÷ propeller area	(-)
A_R	rudder area	(m^2)
B	ship beam	(m)
C_B	block coefficient	(-)
D_P	propeller diameter	(m)
F	force	(N)
h	thickness, depth	(m)
I_N	impulse of steering moment	(kgm^2/s)
I_Y	impulse of steering force	(kgm/s)
L, L_{PP}	ship length	(m)
N	yaw moment	(Nm)
P	propeller pitch	(m)
S	tug force	(N)
T	ship draft	(m)
t	time	(s)
ukc	under keel clearance, referred to draft	(%)
x	longitudinal position	(m)
	parameter	
Y	sway force	(N)
ρ	density (mass per unit of volume)	(ton/m^3)

Subscript

1	water layer
2	mud layer
H	hull
P	propeller
R	rudder
T	tug

1 INTRODUCTION

Ship manoeuvring behaviour is highly influenced by the available water depth below the keel, which is particularly the case for deep-drafted vessels in access channels and harbours. A sufficient under keel clearance is required in order to perform safe and economic manoeuvres. As an example, (ICORELS, 1980) makes following general recommendations on keel clearances: 20% for open sea areas, exposed to strong and long stern or quarter swell; 15% in waiting areas and channels exposed to strong and long swell, 10% for less exposed channels, 10 to 15% for exposed, and 7% for protected manoeuvring and berthing areas.

Fig. 1. Overview of ship manoeuvring in muddy navigation areas.

The available water depth can be measured with common survey techniques as echo-sounding. However when the bottom is covered by a fluid mud layer an exact location of the seabed using echo-sounding is difficult (Kirby et al., 1980). The use of high frequencies (e.g. 210 kHz) allows locating the water-mud interface, while low frequency signals (e.g. 33 kHz) penetrate into the mud layer, but it is uncertain whether this measured level is the solid bottom or not, see Figure 1. Furthermore, monitoring the 33 kHz level appears to depend on many factors and is therefore not always fully reliable.

On the other hand, the question arises whether in muddy navigation areas the under keel clearance of a vessel should be referred to the mud-water interface, the solid bottom or some intermediate level. Indeed, the physical characteristics of the mud layer change with depth. Although contact with the upper mud layer, often called "black water", will not cause any damage to the ship, it is not unlikely that the manoeuvring behaviour of the ship will be affected by the presence of this layer. The lower part of the mud layer will be characterized by a larger viscosity and density, resulting in a larger shear resistance. Contact between the ship's keel and this part of the mud layer may result into a loss of controllability.

As a consequence the term “bottom” cannot be used any longer in muddy navigation areas. A more general term is “nautical bottom” which is defined 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" (PIANC, 1997).

Traditionally the definition of the nautical bottom has been based upon the physical characteristics of the mud layer. In the 1980s a measurement campaign in the harbour of Zeebrugge revealed that a rheological jump occurred in the mud layer at a density which was always higher than 1.15 ton/m³, see Figure 2. A critical density of 1.15 ton/m³ was therefore adopted as the critical limit (Kerckaert P. et al, 1985, 1988). An important reason to choose the mud density as a critical parameter to define the nautical bottom is the lack of a measurement tool to generate rheology profiles on a continuous base. As stated in (Van Craenenbroeck K. et al, 1998) continuous survey techniques have improved, but are still all based on density measurements. Techniques for measuring both viscosity and density profiles are available (Greiser N. et al, 2004) but can only be performed by time consuming point measurements.

Due to continuous sedimentation permanent dredging works are required to maintain the nautical bottom level. As the upper part of the mud layer in the harbour of Zeebrugge consists of black water, dredging is a time consuming activity of low efficiency. A measuring campaign in 1997 revealed that the rheology profile of the harbour of Zeebrugge had significantly changed. A first, small rheological jump occurred just below the water-mud interface while a second and more important one occurred at a depth of 3 to 4 m under the interface, corresponding with a density that is significantly higher than the current critical value of 1.15 ton/m³. The interested parties consequently asked whether an increase of the critical density limit could be considered. For maintenance dredging the intrinsic dredge output could be significantly improved by dredging mud of a higher density.

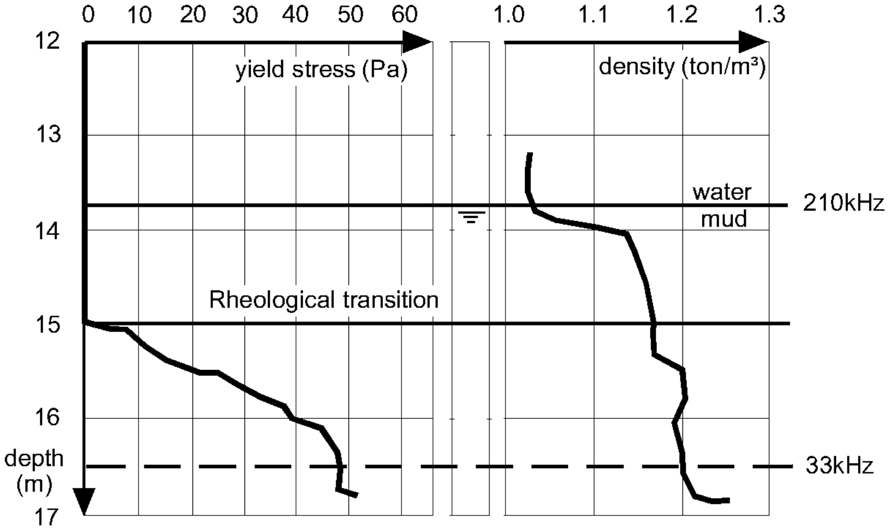

Fig. 2. Rheology profile of the mud layer in the harbour of Zeebrugge. (De Meyer C. & Malherbe B., 1987)

With a critical density of 1.15 ton/m³ and an under keel clearance of 10% of draft the ship's keel hardly ever touches the mud layer, but an increase of the critical limit results in possible contact between the keel of deep-drafted container ships and the mud layer and possible unacceptable effects on ship handling. Only a few research institutes have investigated ship behaviour in muddy areas: Marin, Wageningen (Sellmeijer et al, 1983); Sogreah, Grenoble (Brossard et al, 1990); Flanders Hydraulics Research, Antwerp (Van Craenenbroeck et al, 1991; Vantorre, 1991). However, the information available appeared to be insufficient for a complete assessment of controllability of ships in contact with mud layers, so that more in depth research is needed (PIANC, 1997; Vantorre, 1994). Indeed, the previous work only considered low viscosity mud layers, so that the present range of rheological characteristics of the Zeebrugge mud was not covered. Moreover, only full form ships, mainly tankers, were investigated, while at present container traffic has the highest priority for the harbour of Zeebrugge. Furthermore, a complete mathematical model for operations in the four quadrants is required for the assessment of the full range of manoeuvres that a ship arriving at or departing from the harbour has to carry out by means of real-time simulation runs. An extensive research program 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 shiphandling in muddy areas.

2 EXPERIMENTAL PROGRAM

2.1 Test facilities

Flanders Hydraulics Research (Waterways and Maritime Affairs Administration of the Ministry of Flanders) 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. 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 3. Thanks to computerised control and data-acquisition, the facilities are operated in a fully automatic mode.

Fig. 3. Flanders Hydraulics Research shallow water tank.

2.2 Ship models

Captive manoeuvring tests were carried out with three ship models, equipped with propeller and rudder: a 6000 TEU container carrier (model D), a 8000 TEU container carrier (model U) and a tanker (model D). Most runs were carried out with model D, which is significant for the container traffic in Zeebrugge. The main characteristics of the ship models are summarised in Table 1.

Table 1. 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 (m^2)	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

2.3 Bottom condition

Covering the bottom of the towing tank with natural mud seemed difficult as the characteristics of the mud layer cannot be controlled and the composition of the mud changes after each run due to the turbidity caused by the passing ship. Mud was therefore simulated using a mixture of chlorinated paraffins and petrol; preliminary tests had revealed that such a material behaves in a similar way compared to natural mud, as the effects on a ship's performance and the interface motions are comparable (Vantorre, 1994). Density and viscosity values could be controlled in a certain range. The selected density-viscosity combinations (see Table 2) 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 density values mentioned in Table 2 are corrected values, taking account with the density ratio of sea water to fresh water, as interface deformations and hull, rudder and propeller forces mainly depend on the mud to water density ratio. In comparison with earlier investigations, the range of viscosities covered is much broader (e.g. Sellmeijer & van Oortmerssen, 1983: 0.028 – 0.031 Pa s). Unlike natural mud, the mud simulation materials were Newtonian fluids without yield stress, as no suitable Bingham fluid could be found. On the other hand, the effect of yield stress is reduced by the thixotropic characteristics of natural fluid. Another simplification concerns the uniformity of the simulated mud layers: in a 10 to 40 mm layer it is impossible to create gradients of density or rheologic characteristics.

Table 2. 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			

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.

2.4 Test types

For each combination of mud type, layer thickness and under keel clearance, a captive test program was carried out for determining mathematical manoeuvring models covering a range of forward speeds between 2 knots astern and 10 knots ahead. Taking account of the type of manoeuvres that has to be simulated, a large range of kinematical and control parameters was covered: drift and yaw rate angles from 0 to 360 deg, propeller actions ahead and astern, rudder angles from hard port to hard starboard.

The experimental program consisted of: bollard pull tests with varying rudder angle and propeller rate; stationary tests with varying forward speed, rudder angle, drift angle and propeller rpm; harmonic sway and yaw tests; multimodal tests with variable speed, rudder angle or propeller rpm.

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.

3 MATHEMATICAL MODELLING

A comprehensive mathematical model for the longitudinal and lateral force components and the yawing moment, that is valid for a wide range of forward and lateral speeds, yaw rates, rudder angles and propeller loadings, has been developed for each tested situation. 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:

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

As the mathematical models have to be valid in a broad range of conditions (four-quadrant propeller action, 360 deg drift and yaw angle), 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 PROGRAMME

4.1 Setup

Real-time simulations were performed with the cooperation of the Zeebrugge pilots. 15 pilots carried out 63 runs during 8 days above different bottom conditions. During this short span of time an optimal selection of bottom conditions and trajectories had to be made. In general three objectives had to be met:

- ✓ 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.

The selected conditions are represented in Figure 4.

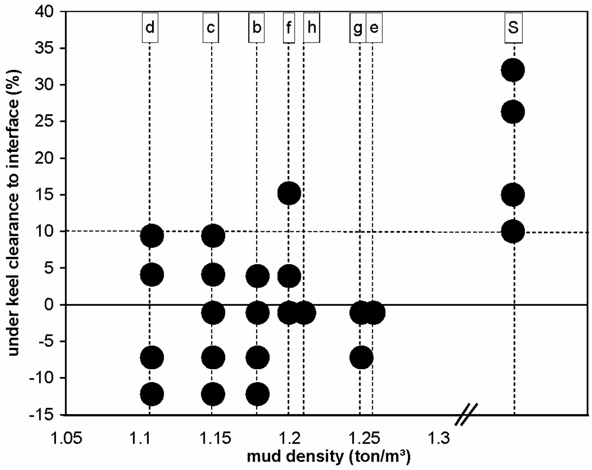

Fig. 4. Selected conditions for real-time simulation runs with ship D.

Table 2. Selected trajectories and division into sub-trajectories.

Trajectory	Sub-trajectory	Tugs	# runs
1. Arrival, berthing on starboard side at quay 205	1.1. Entering breakwaters	no	10
	1.2. Deceleration	yes	
	1.3. Rounding old mole	yes	
	1.4. Berthing	yes	
2. Arrival, berthing on port side at quay 205	2.1. Entering breakwaters	no	23
	2.2. Deceleration	yes	
	2.3. Rounding old mole	yes	
	2.4. Swinging	yes	
	2.5. Berthing	yes	
3. Departure from quay 205, moored on port side	3.1. Unberthing	yes	26
	3.2. Proceeding	yes	
	3.3. Rounding old mole	yes	
	3.4. Acceleration	no	
4. Arrival at Flanders Container Terminal.	4.1. Entering breakwaters	no	4
	4.2. Berthing	yes	

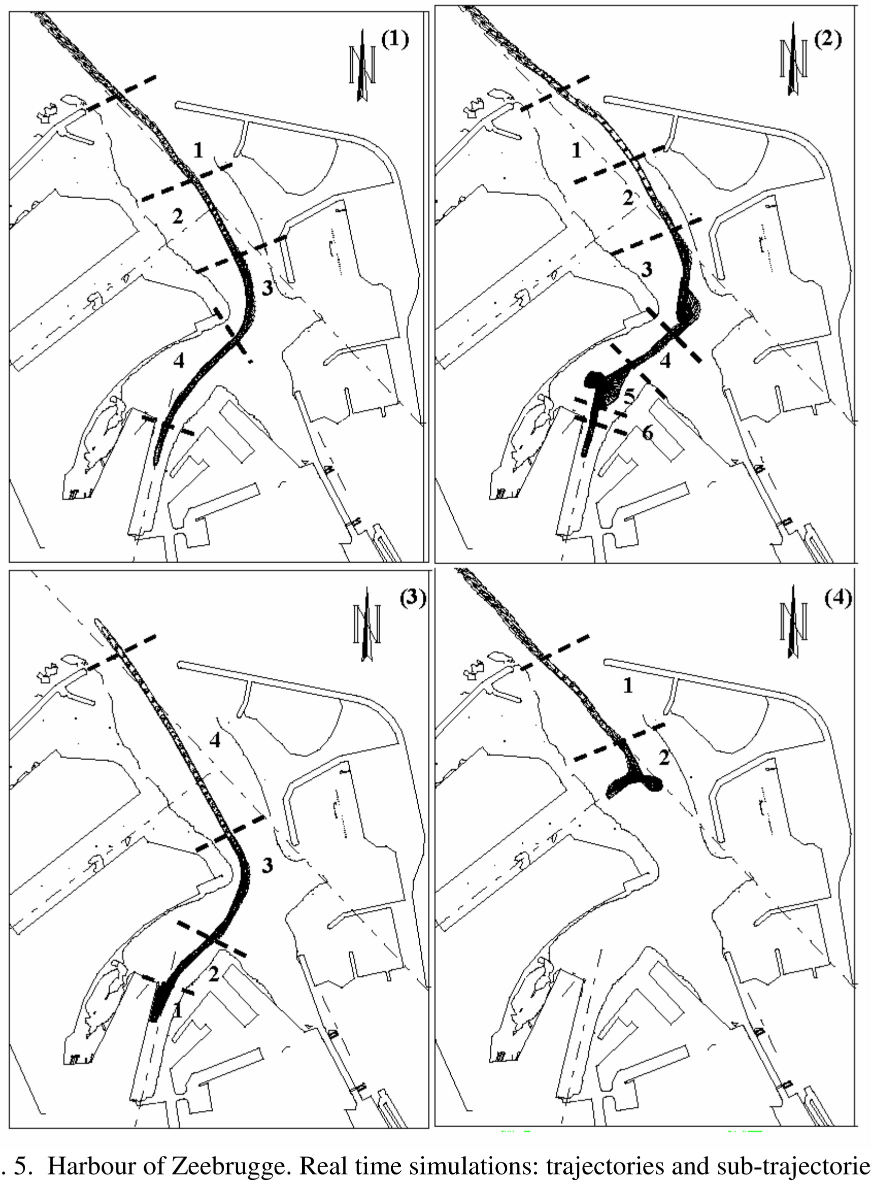

Fig. 5. Harbour of Zeebrugge. Real time simulations: trajectories and sub-trajectories.

Four trajectories that are typical for large deep-drafted container vessels calling at Zeebrugge were selected (see Table 2 and Figure 5). A link with the common practice in Zeebrugge and, therefore, the pilots' experience was guaranteed in this way; moreover, the manoeuvres involved covered a wide range of hydrodynamic conditions, such as different drift angles, propeller rates, forward speeds,…

During simulation runs pilots could rely on the capacity of two tugs of 40 ton bollard pull each. In some runs, the capacity was increased to 60 ton bollard pull. A moderate, frequently occurring wind condition (SW 4Bf) was selected, so that the evaluation of the manoeuvres would not be disturbed by extreme wind conditions. In some runs, the ship was subjected to stronger wind.

Tidal currents affect the ship behaviour in the area outside the breakwaters. At low tide, the magnitude of cross currents takes values of 2 to 2.5 knots. As these currents greatly affect the shipping traffic, realistic current patterns were introduced into the simulation environment.

4.2 Criteria of analysis of the simulation runs

After each simulation run pilots had the opportunity to give both oral and written comments. The following three criteria were decisive, and were used as a base for further analysis of the simulation runs:

- ✓ Speed. Is the vessel capable to reach a sufficient speed to counteract the tidal current when leaving the harbour (sub-trajectory 3.4)?
- ✓ Course stability. Can the vessel maintain its course by own means without excessive use of rudder and/or propeller (sub-trajectory 3.4)?
- ✓ Control power. Are the ship's own controls and the offered tug assistance sufficient to carry out the manoeuvres smoothly and safely?

4.3 Analysis based on the speed criterion

Figure 6 shows the speed of the vessel when reaching the breakwaters while leaving the harbour. To counteract the tidal current safely, pilots pointed out a speed of 10 knots was required. A speed of 8 knots or less was insufficient, as the ship drifted away to the sand banks outside the harbour. A speed between 8 and 10 knots was still acceptable.

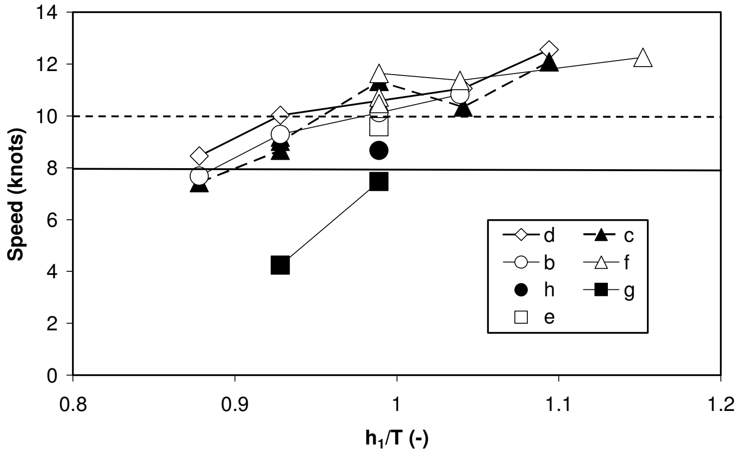

Fig. 6. Ship D, real time simulations.
Ship speed at the breakwaters when leaving the harbour (subtrajectory 3.4).

The speed criterion is decisive when navigating in contact with high density mud layers, as the ship resistance significantly increases. However in other harbours, which are not subjected to strong tidal currents, the speed the vessel reaches may be less important from the point of view of safety. On the other hand, significant speed reduction in long access channels may lead to unacceptable transfer times from an economic standpoint.

4.4 Analysis based on the course stability

Course stability is assessed by means of the standard deviation of the yaw rate of the ship while following a straight course: a large value means the ship has difficulty to maintain a constant heading. The standard deviation of the yaw rate when leaving the harbour (sub-trajectory 3.4) is represented in Figure 7.

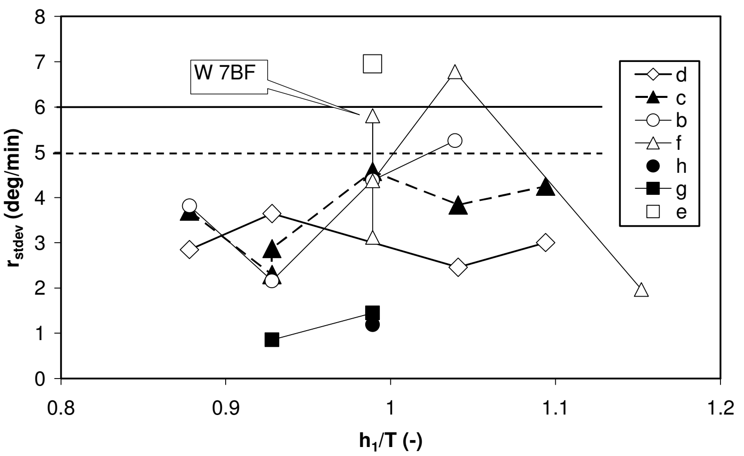

Fig. 7. Ship D, real time simulations.
Standard deviation of the yaw velocity of the ship's when leaving the harbour (subtrajectory 3.4).

Runs with a standard deviation exceeding 6 deg/min were explicitly rejected by the pilots due to lack of course stability. The use of the standard deviation of the yaw is therefore a relevant decision factor. Runs with standard deviation between 5 and 6 deg/min were labelled as marginally acceptable.

4.5 Analysis based on the control power

Introduction

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

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

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

S_i being the the force of tug 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.

Expressions (2) and (3) offer the advantage that both the force and the span of time required to carry out the manoeuvre are taken into account. If only the force were analysed, an excessive force yielding a fast manoeuvre would result into a rejection, while the pilot was only in a hurry to finish his work. On the other hand some dynamic effects are not taken into account by (2) and (3). As the execution time of the manoeuvres only varies within a rather limited range, this effect will only be marginal.

Because the contribution of own controls to the impulse functions I_Y and I_N does not vary significantly for the different simulation runs, following expression can be used to assess the manoeuvrability of the ship when assisted by tugs with different bollard pull:

$$I_{Y,\max}^{(x\ \text{ton})} = I_{Y,\max}^{(45\ \text{ton})} \left(\frac{I_{YR}}{I_Y} + \frac{x}{45} \frac{I_{YT}}{I_Y} \right) \qquad (4)$$

For the different sub-trajectories carried out with tug assistance, the control power above different bottom conditions is compared. Sub-trajectories in which the lateral movement is dominating, as (un)berthing, are assessed using the impulse I_Y. On the other hand, if the ship carries out a yaw manoeuvre, as with rounding the old mole, the control power is examined with the impulse I_N. The emphasis is put on the (un)berthing manoeuvre and rounding the old mole as those proved to be the most critical manoeuvres.

Berthing and unberthing

The comparison of the impulse I_Y when leaving quay 205 is represented on Figure 8. Runs, in which pilots commented the control power was not sufficient to guarantee a safe berthing manoeuvre, are encircled. Based on Figure 8 an acceptability limit can be defined for different tug power using expression (4).

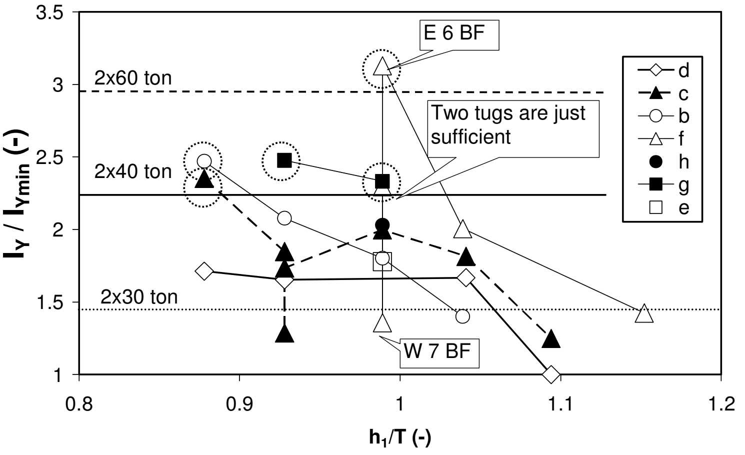

Fig. 8. Ship D, real time simulations. Impulse of steering force when leaving quay 205 (subtrajectory 3.1); encircled symbols denote unacceptable conditions.

Of particular interest is the effect of the wind condition. It can be noted that the wind has a far more important influence on the manoeuvre than the bottom condition. Due to the location of quay 205, see Figure 5, a SW wind will facilitate the departure, while an arrival will be more difficult. Due to lack of time the arrival manoeuvres were not fully executed, but the limits at arrival will be somewhat more severe as the SW wind counteracts the manoeuvre. Also the role of the E and W wind will be inversed.

Rounding the old mole

Rounding the old mole will be different during arrival compared with departure, as in the first case the ship, which needed sufficient speed to counteract the tidal current when entering the harbour, has to slow down. The speed at the beginning of the manoeuvre will therefore be higher, and the ship will be still relying more on its own controls. This explains the difference between the two sub-trajectories concerning the critical values, see Figures 9 and 10, where both I_{Nmin} are of the same magnitude.

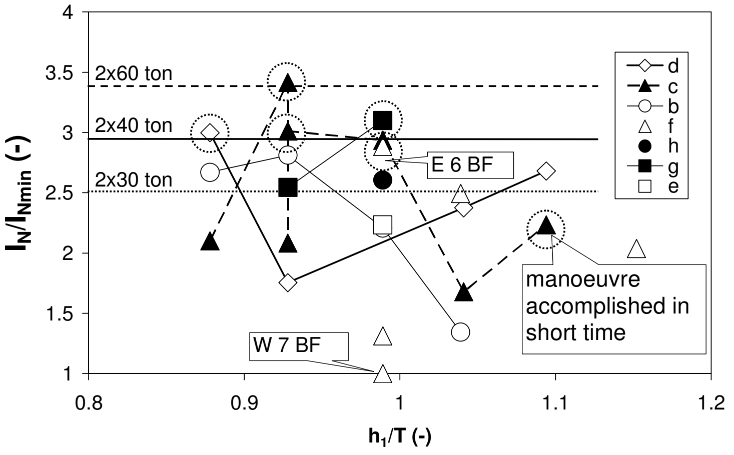

Fig. 9. Ship D, real time simulations. Impulse of steering moment of the ship's when turning around the old mole (subtrajectory 3.3); encircled symbols denote unacceptable conditions.

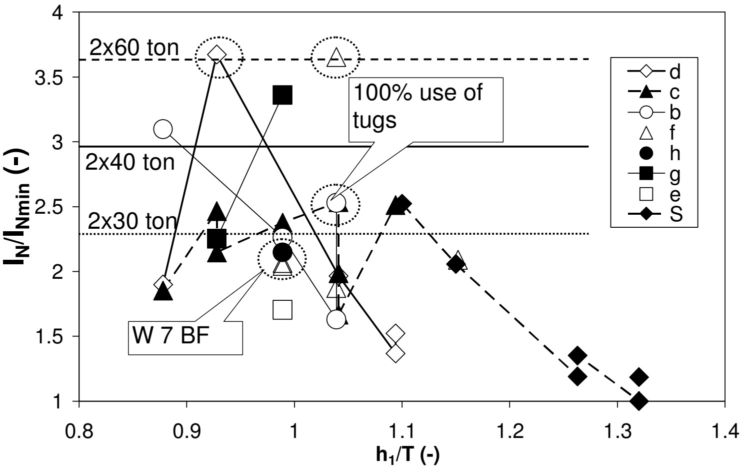

Fig. 10. Ship D, real time simulations. Impulse of steering moment of the ship's when rounding the old mole (subtrajectories 1.3 and 2.3); encircled symbols denote unacceptable conditions.

A limit is drawn for assistance by two tugs of 45 ton bollard pull when arriving at the harbour. The figures also show manoeuvres characterised by rather low impulse values that had nevertheless been rejected by the pilots, claiming that no redundant tug power was left. The analysis, on the other hand, revealed that the manoeuvres would have been completed successfully with less tug power, as they were accomplished in a record time.

Analysis of the control power clearly shows the importance of the available tug assistance. If only two tugs of 30 ton bollard pull were available, touching the mud layer always results in dangerous situations, so that the nautical bottom should be at least located near the water-mud interface.

4.6 Analysis based on all criteria

Taking all criteria into consideration, a classification of the runs above different bottom conditions has been made when the ship is assisted by two tugs of 45 ton bollard pull, see Figure 11. The manoeuvring behaviour is unacceptable when the keel touches a mud layer of a density of 1.20 ton/m³ or more. According to the definition of the nautical bottom, the nautical bottom can be defined at 1.20 ton/m³.

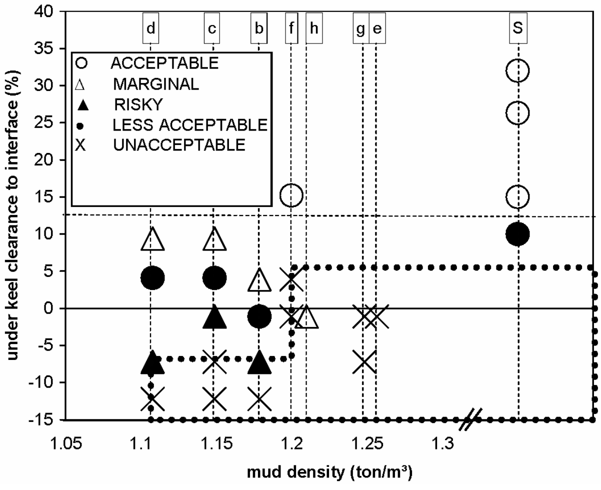

Fig. 11. Ship D, real time simulations. Quantitative evaluation of all criteria with assistance by two tugs of 45 ton bollard pull (dotted area = "unacceptable").

The navigability through lower density mud layers is also constrained to -7% under keel clearance. Assistance of two tugs of 60 ton bollard pull does not change the level of the nautical bottom, but does increase the navigability through lower density mud layers up till -12% under keel clearance, as can be seen on Figure 12.

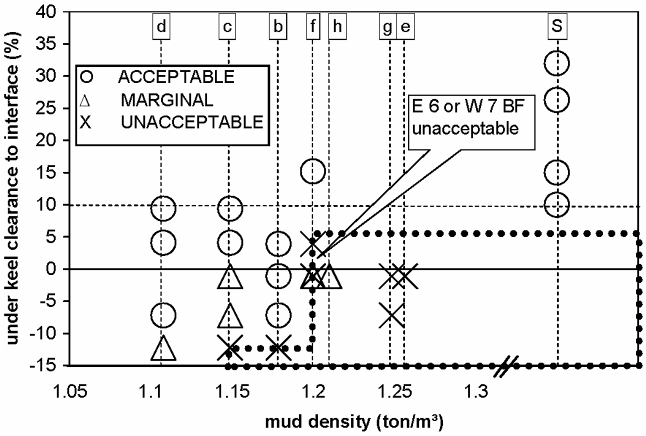

Fig. 12. Ship D, real time simulations. Quantitative evaluation of all criteria with assistance by two tugs of 60 ton bollard pull (dotted area = "unacceptable").

As pointed out in paragraph 4.3 the speed criterion is mainly dependent of the specific situation of Zeebrugge. A classification is therefore also made excluding this speed criterion, see Figures 13 and 14. Excluding the speed criterion has no effect on the definition of the nautical bottom, but increases the navigability through lower density mud layers when assisted by two tugs of 60 ton bollard pull. With assistance of two tugs of 45 ton bollard pull, the classification is only affected marginally, as the control power is the decisive factor.

Finally, it is also worthwhile to mention that manoeuvring in muddy areas is completely different compared to hard bottom conditions, and that pilots should be informed about the modified ship behaviour and trained accordingly. Especially with a small positive under keel clearance relative to the water-mud interface, difficulties in ship handling are observed. Therefore, pilots should not only have full knowledge of the position of the nautical bottom, but also of the interface.

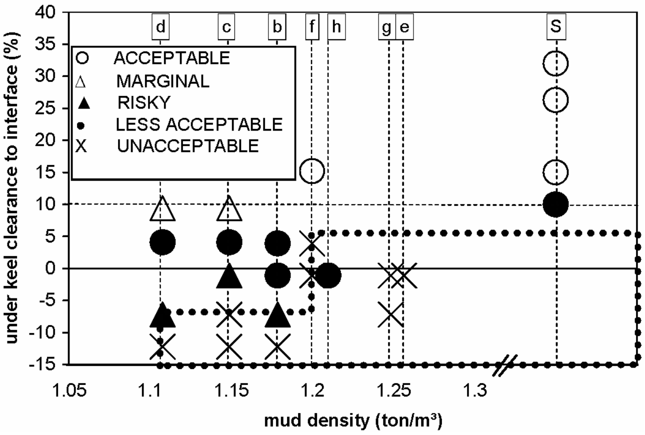

Fig. 13. Ship D, real time simulations with assistance by two tugs of 45 ton bollard pull. Quantitative evaluation of all criteria excluding the speed criterion (dotted area = "unacceptable").

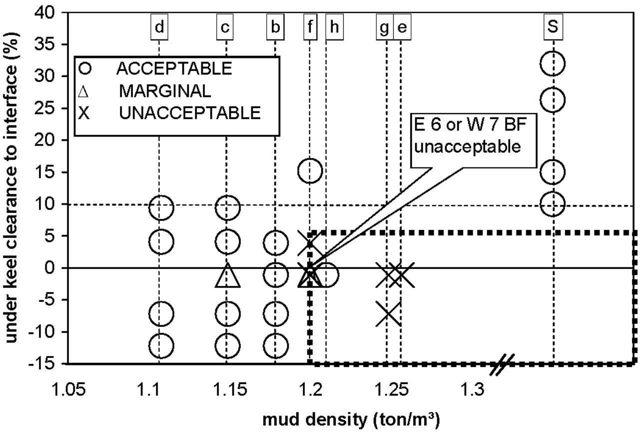

Fig. 14. Ship D, real time simulations with assistance by two tugs of 60 ton bollard pull. Quantitative evaluation of all criteria excluding the speed criterion (dotted area = "unacceptable").

5 CONCLUSIONS

A series of real-time full mission bridge simulations has been carried out by the Zeebrugge pilots in order to define the nautical bottom of the harbour of Zeebrugge. As a result, the nautical bottom can be redefined at a critical density of 1.20 ton/m³. This definition is certainly not without limitations:

- ✓ At least two tugs of 45 ton bollard pull have to assist manoeuvres of deep drafted container vessels;
- ✓ Navigability through lower density mud layers is constrained to -7% of under keel clearance;
- ✓ More tug power reduces this constraint, but does not affect the definition of the nautical bottom;
- ✓ If less tug power is available the mud-water interface should be considered as the nautical bottom;
- ✓ The present situation in the access channel outside the breakwaters should not be changed;
- ✓ Pilots must be informed on the mud layer properties between the interface and the nautical bottom;
- ✓ Pilots must be aware of the modified controllability of a ship navigating with reduced ukc or negative ukc relative to the mud-water interface, and should receive an appropriate training.

It should be emphasized that these specific conclusions are only valid for deep-drafted container carriers calling at or leaving 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.

An increase of the nautical bottom from 1.15 to 1.20 ton/m³ has some important advantages for the harbour of Zeebrugge. In the first place, the navigable depth (temporarily) increases without additional dredging efforts. More fundamentally, the efficiency of dredging activities will be improved, as dredging will take place in mud layers of higher density.

6 FUTURE EFFORTS

Efforts will be carried out in the near future to take full advantage of the results of the current research project.

- ✓ 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.
- ✓ Additional simulation runs in a larger range of bottom and weather conditions will be carried out in order to improve the decision scheme to be used by the pilots as a guideline. The involvement of a large group of pilots is important, as the human factor plays an important role in the simulation results.
- ✓ Training sessions will be organised for the Zeebrugge pilots to familiarise themselves to the modified ship behaviour.

- ✓ The simulation runs carried out during the current research project were performed above a constant bottom condition throughout the harbour. A mathematical simulation model allowing transitions between several types of muddy bottoms will be developed in order to increase the realism of the simulations.
- ✓ Additional model testing is planned to extend the mathematical model to bow thruster assisted manoeuvres. Indeed, pilots criticized the lack of a bow thruster during the simulations.

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