A NOVEL METHODOLOGY FOR REVISION OF THE NAUTICAL BOTTOM

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Abstract

Since the 1980s, the nautical bottom in the outer harbour of Zeebrugge is determined by the 1150kg.m^{-3} density level, as due to siltation conventional bottom survey techniques are not adequate. As a consequence of modifications of the mud layer characteristics, a revision of this criterion was required. A research project, involving comprehensive captive model testing in a manoeuvring tank with a bottom covered with mud simulating materials, mathematical modelling and real-time full mission bridge simulator runs, resulted in new criteria, based on the ship behaviour and controllability in muddy navigation areas. The application of the results of this research project increases the efficiency of maintenance dredging works and contributes to the safety of shipping traffic, as the pilots involved in the manoeuvres obtain a more profound insight into specific aspects of ship behaviour.

Motivation

Introduction

Due to sedimentation, permanent maintenance dredging works are required to keep many ports accessible for deep-drafted sea-going vessels. In case of hard bottoms such as rock, clay or sand, the depth of the navigation areas can be determined unambiguously by means of echo sounding techniques; if the bottom is covered with soft mud layers, however, the boundary between water and bottom may be hard to define. In this case, the customary concepts 'bottom' and 'depth' are to be replaced with 'nautical bottom' and 'nautical depth'.

Navigation in muddy areas is not a new problem. The Flemish coastal harbour of Zeebrugge is subject to sedimentation since its major extension in the 1970s. Also in other harbours all over the world, the definition of the bottom and sounding techniques needs to be adapted to the presence of sedimentations: this is the case for the access channels to several harbours in the Netherlands (Rotterdam), France (Bordeaux, Nantes – Saint-Nazaire, Cayenne), Germany (Moderort, Emden, Weser, Brunsbüttel fairways) and the USA. In many harbours (e.g. Bangkok, Maracaibo), it is even common practice to navigate through the mud layer.

Neither is ship controllability in muddy navigation areas a new research topic. The first tests with a tanker model above and in contact with mud layers simulated by a mixture of chlorinated paraffin and kerosene were carried out in 1976 at MARIN (Wageningen, the Netherlands: Sellmeijer *et al.*, 1983). In 1986-89, a preliminary test facility for self-propelled ship models was constructed at Flanders Hydraulics Research (Antwerp, Belgium: Van Craenenbroeck *et al.*, 1991; Vantorre, 1991) in order to investigate some aspects of a ship's behaviour in muddy waterways; for this purpose, both natural, artificially composed and simulated mud layers were used. Also at SOGREAH (Grenoble, France: Brossard *et al.*, 1990) towing tests with a tanker model were carried out in 1989. More recently, model tests were conducted at the Bundesanstalt für Wasserbau in Hamburg (Uliczka, 2005). Not only model tests were conducted: reports of full scale experiences with ships navigating with reduced and even negative under keel clearance referred to the water-mud interface in Rotterdam, Nantes – Saint-Nazaire and Zeebrugge were published in the 1970s and 80s.

The present paper intends to give an overview of a comprehensive research project executed in 2001-2004 at Flanders Hydraulics Research (Antwerp) in close cooperation with the Maritime Technology Division of Ghent University, with the main purpose of redefining the boundaries of safe navigation in the harbour of Zeebrugge. This investigation, that was required due to considerable modifications of the local mud properties, followed an innovative approach as the definition of the nautical bottom is closely linked to the acceptable limits of ship behaviour and controllability.

Nautical bottom concept

Definition

The navigation of ships in channels and harbours subject to sedimentation is closely linked to the nautical bottom concept that is often introduced in these areas in case of difficulties with bottom survey techniques or with the interpretation of survey results. A typical example is the frequency dependence of the results of echo-sounding: while high-frequency echoes (e.g. 210kHz) reflect at the mud-water interface, lower frequency signals (e.g. 33kHz) penetrate much deeper into the mud and also give less clear results.

A joint PIANC-IAPH working group (PIANC, 1997) defined the 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'. In this way, the nautical bottom is identified as the level that should not be touched by the ship's keel. In case of a hard bottom, this is an obvious statement, but the definition is valid in other situations where the bottom can be defined in different ways, e.g. when the bottom is covered with boulders or sand dunes. In muddy areas, the nautical bottom can be interpreted as the level where the navigable fluid mud ends and the non-navigable seabed begins.

Implementation

The strength of this definition is, therefore, the very general application field. On the other hand, this definition rather suggests a general philosophy, without giving a practical solution. On the contrary, a number of questions are raised:

- Which physical characteristic should be selected?
- Which numerical value for this characteristic should be considered as a critical value?
- What is meant by 'unacceptable effects'?

With respect to the last question, it is clear that the degree of acceptance depends on a huge variety of – objective and subjective – parameters, including local environmental conditions, degree of training and expertise of the pilots, availability of tug assistance, quality of aids to navigation, economic considerations.

Considering the first two questions, it is most obvious that a physical characteristic should be selected that is directly linked with forces exerted by contact between a ship's hull and mud layers. In this respect, a rheological property – such as viscosity or yield stress (i.e. the shear stress to be overcome in order to initialise material flow) – could be used to determine a suitable criterion. A typical depth-rheology relation is shown in Fig. 1, left. Just below the water-mud interface, the rheological properties of the mud are hardly different from those of water. At a certain level, defined as the ‘rheological transition’, yield stress and viscosity increase very quickly with depth. Moreover, full scale tests with a suction hopper dredger in Zeebrugge have shown that a ship’s behaviour becomes unacceptable if her keel touches this level: a ship becomes uncontrollable and follows the ‘easiest’ way in the mud. At the same time, it is practically impossible to decrease speed, even not at one or two knots. This rheological transition level could therefore be identified as the nautical bottom.

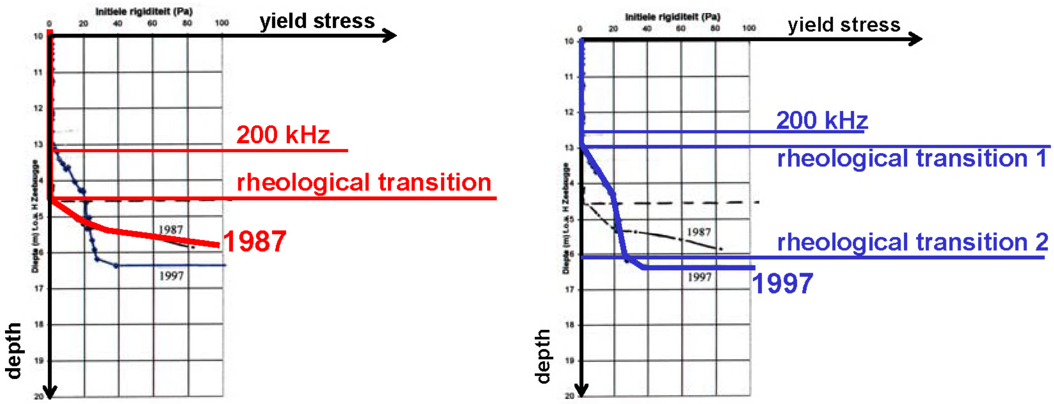

Fig. 1. Rheology as a function of depth in Zeebrugge harbour: measurements in 1987 (De Meyer and Malherbe, 1987) and 1997.

Nevertheless, most harbour and waterways authorities that have introduced the nautical bottom concept make use of a density criterion: in Rotterdam, Nantes – Saint-Nazaire and Bordeaux a density level of 1200kg.m^{-3} has been adapted; in Cayenne, the nautical bottom coincides with a density of 1270kg.m^{-3}. An exception should be made for the methodology applied in the access channels to German harbours, where a dynamic viscosity of 10Pa.s is used as a criterion; the corresponding density values vary from 1100 to 1250kg.m^{-3} (Uliczka and Liebetruth, 2005). The reason for this variation can be found in the fact that there is no fixed relationship between the mud density – a characteristic that is directly related to the concentration of solid material in the suspension – and the rheological properties of the mud. It is clear that the latter increase with increasing density, but also the dimensions of the solid particles matter: for an equal density, the viscosity increases if the fraction of small particles is larger. Therefore, the rheological properties also depend on the mud content, i.e. the fraction of particles smaller than 63μm. Therefore, it is impossible to define a universal value for the critical density.

The reason why the nautical bottom is usually expressed in function of a critical density, is related to the disadvantages of rheological *in-situ* measurements. A continuous rheological survey method, comparable to echo-sounding, is not available. Furthermore, mud rheology is influenced by the sampling method, which makes it difficult to compare data from different sources. This is a consequence of the thixotropy of the mud: the yield stress decreases if the material is disturbed, so that mud behaves more like a liquid after it has been stirred.

It can therefore be concluded that a rheology-based property such as the rheological transition level provides an excellent criterion, but can only be determined by time-consuming point measurements. In order to provide a practical criterion, a critical density is selected, based on considerations about the rheological properties of the local mud. In Zeebrugge, the density corresponding with the rheological transition was determined at a large number of locations;

eventually, the 1150kg.m^{-3} was selected as at all locations the rheological transition was located below that horizon (Kerckaert *et al.*, 1985, 1988).

The use of classical echo-sounding techniques in a nautical bottom approach requires some attention (Fig. 2). If acoustic signals with different frequencies reflect at different levels, a useful qualitative indication is given about the presence of fluid mud layers. High frequency echoes (100-210KHz) indicate the interface water-mud, while low frequency signals (15-33KHz) penetrate deeper and are normally reflected somewhere in the consolidated mud layer or the hard bottom.

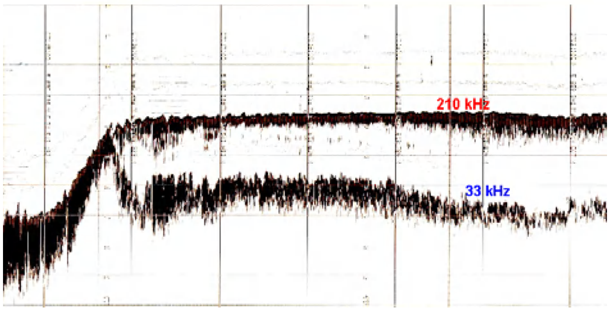

Fig. 2. Echo sounding in muddy areas: high and low frequency signal (De Brauwer, 2005).

At some locations, the low frequency echo is considered to coincide with the nautical bottom. This approach offers the advantage of simplicity: no additional instrumentation is required. On the other hand, the interpretation of low frequency echoes in mud layers is rather subjective, as several echoes may be registered. Moreover, several observations show that the reflection of a low frequency signal takes place at a level where the mud is characterised by a considerable yield stress and viscosity.

Additional requirements

In order to guarantee safe navigation in muddy areas, a clear definition and practical survey method for determining the nautical bottom is a first requirement. However, additional information is required to assess safety of navigation.

In the first place, a minimum value of the under keel clearance (UKC) needs to be determined; this value may depend on temporal and local conditions, as is also the case above a hard bottom.

The pilot and master should also have a clear insight into the ship behaviour in the given conditions. A ship may be controllable, but her reactions to actions of rudder, propeller, bow thruster or tugs may be completely different compared to solid bottom conditions. This behaviour may depend on a variety of parameters, such as vessel speed, the ship's (positive or negative) under keel clearance referred to the mud-water interface, the physical characteristics of the mud layers touching the ship's keel, etc.

Revision of the nautical bottom criterion for the harbour of Zeebrugge

The methodology described above to determine the nautical bottom by means of a critical density is a pragmatic one, but has several drawbacks. In the first place, it should be borne in mind that this density level has no absolute value, but is linked to the local mud characteristics.

Secondly, the validity of this critical density value should be checked on a regular base, as mud characteristics such as mud/sand content may vary over the years.

In the outer harbour of Zeebrugge, the determination of the nautical bottom based on a critical density value of 1150kg.m^{-3} worked well in practice for several years. In the mid 1990s, however, an increase of the mud layer thickness was observed; moreover, it appeared to be more difficult to control the 1150kg.m^{-3} level by maintenance dredging works. A measuring campaign in 1997 revealed that the rheology profile of the mud had significantly changed (Fig. 1, right). A first, small rheological jump occurred just below the water-mud interface while a second, more important one occurred at a depth of 3 to 4m under the interface, corresponding with a density that is significantly higher than the current critical value of 1150kg.m^{-3}. The interested parties consequently considered an increase of the critical density limit. For maintenance dredging the intrinsic dredge output could be significantly improved by dredging mud of a higher density.

From a nautical perspective, however, an increase of the critical density would have important consequences. With a critical density of 1150kg.m^{-3} 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 would inevitably result in contact between the keel of deep-drafted container ships and the mud layer and possibly in unacceptable effects on ship handling. In order to investigate these effects, a research project was started at Flanders Hydraulics Research in Antwerp, with the scientific support of the Maritime Technology Division of Ghent University. Indeed, 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 was required (PIANC, 1997; Vantorre, 1994).

Initial state of the art

As mentioned above, only a few research institutes have investigated ship behaviour in muddy areas. A summary of the results of these research projects will be given in order to define the initial state of the art.

Causes of deviating behaviour

At first, the causes of different behaviour due to the presence of mud layers compared to a solid bottom situation are considered. Two main causes can be identified:
- the rheological properties of the mud;
- the presence of a second fluid layer and, therefore, a second interface: above a solid bottom, only a water-air interface is present, while in muddy areas also a water-mud interface occurs.

Although interactions cannot be denied, in general it can be stated that the first cause is mainly of importance in case of contact between the ship's keel and the mud layer; the second, on the other hand, also affects the ship's behaviour in case no contact takes place, as a result of undulations – vertical interface motions – generated in the mud-water interface due to the pressure field around the moving hull.

Interface undulations

These vertical interface motions are influenced by the ship's forward speed (Fig. 3):

- At very low speed, the interface remains practically undisturbed (1st speed range).

- At intermediate speed, an interface sinkage is observed under the ship's entrance, which at a certain section changes into an elevation. This internal hydraulic jump is perpendicular to the ship's longitudinal axis and moves towards the stern with increasing speed (2nd speed range).
- At higher speeds, the interface jump occurs behind the stern (3rd speed range).

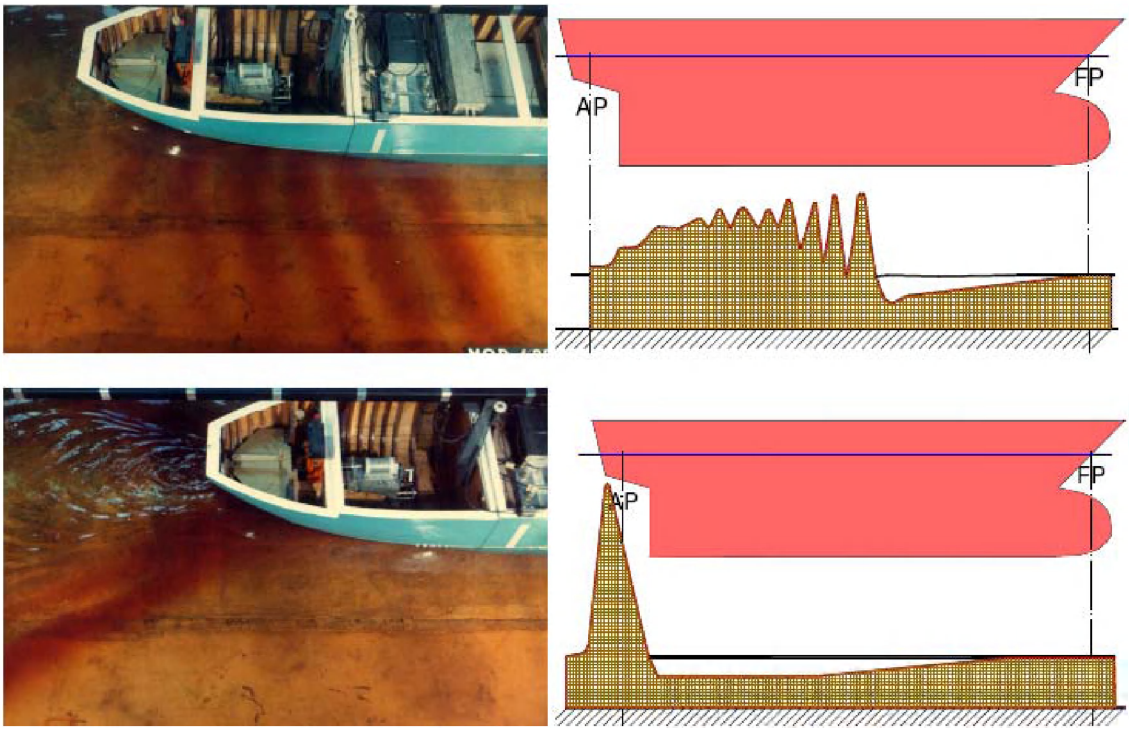

Fig. 3. Mud-water interface undulations: second speed range (above), third speed range (below) (Vantorre, 2001).

It can be shown by means of a simplified theory that the critical speed separating the second and third speed ranges can be calculated as a function of the mud to water density ratio and the water depth (Fig. 4). It is clear that this critical speed value is situated in the usual speed range at which harbour approach takes place.

Resistance and propulsion

The effect of interface deformation on the propulsive properties of a ship is clearly illustrated by the relation between forward speed and propeller rate. In the second speed range, a given propeller rpm results in a significantly lower speed compared to a solid bottom situation; it appears to be difficult to overcome the critical speed. In the third speed range, the effect of the muddy bottom is practically nil (Fig. 5). The transition between second and third speed range is very clear at under keel clearances of 10 to 20% of draft relative to the interface, but is smoothed with decreasing under keel clearance.

One would expect this effect to be caused by increased resistance in the second speed range. There are indications, however, that the speed reduction in the second speed range observed in the speed-rpm relationship is not caused by increased resistance, but by obstruction of the flow to the propeller due to contact between the ship's keel and the risen interface. An important increase of the thrust coefficient is observed in these conditions, which indicates an increase of the wake factor.

It can be concluded that poor propulsive efficiency can occur in the second speed range, if the risen interface touches the ship's keel, while the entrance is fully in contact with the water. In these conditions, controllability problems with a backing propeller are expected as well, which may affect the stopping distance.

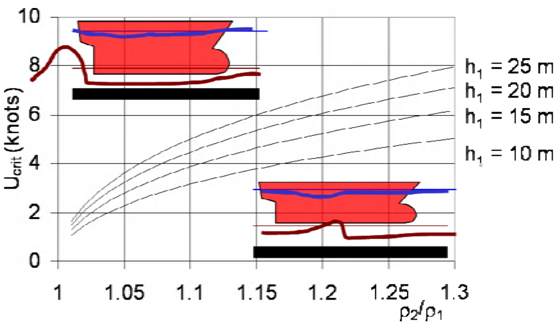

Fig. 4. Critical speed separating 2nd and 3rd speed ranges as a function of mud-water density ρ_2/ρ_1 ratio for different water depths h_1:

$$U_{crit} = \left[0.296\, g h_1 \left(1 - \rho_1/\rho_2\right)\right]^{0.5}$$

(Vantorre, 2001).

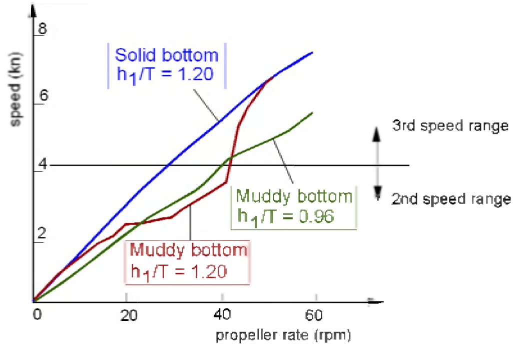

Fig. 5. Relationship speed – propeller rate: influence of bottom characteristics and under keel clearance (Vantorre, 2001).

Manoeuvrability

Simulations based on the captive model tests carried out at MARIN resulted into following conclusions concerning the effect of mud on ship manoeuvrability:

- The effect of mud is larger at low speed (3 knots) than at higher speed (7 knots).
- Manoeuvres are slower with mud, especially at low positive UKC relative to interface.
- Mud slackens steady motions (speed, drift, rate of turn during turning circle tests), but accelerates dynamic motions (overshoot and swept path during zigzag tests).
- A correlation between manoeuvrability and internal waves is observed.

Rudder action is affected due to the presence of a fluid mud layer in several ways. The most striking effect is so-called instability of rudder action which was observed during self-propelled model tests at Flanders Hydraulics Research if the ship's keel touches both water and mud: in these conditions, a rudder deviation may lead to reversed effects at small rudder angles.

Summarised, manoeuvrability and controllability are mainly affected at low speed and small positive under keel clearance referred to the mud-water interface.

Discussion

The conclusions of former research programs are certainly useful for a better understanding of the physical mechanisms that cause the modified ship behaviour in muddy navigation areas.

However, the available information was certainly not sufficient for redefining the nautical bottom in the harbour of Zeebrugge. As a matter of fact, several questions remained unanswered:

- According to the information summarised above, ship behaviour is mostly affected at small positive under keel clearance with respect to the mud-water interface; further penetration into the mud would lead to an improvement of the controllability of the ship. On the other hand, common practice indicates that there must be a maximum acceptable penetration into the mud.
- Previous work mainly considered low viscosity mud layers, so that the present range of rheological characteristics of the Zeebrugge mud was not covered (Fig. 6).
- Only full form ships, mainly tankers, were investigated in the past, while presently container traffic has the highest priority for most harbours, including Zeebrugge.
- A complete mathematical model allowing simulation of harbour manoeuvres, including backing and berthing, has to be available to assess 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.

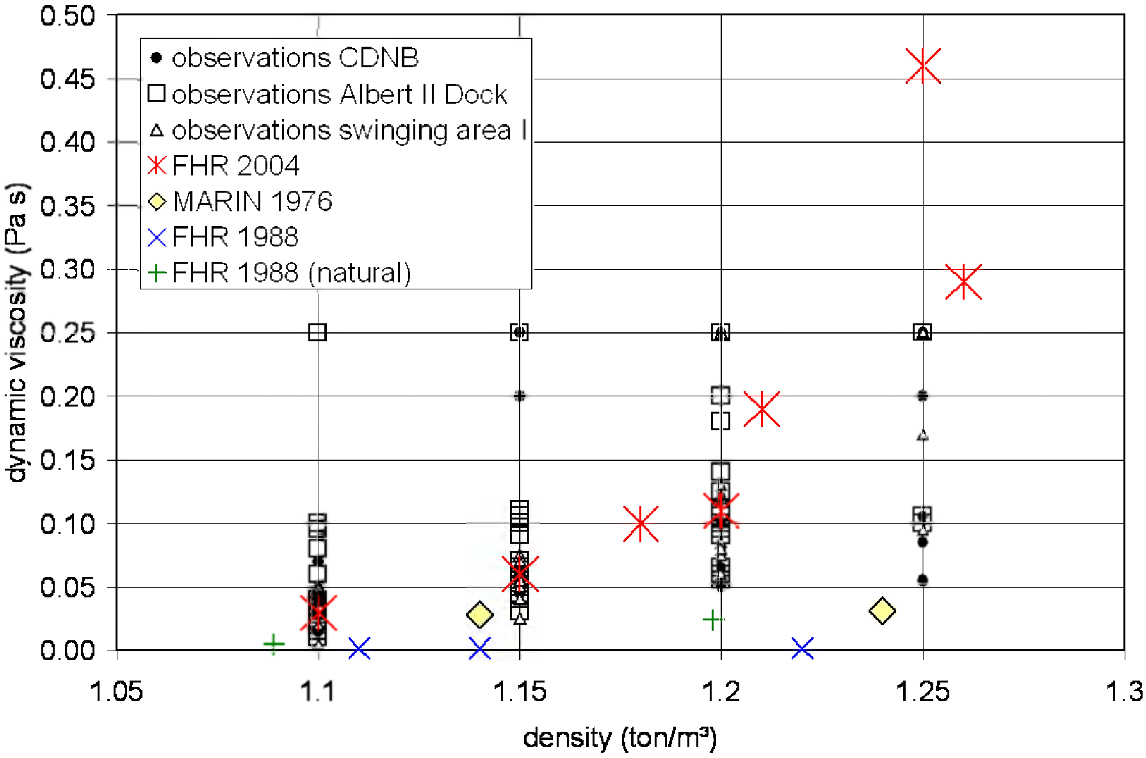

Fig. 6. Density-viscosity combinations: observations in Zeebrugge (1998) and model tests.

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 project consisted of three phases:

- captive model tests in the towing tank for manoeuvres in shallow water with ship models navigating above and through simulated mud layers;
- development of mathematical models suited for manoeuvring simulation based on the model test results;
- execution of fast-time and real-time simulation runs in realistic situations.

Experimental program

Test facilities

Flanders Hydraulics Research, the hydraulic research station of the Waterways and Maritime Affairs Administration of the Ministry of Flanders, is particularly concerned with the investigation of ship hydrodynamics for problems in relation with the concept, adaptation and operation of navigation areas. Therefore, the (very) shallow water range – occurring in access channels, canals, harbours – is a main research domain.

Nautical aspects of these problems can be investigated by means of two full mission ship manoeuvring simulators. In order to provide the mathematical model of these simulators with reliable and realistic data, experimental facilities for ship model testing have been developed. At present the latter consist of a shallow water towing tank (88m*7.0m*0.6m), equipped with a planar motion carriage, a wave generator and an auxiliary carriage for ship-ship interaction. The computerised control and data-acquisition allows fully automatic operation of the facilities, so that tests can be performed twenty-four hours a day, seven days a week.

Ship models

For the investigation of navigation in muddy areas, two 1/75-scale models were selected: a 6000 TEU container carrier (model D: L_{pp}= 289.8m; B= 40.25m; T= 13.50m; C_B= 0.59) and a full form (type tanker / bulk carrier, model E: L_{pp}= 286.8m; B= 46.77m; T= 15.50m; C_B=0.82). A limited number of model tests was also conducted with an 8000 TEU container carrier (model U: L_{pp}=331.8m; B=42.8m; T=14.5m; C_B=0.65; scale 1/80). Most experiments have been carried out with model D, taking account of the importance of container traffic for the harbour of Zeebrugge. All ship models were equipped with a propeller and a rudder.

Bottom conditions

The mud was simulated by a mixture of two types of chlorinated paraffin and petrol, so that both density and viscosity could, within certain ranges, be controlled. For environmental reasons, the tank was divided into three compartments: a test section, a 'mud' reservoir and a water reservoir. Bottom and walls were covered with a polyethylene coating (Fig. 7).

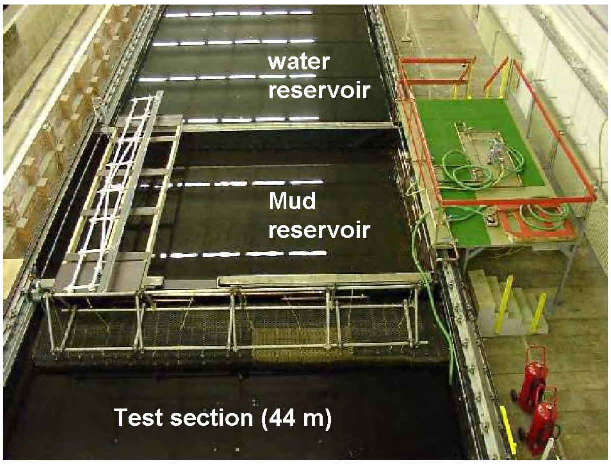

Fig. 7. Towing tank lay-out (photograph Flanders Hydraulics Research).

The selected density-viscosity combinations and the tested bottom conditions are represented in Fig. 6. This selection was based on measurements of density and rheology profiles *in situ* 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 (0.75m, 1.50m and 3.00m, respectively). Tests carried out above a solid bottom are referred to as 'S'. The bottom conditions applied to ship model D are listed in Table I.

Table I. Tested bottom conditions for model 'D' (6000 TEU container carrier)

Mud type	'd'	'c'	'b'	'f'	'h'	'e'	'g'	'S'
Density (kg.m^{-3})	1100	1150	1180	1200	1210	1260	1250	–
Dynamic viscosity (Pa.s)	0.03	0.06	0.10	0.11	0.19	0.29	0.46	–
Layer thickness no.	1/2/3	1/2/3	1/2/3	2	1/2/3	2	1/2/3	–

For model D the under keel clearance relative to the tank bottom was varied between 7 and 32% of draft, yielding an under keel clearance relative to the mud-water interface varying between –12 and +21% (see Fig. 8). For model 'E' the values for the under keel clearance were extended between 10 and 15% of draft referred to the tank bottom, and from –10% to +10% relative to the mud-water interface.

3.0 m				1.5 m				0.75 m	
+10%	+15%	+26%	+32%	+10%	+15%	+26%	+32%	+10%	+15%
–12%	–7%	+4%	+10%	–1%	+4%	+15%	+21%	+4%	+9%

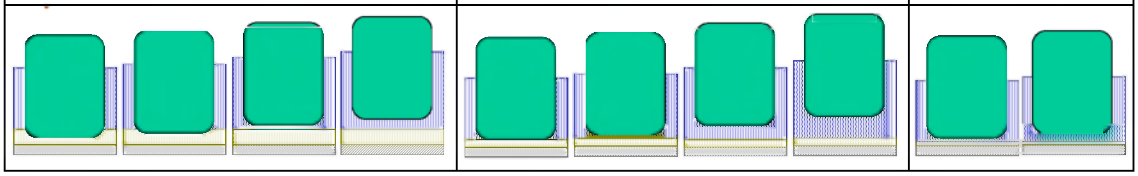

Fig. 8. Tested combinations of mud layer thickness (1st row), under keel clearance to solid bottom (2nd row) and to mud-water interface (3rd row).

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. During captive model tests, a trajectory in the horizontal plane – involving combined longitudinal (surge) and lateral (sway) translations and rotation about the vertical axis (yaw) – is imposed to the ship model by means of the planar motion carriage; however, the ship model is free to move in the vertical plane (heave, pitch). The roll motion was fixed during the test program. These motions can be combined with rudder and propeller actions, which do not influence the ship's trajectory, but make it possible to investigate the effect of control parameters on the hydrodynamic forces and moment acting on the ship. Indeed, during captive tests, lateral and longitudinal force components are measured at two measuring posts, fore and aft, so that the horizontal force components and yaw moment due to a combination of kinematic (velocities, accelerations) and control (rudder angle, propeller rate) on the ship. Forces acting on the rudder (normal and tangential components, torque) and the propeller shaft (thrust, torque) are measured too, as well as the vertical ship motion (sinkage, trim). In particular cases, the vertical motion of the mud-water and water-air interfaces were registered as well.

The experimental program consisted of:

- Bollard pull tests: tests at zero speed with varying rudder angle and propeller rate;
- Stationary straight-line tests ('oblique towing'): combination of ship speed, propeller rate, rudder angle and drift angle;
- Harmonic yaw and sway tests: combinations of speed, rpm, amplitude and period;
- Multimodal tests: harmonic variation of propeller rpm, rudder angle or ship speed;
- Combined multimodal tests for validation.

For each combination of ship model, bottom condition and under keel clearance, a standard test program of 224 runs was carried out.

Mathematical manoeuvring model

General concept

Based on the results of the captive model tests, a mathematical manoeuvring model for simulation purposes has been developed for each combination of ship model, bottom condition and under keel clearance. A mathematical manoeuvring model consists of a set of equations expressing the longitudinal (X) and lateral (Y) force components and the yawing moment (N) as a function of the ship's horizontal motion (velocities, accelerations) and control parameters (rudder and propeller actions). 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: $F = F_H + F_P + F_R$.

The mathematical models have to be valid in a broad range of conditions; during the access to a harbour, all combinations of speeds (ahead and astern) and propeller rates (forward and reversed) occur, so that the model should be able to simulate four-quadrant propeller action, together with drift and yaw angles from 0 to 360deg. 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.

For more details about and a complete formulation of the mathematical model, reference is made to Delefortrie *et al.* (2005). Only some typical aspects regarding the influence of the bottom properties on ship manoeuvrability will be mentioned in this chapter.

Hull forces

Following results are of interest for a better insight into the physical mechanisms determining a ship's behaviour in muddy navigation areas:

- The effect of the under keel clearance on the ship's resistance is shown in Fig. 9 for several bottom conditions. A very sharp increase of resistance is observed in case of contact with high density mud layers; in case of lower density mud, on the other hand, the interface does not appear to be a strict boundary.
- Hydrodynamic inertia ('added mass') terms for sway and yaw increase significantly with decreasing water depth and increasing density and viscosity of the mud layer, as is illustrated in Fig. 10. In case the ship's keel penetrates deep into the mud, very large values are observed, up till seven times the ship's mass – which implies that for inducing a lateral

motion, an equivalent mass equal to eight times the ship's own mass needs to be accelerated. The layer characteristics appear to be important parameters, even if no contact occurs with the mud layer: the shallow water effect is smoothened with increasing layer thickness and decreasing mud density and viscosity. Indeed, an abrupt transition cannot be observed at $h_1/T = 1$.

- The magnitude of lateral force and yawing moment due to drift increases significantly with decreasing water depth, as is illustrated in Fig. 11 (left). However, this increase appears to stagnate when the keel touches the interface; penetration into the mud layer does not result into a further increase. For a given positive under keel clearance relative to the interface, the presence of a mud layer appears to smooth the shallow water effects, especially in case of layers with low density and viscosity (Fig. 11, right).

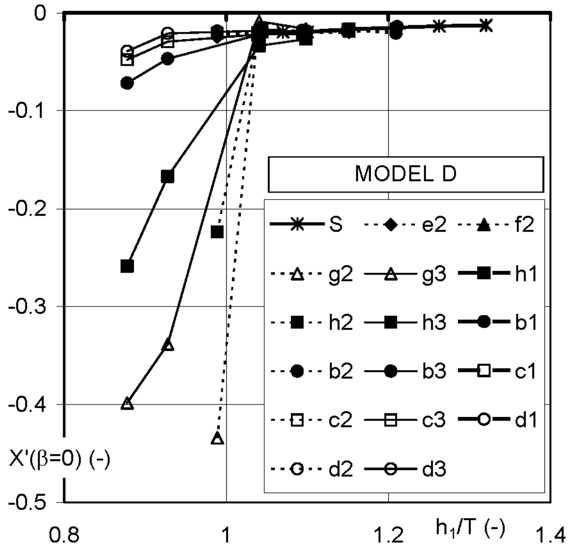

Fig. 9. Non-dimensional ship resistance: influence of bottom characteristics and under keel clearance.

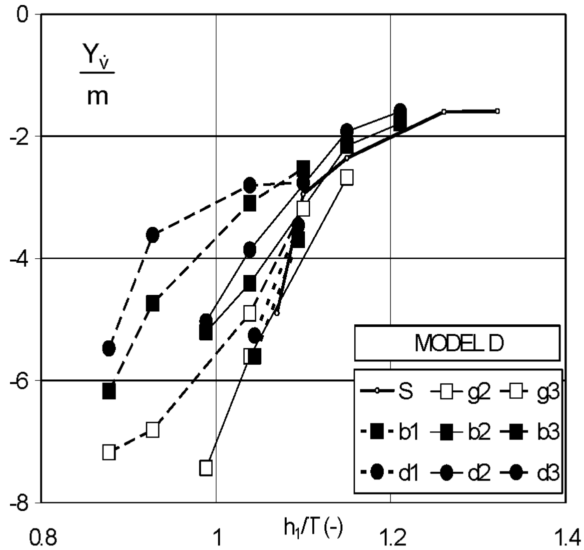

Fig. 10. Sway added mass: influence of bottom characteristics and under keel clearance.

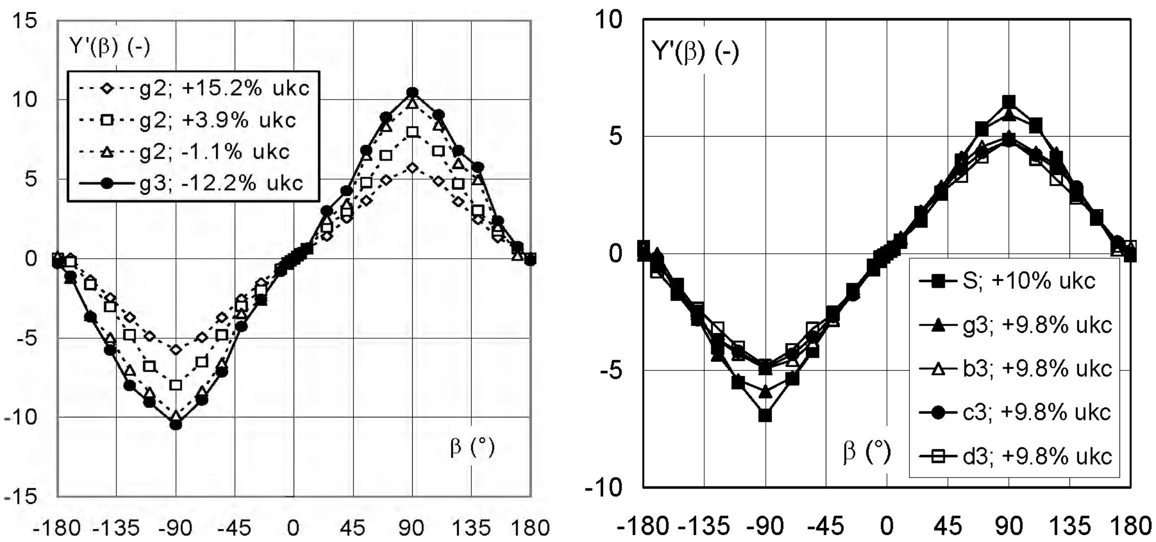

Fig. 11. Ship model D. Non-dimensional drift induced lateral force as a function of drift angle: influence of under keel clearance (left) and bottom characteristics (right).

Propeller induced forces

The longitudinal force acting on the ship due to propeller action depends on the propeller thrust, but also on the thrust deduction factor; the larger the thrust deduction factor, the smaller the fraction of the thrust that is useful for the ship's propulsion. A larger value for this factor – which implies a smaller longitudinal force for a given thrust – is obtained at positive under keel clearances relative to the interface with high density mud layers; if the ship's keel touches the mud, on the other hand, the thrust deduction factor is larger for the lightest mud layers.

The propeller thrust is determined by the propeller rate and the axial inflow velocity. The latter depends on the ship's forward speed, but also on the wake factor: a larger value for this factor implies a smaller inflow velocity and, therefore, a larger propeller loading. The wake factor is clearly affected by the bottom conditions:

- the wake factor increases with decreasing mud density, which implies an obstruction of the flow to the propeller; this phenomenon can be ascribed to the vertical interface motions;
- contact between the ship' s keel and higher density mud layers causes an inflow of two fluids into the propeller, resulting into higher thrust and torque and, therefore, small wake factor values.

Fig. 12 shows that the effect of the presence of mud on the overall efficiency of the propeller: compared to a solid bottom, a significant loss of efficiency is stated, especially for negative under keel clearances.

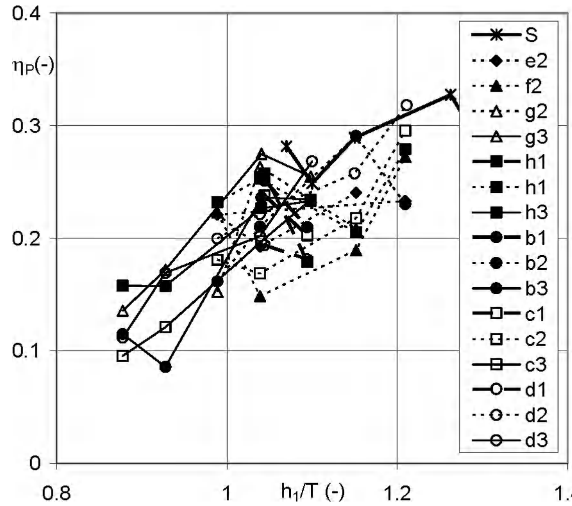

Fig. 12. Ship model D. Overall propeller efficiency: effect of bottom characteristics and under keel clearance.

Besides a longitudinal force, propeller action also causes a lateral force and a yawing moment, due to asymmetry of the flow. This phenomenon is especially important in the 2nd and 4th quadrant (combination of forward speed and backing propeller, or motion astern and propeller ahead). In shallow water, it is observed that these actions are not constant in time, but contain an important slowly oscillating component, the amplitude of which is in the order of magnitude of the propeller thrust. This effect was also included in the mathematical model.

Rudder induced forces

The forces and yawing moment caused by rudder action depend on the axial flow into the rudder. The latter is a function of the forward speed and the propeller rate, but also of the (longitudinal and lateral) rudder wake factors. The latter are significantly affected by the bottom condition and the under keel clearance: the wake factors decrease – and, consequently, the flow to the rudder improves – with increasing mud density and with increasing under keel clearance. As a result, the inflow to the rudder is very unfavourable when the ship penetrates deep into soft, low density mud layers.

Interface undulations

Several phenomena described above are at least partially linked to the deformation of the mud-water interface. Some examples of measured interface motions are shown in Fig. 13. The amplitude of the rising increases and its position moves more aft with increasing ship velocity and decreasing mud density. However, there is a limit to this increase. Once the maximum occurs at a certain distance after the ship, the rising will even diminish. When the ship's keel penetrates the mud layer, two maxima are observed, one amidships and a second one aft. The second maximum will increase, while the first maximum will decrease, with increasing speed and decreasing mud density.

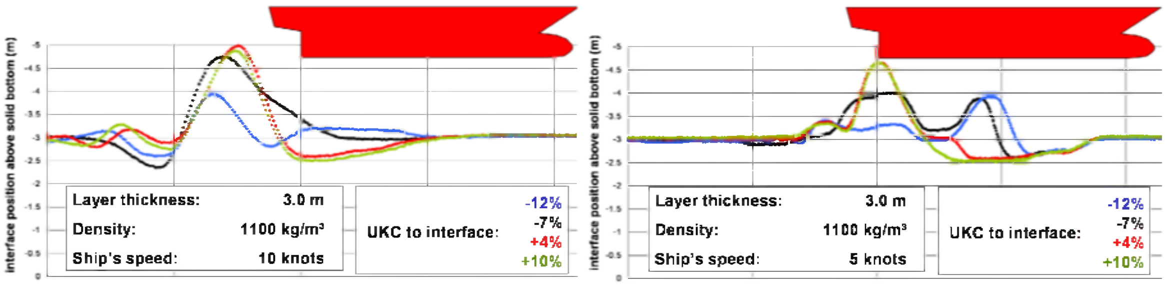

Fig. 13. Undulations of the interface: influence of speed and under keel clearance.

With the present measurements the transition from the second to the third speed range takes place at a higher speed than calculated with the formula mentioned in Fig. 4, probably due to viscosity effects.

Real-time simulation runs

Purpose

The final purpose of the research program consisted in determining revised operational limits for the navigation in the muddy areas of the harbour of Zeebrugge. As the pilots play a central role in the shipping traffic to and from Zeebrugge, the input of their experience and assessment in this project was required and highly appreciated. For a selection of bottom conditions, a real-time simulation programme was organised with Zeebrugge pilots at the full mission bridge simulator of Flanders Hydraulics Research, Antwerp. All runs were carried out with a container carrier (length over all: 300.0m; beam: 40.25m; draft: 13.5m) calling at and departing from the harbour of Zeebrugge.

Two full bridge ship-manoeuvring simulators have been installed at Flanders Hydraulics Research for research and training: SIM225 with a visual system of 225° view and SIM360+ with 360° view and lateral view of the ship's hull. Simulation runs in muddy navigation areas were carried out with SIM225 (Fig. 14). Both simulators consist of a mock-up of a ship's navigation bridge with telegraph, rudder, radar, etc. Communication equipment is available and manoeuvres can be assisted by up to four tugs.

Fig. 14. Flanders Hydraulics Research, outside view of full mission bridge simulator SIM225.

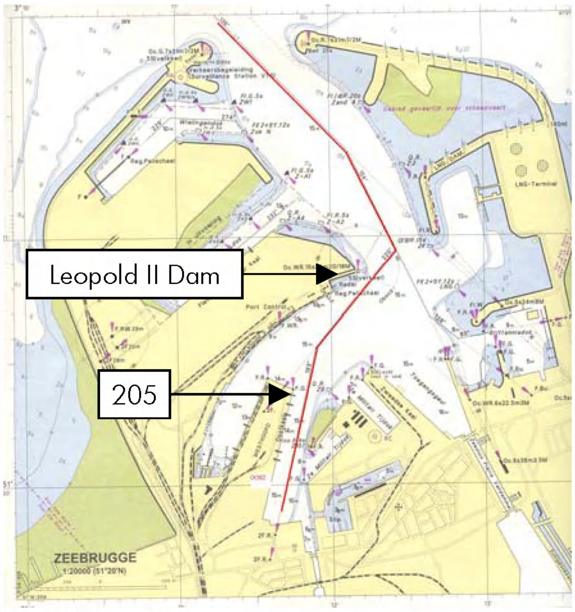

Fig. 15. Simulation runs: trajectory.

The simulation programme was composed paying attention to several aspects:

- Qualitative validation of the mathematical models. In order to evaluate the realism of the simulated ship's behaviour, simulations were carried out in situations that may be comparable with existing or realistic situations. For this purpose, a number of conditions above a solid bottom and above muddy bottoms with reduced under keel clearance was selected.
- Determination of the limits of the controllability. According to the PIANC definition, contact between the nautical bottom and the ship's keel causes unacceptable effects on controllability and manoeuvrability. In order to make an assessment in these matters, a series of simulation runs was carried out during which contact occurred between the ship's keel and mud layers with higher density and viscosity.
- Evaluation of the navigability of mud layers. An increase of the critical density level will possibly imply a penetration of the ship's keel into mud layers with low density and viscosity. A number of these conditions was selected for simulation runs.

Simulation programme

In total, 63 runs were carried out by 15 pilots during 8 days. The selected scenarios had to fulfil the following conditions:

- The manoeuvres should be typical for large container carriers calling at Zeebrugge, so that a feedback to the pilots' experience was guaranteed;
- The simulation runs should cover a broad range of hydrodynamic conditions (speeds ahead/astern, propeller rpm ahead/astern, drift angles, yaw rates, …).

A selection of four manoeuvres was considered; most of them concerned arrival at or departure from quay 205 (Fig. 15). The arrival scenario implies a deceleration phase, tugs making fast, turning the old harbour mole (Leopold II Dam) and berthing on either starboard or port side, the latter implying an additional swinging manoeuvre. Departure manoeuvres did not include swinging manoeuvres.

During each single run, the bottom characteristics were assumed to be constant over the entire harbour area. If such a situation appeared not to be realistic in the access channel 'Pas van het Zand', the manoeuvre was started at lower speed in the outer harbour. The selected bottom conditions are displayed in Fig. 16.

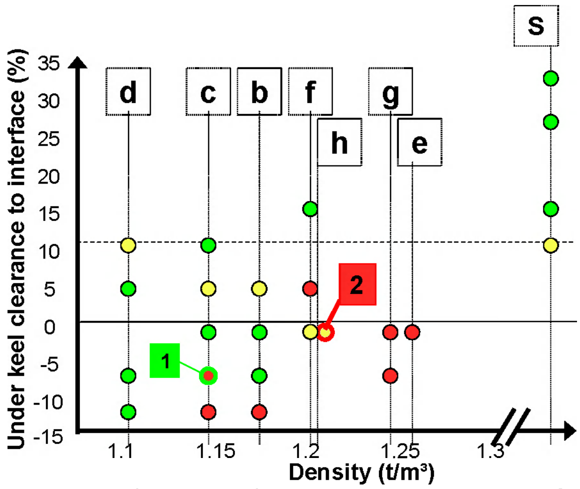

Fig. 16. Real time simulation program: overview of simulated conditions, with overall pilots' assessment (1: with extra tug assistance; 2: wind E, 6Bf).

The access channel to the harbour is characterised by important tidal currents in the zone beyond 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 arriving and departing from Zeebrugge, realistic current patterns were introduced into the simulation environment.

All manoeuvres were carried out in frequently occurring, moderate wind conditions (SW, 4Bf); during some runs, more severe winds (up to 7Bf) were applied.

Tug assistance was guaranteed by two tugs of 45 ton bollard pull each; during some runs the available tug power was increased to 2 x 60 ton.

Qualitative evaluation of the simulation runs

All pilots were requested to complete a questionnaire just after the simulation run; this resulted into a first, very important assessment of the manoeuvres. According to the opinion of a large majority of the pilots, the simulation of the outside view, the ship's behaviour and the tug assistance could be considered as 'good' to 'very good'.

After each run, the pilot was asked whether it would be advisable to carry out the manoeuvre in reality. Based on this assessment, the conditions were classified as 'acceptable', 'marginal' and 'unacceptable'; the results are shown in Fig. 16.

Analysis based evaluation of the simulation runs

Taking account of the comments of the pilots on the simulated manoeuvres, it was clear that several criteria should be considered for assessing the bottom conditions. Two criteria concern the controllability of the ship controlled by own means, which is especially of importance during the last phase of the departure scenario, after turning the old mole with tug assistance:

- Is a departing ship able to develop a speed that is sufficient to compensate for the cross current acting beyond the breakwaters? Based on the pilots' qualitative assessment, a speed of 10 knots is acceptable; speeds under 8 knots are unacceptable. Situations leading to intermediate speeds are considered as marginal.
- Can a straight course be obtained without extreme use of rudder and propeller? Taking account of the pilots' evaluation, the standard deviation of the rate of turn of the ship appears to be an adequate indicator, with critical limits of 5 and 6deg.min^{-1}.

The third criterion concerns manoeuvrability with tug assistance: are the ship's control devices (rudder, propeller) and the tug assistance sufficient to perform the manoeuvres safely within acceptable time limits? In order to evaluate this property in a quantitative way, the impulse of steering force was introduced, being the time integral of the sum of the lateral rudder and tug induced forces. Similarly, the impulse of steering moment was defined as well. The values of these impulses were calculated for each sub-trajectory, and compared to the pilots' evaluation of the adequacy of tug assistance. In this way, it was not only possible to quantify the third criterion, but extrapolations to assistance by more or less powerful tugs could be made as well.

Results and future developments

The research project resulted into a new value for the critical density to define the nautical bottom. If a number of conditions are fulfilled, 1200kg.m^{-3} may be considered as a safe value:

- Assistance of at least two tugs of 45 ton bollard pull is required for deep-drafted container carriers.
- Navigability through lower density mud layers (1100kg.m^{-3}) is constrained to -7% of under keel clearance (Fig. 17, left).
- More tug power (2 x 60ton) reduces this constraint (to -12%), but does not affect the definition of the nautical bottom (Fig.17, right); on the other hand, if less tug power (2 x 30ton) is available, the ship should not contact the mud-water interface;
- The present situation in the access channel outside the breakwaters should not be changed;
- Pilots must receive updated information on the levels of the mud-water interface and the nautical bottom;
- Pilots must be aware of the modified controllability of a ship navigating with reduced or negative under keel clearance relative to the mud-water interface, and should receive an appropriate training.

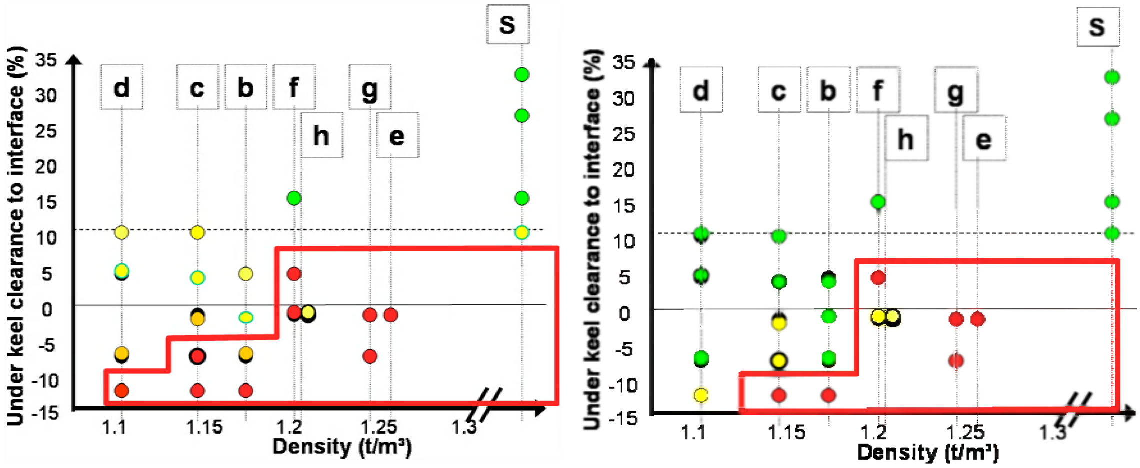

Fig. 17. Real time simulation program. Acceptability of manoeuvres taking account of all criteria, with assistance of 2 tugs with 45 ton (left) and 60 ton (right) bollard pull each.

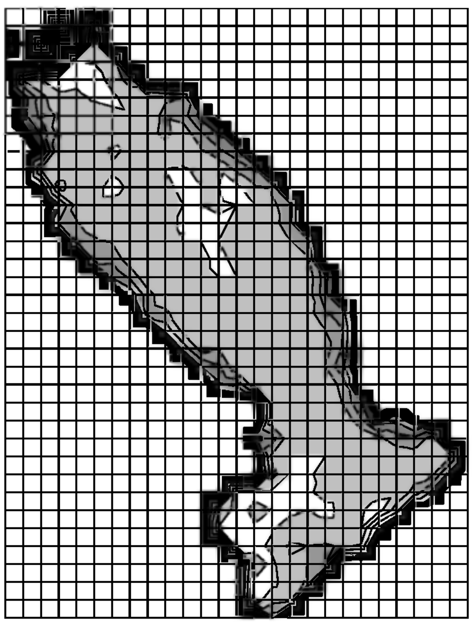
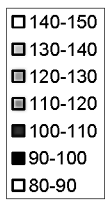

Fig. 18. Maximum allowable draft (in dm) in the outer harbour with tug assistance of 2*60 ton bollard pull.

At present, the conclusions mentioned above are implemented: the 1200kg.m^{-3} level is considered as the nautical bottom; the pilots tend to keep a 10% under keel clearance referred to this level, but also respect the maximum penetration of 7% of draft (typically 1m) into the mud layer. New efforts are presently carried out to take full advantage of the results of the current research project:

- A methodology to interpret bottom surveys in terms of navigability is being developed; as an example, Fig. 18 shows a map of the outer harbour of Zeebrugge indicating the maximum allowable draft at low tide.
- Detailed registrations of manoeuvres carried out with deep-drafted vessels at low tide are planned to validate the concept in general and the mathematical models in particular, as the latter 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 pilots' decision scheme. 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 specific ship behaviour.
- The realism of the simulations will be increased by adapting the mathematical simulation model so that transitions between several types of muddy bottoms will be allowed.
- 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.

Conclusion

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 and to guidelines for the pilots concerning handling of deep-drafted container vessels in the muddy conditions of the harbour of Zeebrugge.

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.

Acknowledgements

The research project 'Determination of the nautical bottom in the harbour of Zeebrugge: Nautical implications' was carried out co-operatively by Ghent University and Flanders Hydraulics Research (Antwerp), commissioned by TV Noordzee & Kust (Ostend) – a joint venture of NV Baggerwerken Decloedt & Zoon, NV Dredging International and NV Ondernemingen Jan De Nul – in the frame of the optimisation of the maintenance dredging contract for the harbour of Zeebrugge, financed by the Department Maritime Access of the Ministry of Flanders, Waterways and Maritime Affairs Administration. The real-time simulation programme was carried out in close co-operation with the Flemish Pilotage.

References

Brossard C., A. Delouis, P. Gallichon, J. Grandboulan and P. Monadier . 1990. Navigability in channels subject to siltation – Physical scale model experiments. p. 3088-3103. In: Proceedings 22nd Coastal Engineering Conference, ASCE, Delft, Volume 3.

De Brauwer D. 2005. Maintenance dredging and bottom survey in the harbour of Zeebrugge. Workshop Nautical Bottom, Flanders Hydraulics Research & Ghent University, Antwerp, 2005.
http://watlab.lin.vlaanderen.be/nautische/WorkshopNauticalBottom_DirkDeBrauwer.pdf

Delefortrie G., M. Vantorre and K. Eloot. 2005. Modelling navigation in muddy areas through captive model tests. Journal of Marine Science and Technology 10(4):188-202.

De Meyer C.P. and B. Malherbe. 1987. Optimisation of maintenance dredging operations in maritime and estuarine areas. Terra et Aqua 35 :25-39.

Kerckaert P., B. Malherbe and A. Bastin. 1985. Navigation in muddy areas: the Zeebrugge experience. PIANC Bulletin 48.

Kerckaert P., D. Vandenbossche, B. Malherbe, M. Druyts and K. Van Craenenbroeck. 1988. Maintenance dredging at the port of Zeebrugge: Procedures to achieve an operational determination of the nautical bottom. p.4.13-32. 9th KVIV Harbour Congress, Antwerp.

PIANC. 1997. Approach channels – A guide for design. Final report of the joint Working Group PIANC and IAPH, in cooperation with IMPA and IALA. Supplement to PIANC Bulletin 95. 108p.

Sellmeijer R. and G. van Oortmeersen. 1983. The effect of mud on tanker manoeuvres. Spring Meetings, RINA, London, Paper 7.

Uliczka K. 2005. Investigations of the BAW to the nautical bottom. Workshop Nautical Bottom, Flanders Hydraulics Research & Ghent University, Antwerp, 2005.
http://watlab.lin.vlaanderen.be/nautische/WorkshopNauticalBottom_KlemensUliczka.pdf

Van Craenenbroeck K., M. Vantorre and P. De Wolf. 1991. Navigation in muddy areas: Estabilishing the navigable depth in the port of Zeebrugge. CEDA-PIANC Conference Accessible Harbours, Amsterdam.

Vantorre M. 1991. Ship behaviour and control at low speed in layered fluids. Proceedings International Symposium on Hydro- and Aerodynamics in Marine Engineering (HADMAR), BSHC, Varna.

Vantorre M. 1994. Ship behaviour and control in muddy areas: state of the art, manoeuvring and control of marine craft. p.59-74. 3rd International Conference, MCMC'94. Southampton, UK.

Vantorre, M. 2001. Nautical bottom approach - Application to the access to the harbour of Zeebrugge. HANSA – Schiffahrt – Schiffbau – Hafen, 138. Jahrgang, Nr. 6:93-97.