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SHIP MANOEUVRING BEHAVIOUR IN MUDDY NAVIGATION AREAS: STATE OF THE ART

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SUMMARY

The manoeuvring behaviour of vessels is highly affected by their small under keel clearance in access channels and harbours. If sedimentation and the formation of mud layers occur in these areas the manoeuvring behaviour becomes even more challenged, especially because the exact location of the bottom is not unequivocally determined. In such areas the nautical bottom definition, as stated by PIANC, is useful: *The nautical bottom is 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.* Over the past decades research has been focussing on both the determination of the physical characteristics of the mud and the manoeuvring behaviour in such areas. The paper tends to give an overview of this research and of practical applications in harbours worldwide, and to provide an outlook for future research.

NOMENCLATURE

A	ship's cross section area (m²)
g	gravity constant (m/s²)
h	depth (m)
h^*	hydrodynamically equivalent depth (m)
L_{PP}, L_{OA}	ship length (m)
m	blockage (-)
U	ship speed (m/s)
W	channel width (m)
z_A	sinkage aft perpendicular (m)
z_F	sinkage fore perpendicular (m)
η	dynamic viscosity (Pa.s)
ρ	density (kg/m³)
τ_y	yield stress (Pa)
Φ	fluidization parameter (-)

Subscripts

1	denotes water layer
2	denotes mud layer

1 INTRODUCTION

When studying the manoeuvring behaviour of vessels in shallow water the bottom of a harbour or access channel is almost always considered to be solid. In reality this is not always the case. Due to the erosive effect of the currents in rivers, particles are transported over a certain distance until they settle again. If those settlements are concentrated in a certain area the formation of a mud layer is possible, depending on the grain size. To avoid excessive formation of mud layers maintenance dredging works are needed so that a minimal under keel clearance can be guaranteed.

The question arises how much of the present mud layer has to be dredged. The mud layer consists of a material, the characteristics of which change with the depth. In general mud characteristics like viscosity or density increase with increasing depth. Therefore the upper part of the mud layer can rather be considered as black water. If the ship's keel touches this upper part it is unlikely that any damage can occur; on the other hand, when a ship navigates above a mud layer an undulation of the water-mud interface can be observed. This undulation can possibly have adverse effects on the manoeuvring behaviour of the vessel.

For these reasons PIANC has introduced the nautical bottom concept [1, 2]: *The nautical bottom is the level where physical characteristics of the bottom reach a critical limit beyond which contact with a ship's keel causes either damage or unacceptable effects on controllability and manoeuvrability.* The nautical bottom concept can be applied to any bottom so that safety and manoeuvrability for the shipping traffic can be guaranteed.

A successful application of the concept implies knowledge on both the physical characteristics of the nautical (in this case muddy) bottom, as well as on the manoeuvring behaviour of the vessels in the vicinity of the nautical bottom. Although in this paper the focus will be more on the latter, some basic information on the behaviour of the mud and how to measure this behaviour will be given in the next paragraph. The remainder of the article will summarize the performed experimental and numerical research on the manoeuvring behaviour in muddy areas and how this information has been used to perform real-time simulations in different harbours all over the world. An outlook on future research and open research topics will be provided as well.

2 BEHAVIOUR OF MUD

2.1 MUD CHARACTERISTICS

Mud layers are formed due to the decrease of kinetic energy that causes sediment particles to deposit on the bottom of a channel. If an increasing amount of particles is settling down the base sediment layer will be subjected to increased pressure due to the weight of the upper layers. As a result water is expelled from the base layers and the sediments are compacted. This process is called consolidation and depends on the variation of permeability, which is the water flux through a unit gross sectional area, and the effective stress, which is the total stress minus pore water pressure [3]. On the other hand, the disturbances in the upper water layer, caused by e.g. currents, waves, shipping traffic, also affect the mud layer characteristics; the fraction of water in the mud layer can consequently increase. This phenomenon results in the opposite effect of consolidation, and is usually called liquefaction (driven by shear stress) or fluidization (driven by fluctuating pore pressure). The combination of these phenomena with internal transports within the mud layer results in the formation of a mud layer with characteristics changing with the depth. One important aspect of the different conditions of the mud layer is that its behaviour not only is location and time dependent, but also varies according to its recent deformation history. The latter is also known as thixotropy. This is also of importance when the rheology of the mud layer has to be measured. An example is shown in Figure 1, where the yield stress decreases with the number of cycles of increasing and subsequently decreasing shear rate.

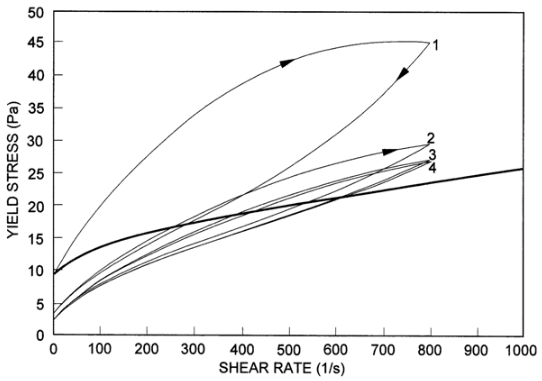


Figure 1. Measuring the rheology of hectorite. Adapted from [4].

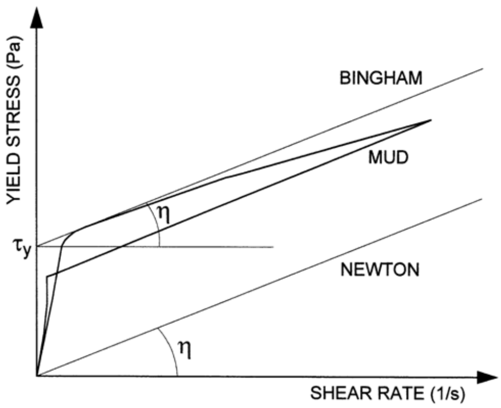


Figure 2. Classification of fluids based on their rheology behaviour.

Another point of interest is the initial yield stress or rigidity. In order for the mud to move an initial resistance has to be overcome. Such a behaviour can be characterized by a Bingham fluid, contrary to a Newton fluid like water, see Figure 2. For numerical purposes the Bingham model, determined by two parameters, is still too simple. More appropriate models could be used, such as Worrall-Tuliani [5] or Toorman [6], involving up to five parameters. A detailed explanation of such models falls outside the scope of this article.

The actual behaviour of the mud highly depends of its composition, e.g. organic matter and sand content play an important role.

2.2 MEASURING TOOLS

2.2 (a) Echo-sounding

In 2012 a questionnaire was organized on the use of in situ measurements to assess mud characteristics [7]. The results cannot be interpreted as real market share, but in 63% of the cases echo sounding was used to determine the nautical bottom. This high percentage can be ascribed to the simple setup. An electromagnetic wave is emitted that reflects at the bottom. The time between emission and reception and the intensity of the received wave is then a measure for the local depth. The frequency of the wave is closely related to its sensitivity for reflection. In case of a soft mud layer on the bottom, a high frequency echo of 210 kHz will reflect on top of the water-mud interface. A lower frequency (e.g. 33 kHz) will reflect at a level somewhat deeper into the mud (Figure 3). However it is unclear whether this corresponds to the position of the nautical bottom.

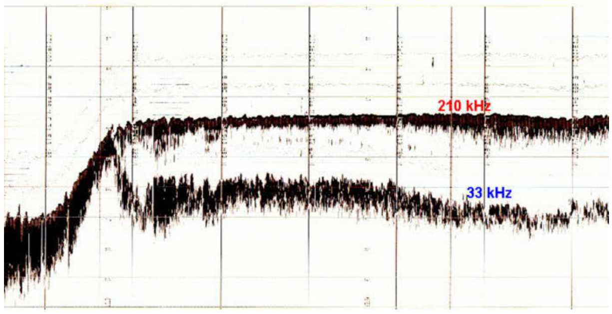


Figure 3. Example of an echo-sound result in the harbour of Zeebrugge [8].

2.2 (b) Monitoring the mud density

The density of the mud layer can be measured with a variety of methods. The acoustic method is based on the relationship between the propagation of sound in a fluid and the density of that fluid. A more accurate method is the nuclear method, which is based on the behaviour of gamma-radiation in mud suspension.

The measurement of the density of the mud can mostly be automated and results are typically presented in combination with echo-sounding, as shown in Figure 4. According to the questionnaire [7], a density based method is used in 31% of the cases.

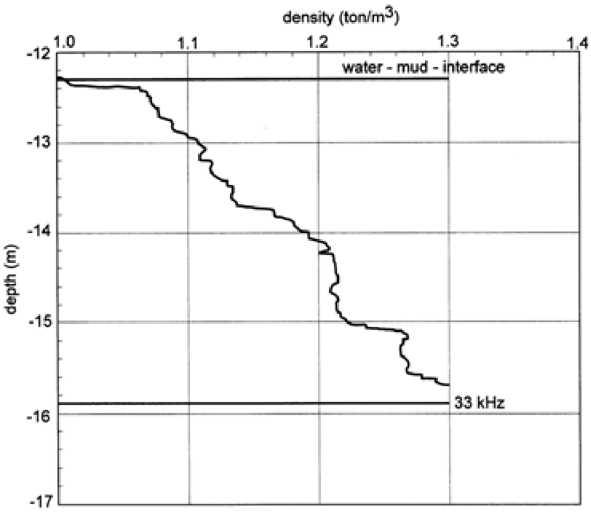


Figure 4. Density profile in function of the water depth.

2.2 (c) Monitoring the mud rheology

Rheology measurements commonly focus on the measurement of the yield stress (viscosity measurement). These measurements are mostly more labour intensive, because single point measurements have to be carried out and post-processing of the measurements is needed to take account of the thixotropic and hysteresis of the mud. For that reason only a small percentage in [7] uses rheology like methods.

2.2 (d) Ongoing research

At present none of the mentioned tools is capable of capturing the actual physical limit in the fluid mud layer. For this reason FHR (Flanders Hydraulics Research) built a Sediment Test Tank [9] to better observe the behaviour of natural mud and to test the actual instruments on the market in a controlled environment. To determine the mud properties in an unequivocal way a measurement protocol has been established together with KU Leuven, dotOcean and Antea Group [10].

2.3 NAUTICAL BOTTOM CRITERION

Due to the complex structure and behaviour of the mud it is indeed difficult to find a straightforward physical limit. Moreover variations in time of the mud layer's characteristics require a rather continuous monitoring of this physical limit.

In most cases the mud density is used as a critical limit. This does not mean that mud density is the critical parameter, but that at a certain value of this density a rheological transition in the mud behaviour occurs, which is more easily monitored afterwards when linked to a density value, see Figure 5 for an example in the port of Zeebrugge. In Zeebrugge, the critical density was initially decided to be 1.15 ton/m³, but was later increased to 1.20 ton/m³. Other examples of this approach are Rotterdam (1.20 ton/m³), Nantes (1.20 ton/m³), Paramaribo (1.23 ton/m³), Bangkok (1.20 ton/m³), Cayenne (1.27 ton/m³), and Chinese harbours (1.20 to 1.30 ton/m³) [11, 12].

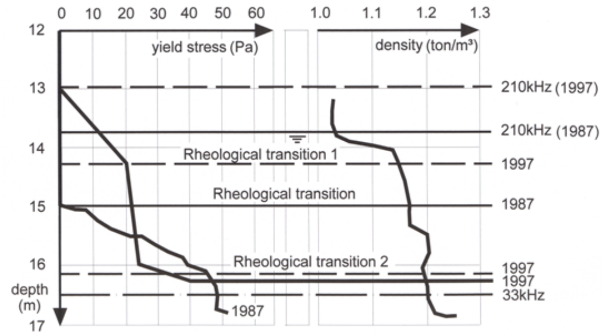


Figure 5. Rheology profile of the mud layer in the harbour of Zeebrugge. Comparison between the 1987 and the 1997 measurement campaign. The single curve for the density is illustrative.

In some harbours alternative methods are used; for instance, in Emden the focus is put on the organic content of the mud layer, which must remain large enough to limit the yield stress to 100 Pa. In this way the harbour remains navigable [13].

In all cases the measurement of mud layer characteristics implies simplifying the mud layer. On top of that most invasive measurement techniques change the characteristics of the mud layers [3].

3 EXPERIMENTAL RESEARCH

3.1 OVERVIEW

Experimental research on navigation in muddy areas is rather scarce. In this section a distinction will be made between model scale and full scale research.

3.2 MODEL SCALE

3.2 (a) Scaling

Since William Froude's experiments with small-scale tests on ship hulls in the 1860s, model tests have been playing an major role in understanding a ship's hydrodynamic behaviour. However, ship model tests have an important drawback: when the speed scale is selected in such a way that Froude's scale law is fulfilled, dynamic similarity will occur between the inertia forces and the gravity and pressure induced forces. A correct scaling of viscous forces, on the other hand, require Reynolds' scale law to be met, which is practically impossible when a free surface is present. In order to overcome this difficulty, empirical correction methods have been developed to deal with scale effects on e.g. resistance tests.

Accounting for the difficulties caused by the viscous effects due to the properties of a fluid with a rather simple rheology such as water, which as a Newtonian fluid can be characterised by its dynamic or kinematic viscosity as the only parameter, a correct scaling of the effects caused by the presence of a fluid mud layer, for which five parameters are required to describe the rheological characteristics in a proper way [6], is not realistic. Moreover, the mud characteristics should even be varied with the depth to model a realistic mud layer. Another difficulty concerns the thixotropy of the mud: the use of a thixotropic material during model tests would make it by definition impossible to perform systematic tests under constant bottom conditions. Most model tests for investigating the effect of the presence of fluid mud layers on a ship's hydrodynamics were therefore conducted with a homogeneous mud-simulating fluid with the correct density ratio with respect to the water in the test facility. For practical reasons, often a material with a Newtonian rheology is selected which is immiscible with water, which guarantees constant test conditions. Sometimes real mud or artificially composed mud has been used as well.

Summarized, model testing for investigating mud-ship interaction always implies an important simplification of the physical reality. Test results should therefore be interpreted cautiously.

In the remainder of this section, a brief summary will be given of the test programs conducted over the past 40 years with respect to the effect of mud layers on ship behaviour.

3.2 (b) MARIN (Wageningen, NL)

Both captive and free running model tests were carried out with a 1/82.5 scale model of a tanker sailing above or in contact with an artificial mud layer of rather small viscosity which was immiscible with water [14]. Two densities and up to three mud layer thicknesses were varied.

One important observation was the undulation pattern that occurred in the water-mud interface when a ship is passing. The amplitude of these undulations increases with the thickness of the mud layer and with decreasing mud density and affect the propeller efficiency as was observed during the free running trials.

3.2 (c) SOGREAH (Grenoble, F)

Model scale tests were conducted in a looped wave flume [15] with a scale model of a tanker (at different scale factors) focussing at resistance and squat variations above an artificially composed mud layer, with properties very close to natural mud. It is the only case where the tested mud layer included a density gradient over the depth; moreover, layers with different yield stresses were applied. Also in this case undulations of the water-mud interface had been observed which show the same behaviour.

3.2 (d) Flanders Hydraulics Research (Antwerp, B)

At FHR experimental research was carried out in three phases. In a first phase self-propelled tests were carried out with scale models of an LNG-tanker and a hopper dredger along a guiding rail above a mud-substituting layer with a negligible viscosity which was immiscible with water [16]. Mud density, mud layer thickness and water depth variations were included in the program. The undulations of the water mud interface could be linked to three different speed ranges (see 5.2). The reaction of the ship models due to these undulations was analogous to the observations by MARIN. Additionally, a limited number of similar model tests were conducted above an artificially composed mud layer, as well as a series of tests with a ship-like body towed above natural mud layers. Although the bottom layers were both miscible with water, similar tendencies were observed. Moreover, the water-mud interface appeared to be relatively stable under the ship; as mixing only occurred behind the ship, this only had a minor effect on ship behaviour.

A second, and more comprehensive research [17], was performed with an extensive captive test program with three different ship models (two container carriers and one tanker) in a variety of artificial muddy environments, including mud thickness variation, water depth variation, densities ranging between 1.10 ton/m³ and 1.26 ton/m³ and dynamic viscosities varying between 0.03 and 0.33 Pa.s (Table 1). During this program the undulations of the water-mud interface were also registered, and similar observations could be made, although the larger viscosity also plays a significant role.

Table 1. FHR: tested mud conditions on prototype scale [17]

Mud	Density [kg/m³]	Viscosity [Pa.s]
B	1179	0.10
C	1149	0.06
D	1108	0.03
E	1257	0.29
F	1206	0.11
G	1248	0.33
H	1207	0.19

An additional, third research specifically focussed on the effect of the muddy environments C and D on a container carrier equipped with a bow thruster [18]. This research was again carried out self-propelled, along a guiding rail.

3.2 (e) Bundesanstalt für Wasserbau (BAW, Hamburg, D)

BAW conducted model tests with a 1/40 scale model of a container vessel to study the sinkage and trim above highly concentrated natural mud [19].

3.3 FULL SCALE

3.3 (a) Rotterdam

In 1975 full scale tests were carried out with a 318 000 deadweight tanker (SS Lepton). The tests consisted of entering the harbour and monitoring the effect of the under keel clearance during a course change [20]. This was done by analysing the steering capacity, i.e. the maximal percentage of available rudder and propulsion and the speed of the vessel during the manoeuvre. The presence of undulations of the water-mud interface could be confirmed during the full scale tests.

3.3 (b) Zeebrugge

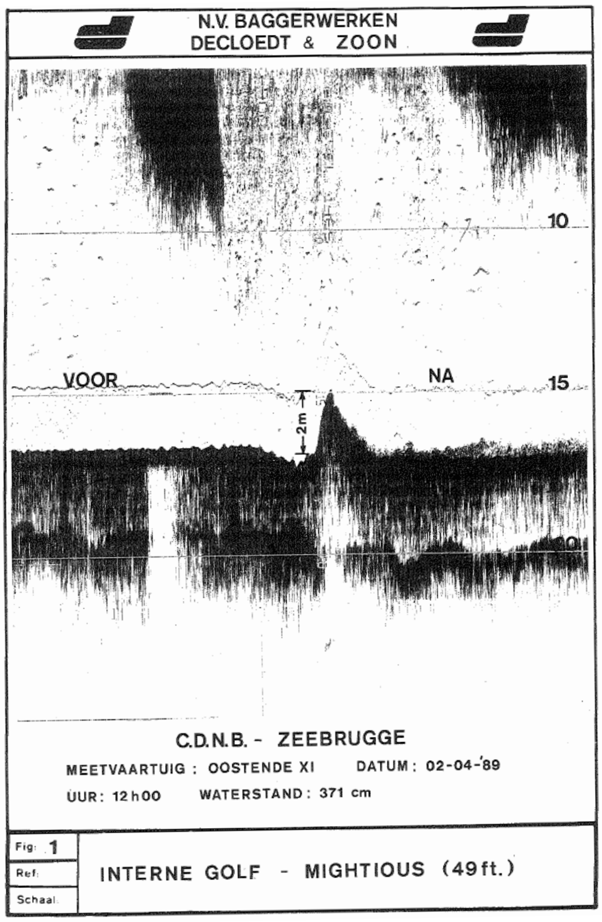


Figure 6. Full scale undulations of the water-mud interface measured in the port of Zeebrugge.

Full scale tests were carried out with the twin screw suction hopper dredger Vlaanderen XVIII (L_{OA} = 124 m) in 1986 and in 1988 [21]. Several test types were performed at under keel clearances varying between -0.35 m and +3 m referred to the water mud interface. It seemed possible to navigate through top mud, with a tested under keel clearance up till -0.35 m, without any major difficulties. On the other hand during one trial the ship became totally uncontrollable. During this trial the ship had intentionally hit the rheological transition level (the nautical bottom). Survey vessels were able to record internal waves in the mud-water interface by their high-frequency echo on several occasions, as illustrated by Figure 6, where a hydraulic jump with a height of about 2 m can be observed due to the passage of a deep-drafted OBO-carrier.

Since 2005 full scale monitoring of deep-drafted container carriers are carried out whenever possible to check the real-time manoeuvring models at FHR.

3.3 (c) Saint-Nazaire

Full scale runs were carried out in the Loire estuary with the tanker Alsace. A good agreement was found with the results of the model scale tests at SOGREAH.

3.3 (d) Delfzijl

In 2013 full scale trials were carried out with the general cargo vessel CSL Rhine in the port of Delfzijl to validate the conclusions from a simulator study [22]. Although tests were conducted at under keel clearances of 14% and larger referred to the top of the mud layer, it could be concluded that both the manoeuvring and propulsion behaviour was influenced by the mud layer at under keel clearances with respect to the water-mud interface smaller than 18%. In 2015 new full scale trials were carried out with the hopper dredger Geopotes 15 at a range of under keel clearances between +14% and -4% referred to the top of the mud layer. In general the ship's behaviour could confirm previous simulation studies [23].

4 NUMERICAL / THEORETICAL RESEARCH

The behaviour of mud has been studied empirically and theoretically by many authors, but mainly for hydraulic and morphologic purposes. Numerical theories have been used to study the ship behaviour in muddy navigation areas [24, 25] indicating that the mud response is especially important at rather slow speeds and that mud viscosity acts as an effective reduction in the total water depth.

The water-mud undulations seem to have a significant influence on the ship's behaviour. In [16] an expression for the critical speed was derived, based on an ideal fluid:

$$U_{crit} = \sqrt{\frac{8}{27} g h_1 \left(1 - \frac{\rho_1}{\rho_2}\right) (1 - m_1)^3} \qquad (1)$$

m_1 is the local blockage factor of the upper fluid layer:

$$m_1 = \frac{A_1}{W h_1} \qquad (2)$$

and A_1 is the ship's cross section area in the upper fluid layer.

Once the ship attains the critical speed, the jump on the water-mud interface occurs behind the ship's stern, where it obstructs the inflow of propeller and rudder. The theory was confirmed with the model experiments where the viscosity of the mud layer was small (< 0.01 Pa.s).

Recently steps were taken to include the mud behaviour with an appropriate rheological model into CFD. As a first part of this project CFD computations with a cylinder towed through mud were compared with model tests at FHR where the same setup was used with a natural mud layer [26].

5 BEHAVIOUR OF A SHIP IN MUDDY AREAS

5.1 OVERVIEW

Based on experimental and numerical research an overview is given on the behaviour of a ship in muddy areas. In some cases mathematical models were developed for real-time simulation purposes, which will be discussed in paragraph 5.4. However, based on the evolution of the coefficients of these mathematical models, effects of the mud layer on the ship will be explained.

5.2 UNDULATIONS OF WATER – MUD INTERFACE

According to [16] three speed ranges can be detected for the behaviour of the water mud interface:

- At low speed a small sinkage near the fore body is detected, which disappears amidships and turns into an elevation abaft;
- At a certain speed value the sinkage at the entrance changes suddenly into an elevation. The section at which the jump occurs moves abaft with increasing speed;
- If the speed increases more, the rising of the interface occurs behind the stern. The amplitude of the elevation can exceed the mud layer thickness several times.

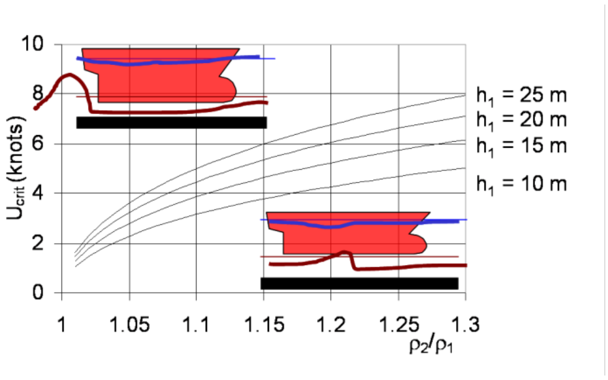


Figure 7. Critical speed in function of water depth and mud density.

The latter occurs at a speed which is given by equation 1 for inviscid fluids. The evolution of this speed is shown in Figure 7. For common manoeuvring speeds in harbour areas, the ship always seems to be in the critical range. However, for larger mud viscosities, equation 1 does not seem applicable [27]. When sailing above the mud layer, the amplitude of the rising is only significant if the viscosity drops below a certain critical value somewhere between 0.12 and 0.18 Pa.s, see Figure 8. Disregarding the viscosity the risings are always significant once the ship's keel touches the mud layer.

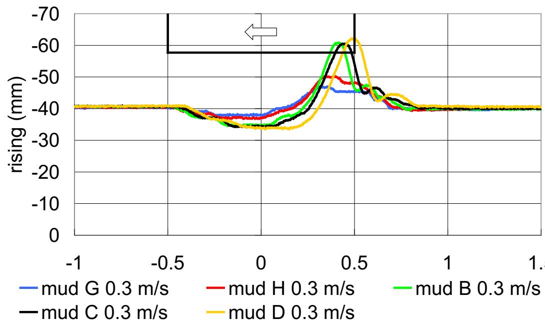
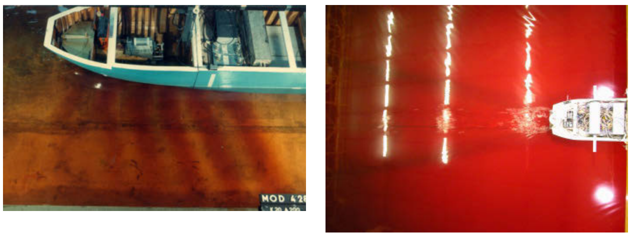


Figure 8. Rising of the water mud interface when a container carrier sails at an under keel clearance of 10% above the top of the mud layer.

The propagation pattern also seems to be influenced by both the viscosity and the speed. At lower speeds, the undulation crests are approximately perpendicular to the ship's heading in case of mud layers with low viscosity (< 0.12 - 0.18 Pa.s), while at higher speeds the undulations seem to behave as a Kelvin pattern (see Figure 9). The perpendicular pattern is observed over a larger speed range in case of mud layers with larger viscosities (> 0.12 - 0.18 Pa.s). The transition between both patterns occurs at a higher speed in case of mud layers of higher viscosity. A more viscous mud layer clearly requires larger speeds to have a critical influence.



η = 0.002 Pa.s η = 0.030 Pa.s

Figure 9. Propagation pattern of undulations of the water-mud interface.

5.3 SHIP'S SQUAT

The behaviour of the sinkage and trim of a vessel in muddy areas is closely related to the undulations of the water-mud interface [27].

When a ship navigates with a small under keel clearance above the mud, contact can occur between the undulating mud-water interface and the ship's keel. The mud will yield a small increase of buoyancy, which results in a small decrease of the sinkage. Sailing in contact with the mud will always generate an increase of buoyancy, see Figure 10. For an equal total depth, the sinkage is thus larger above a solid bottom than above a muddy bottom. At somewhat higher speed, however, an increase of the squat may be observed in case of negative under keel clearance with respect to the mud-water interface, as was observed during model tests at SOGREAH (Figure 11).

An interface rising will have the largest influence on the trim when it takes place amidships. The influence will decrease when the rising moves abaft. In all cases a larger rising causes a larger asymmetry and thus a larger trim compared to solid bottom conditions.

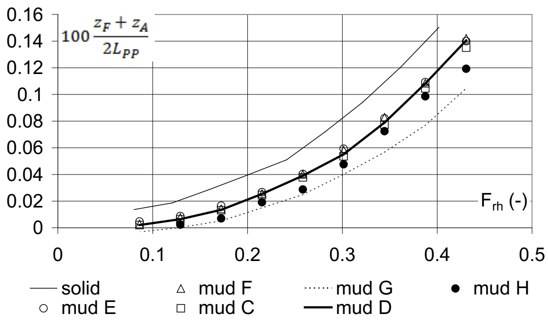


Figure 10. Sinkage in function of the ship speed. Thickness of the mud layer: 1.5 m full scale. No propeller or rudder action. -1.1% under keel clearance referred to the water mud interface [27].

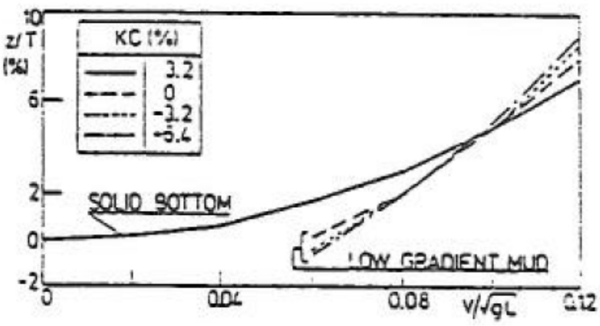


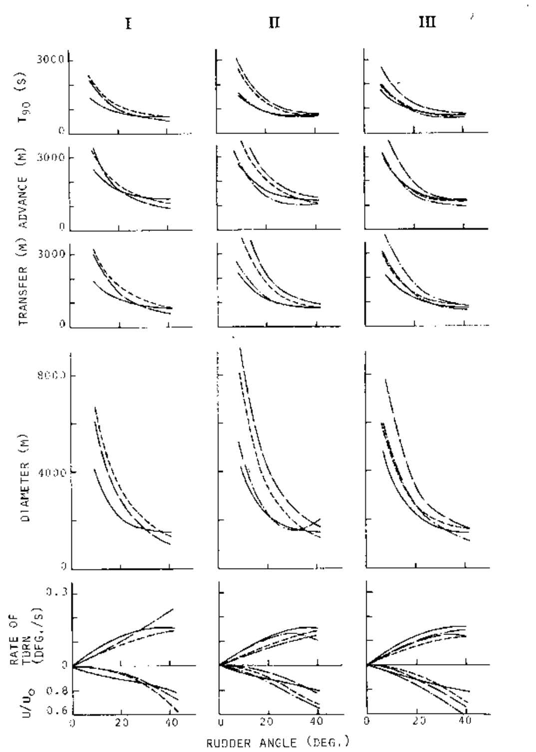
Figure 11. Sinkage in function of the ship speed for different under keel clearances related to low gradient mud. Thickness of the mud layer: 1.5 m full scale. Adapted from [15].

5.4 MATHEMATICAL MANOEUVRING MODELS

5.4 (a) MARIN

Based on the model tests performed at MARIN a mathematical manoeuvring model was developed [14]. The velocity derivatives resulted appreciably higher in muddy conditions (larger damping), while the increase of acceleration derivatives was merely ascribed to the small under keel clearance and not the effect of the mud layer.

Manoeuvres are slower in muddy areas, especially in case of a small positive under keel clearance referred to the water mud interface and when the rising of this interface is high, thus with smaller densities. The mud layer slackens the steady conditions while accelerating the dynamic ones, zigzag tests are for example carried out faster with mud on the bottom, while turning circles are larger in muddy conditions (Figure 12).



Group	Type of line	Mud: Density (kg/m³)	Mud: Thickness	Keel clearance: To mud	Keel clearance: To bottom
I	———	0	0	–	0·20 T
	- - - - -	1140	0·07 T	0·15 T	0·22 T
	— — —	1140	0·13 T	0·10 T	0·23 T
II	———	0	0	–	0·20 T
	- - - - -	1140	0·07 T	0·10 T	0·17 T
	— — —	1140	0·13 T	0·03 T	0·16 T
	—·—·—	1140	0·20 T	−0·03 T	0·17 T
III	———	0	0	–	0·20 T
	- - - - -	1140	0·07 T	0·03 T	0·10 T
	— — —	1140	0·13 T	−0·03 T	0·10 T
	—·—·—	1140	0·20 T	−0·10 T	0·10 T

Figure 12. Turning circles: effect of mud thickness [14].

5.4 (b) FHR

For each of the muddy environments that was tested during the second research phase coefficients of a full four quadrant modular manoeuvring model were determined [28].

The ship's resistance is characterized by a sharp increase once the ship's keel penetrates viscous mud layers. The acceleration derivatives not only increase significantly with decreasing water depth, but also with increasing mud density and viscosity, even if no contact occurs between ship and mud. In general the presence of a mud layer tends to increase the shallow water effects.

The propeller wake increases above or in contact with low density mud layers, while it decreases in case of high density mud layers, which is in agreement with the behaviour of the undulations of the water-mud interface. A mud layer will always increase the propeller shaft torque, which means that the propeller efficiency decreases, especially when penetrating the mud. The asymmetry effect of a single propeller will also be more significant in muddy areas.

The rudder induced lateral force on the hull is significantly larger in muddy areas. At the same time its application point moves towards midships, so the larger lateral force does not yield a larger turning moment.

At slow speeds (smaller than 3 knots) the effect of a bow thruster seems to diminish once the keel touches a mud layer [29].

The mathematical models were intensely applied for fast-time and real-time simulations (see also 6.1). As an example, the results of turning circle manoeuvres is given in Figure 13, confirming the main conclusions of Figure 12.

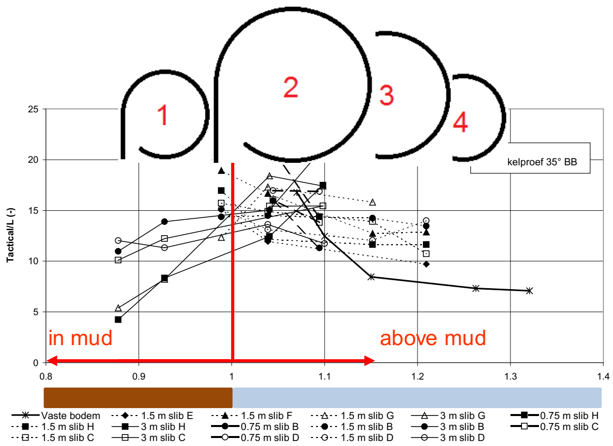


Figure 13. Turning circle tests (full to port) with a 6000 TEU container vessel: tactical diameter as a function of under keel clearance with respect to the mud-water interface for several mud layers [30].

5.5 HYDRODYNAMICALLY EQUIVALENT DEPTH

Based on the fact that the mud layer tends to increase the shallow water effect, a consolidated mathematical model was developed [27, 31, 32] which takes account of mud layer density, viscosity, thickness and water depth based on a hydrodynamically equivalent depth. With h_2 the thickness of the mud layer and h_1 the height of the upper lying water layer, the total depth can be written as:

$$h = h_1 + h_2 \tag{3}$$

The bottom material can vary from water over soft mud to consolidated mud. If the mud has large viscosity and density values, like sand or clay, the material will hardly move when a ship passes by and its top can be considered as the actual seabed. In this case the hydrodynamically equivalent depth h^* is:

$$h^* = h_1 \tag{4}$$

On the other hand if the material is very fluid the mud layer cannot be considered as a solid bottom. In the limit condition of two equivalent water layers, the hydrodynamically equivalent depth is:

$$h^* = h_1 + h_2 = h \tag{5}$$

For intermediate situations a parameter Φ can be defined, so that:

$$h^* = h_1 + \Phi h_2 \leq h \tag{6}$$

Particular values for the parameter Φ are 0 (hard layer of thickness h_2) and 1 (watery layer of thickness h_2), Φ represents consequently the degree of watery behaviour of the bottom layer and is therefore called the fluidization parameter.

Intuitively the fluidization parameter of the mud covering the seabed depends on the following aspects:

- the rheological properties (e.g. viscosity) of the mud: a decrease of the latter means a more fluid mud layer and will logically result in an increased fluidization parameter;
- the under keel clearance referred to the mud-water interface: the fluidization parameter increases when the ship's keel is located closer to the mud or penetrates the mud. In these conditions the mud layer is stirred and will behave more fluidly.

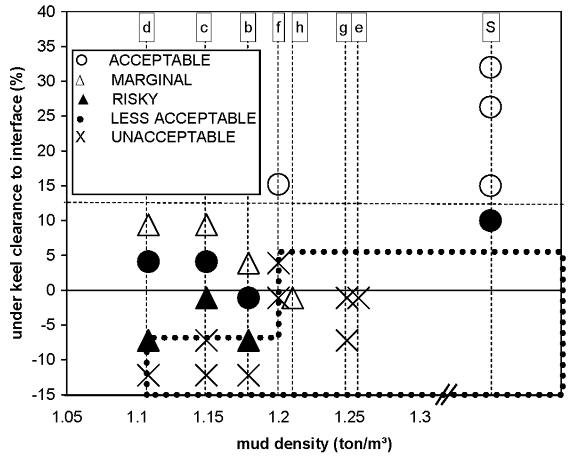


Figure 14. Real time simulations with a 6,000 TEU container carrier, assisted by two tugs of 45 ton bollard pull. Quantitative evaluation for the harbour of Zeebrugge, dotted area = "unacceptable".

6 REAL TIME SIMULATION PROJECTS

6.1 FHR

6.1 (a) Nautical bottom criterion in Zeebrugge

Based on the developed mathematical models [28], real-time simulations were carried out in 2004 [17] to check the position of the nautical bottom in the harbour of Zeebrugge. Based on this real-time simulation program the position of the nautical bottom changed from 1.15 ton/m³ to 1.20 ton/m³. The available tug assistance is critical for the penetration of the ship's keel in the mud, which should be limited to 7% of the ship's draft, see Figure 14.

6.1 (b) Updates to the simulation models

Since 2004 the manoeuvring models were continuously enhanced:

- In 2006 an algorithm was added to cope with the changing characteristics of a mud layer or with a transition from solid bottom towards muddy bottom [33].
- The consolidated model, based on the hydrodynamically equivalent depth, was added to the simulator in 2008.
- In 2010 the nautical bottom criterion was checked against the admittance of container carriers up to 400 m length in the port of Zeebrugge and the effect of mud on bow thrusters was added.

6.2 OTHER INSTITUTES

To the authors' best knowledge no other institutes have developed manoeuvring models in muddy areas to perform real time simulation research. On the other hand, the knowledge developed at FHR on ship behaviour in muddy areas has been used to enable other institutions to perform simulator studies to tackle local navigation problems. Some examples:

- On behalf of Alkyon (nowadays part of Arcadis), FHR suggested modifications to mathematical models for a container vessel, a bulk carrier and a towed barge to simulate manoeuvres in the approach to harbours in Brazil and Surinam.
- A real-time simulation study to investigate the feasibility of introducing the nautical bottom approach in the harbour of Delfzijl (The Netherlands) was performed at the FHR simulators in the frame of a study by Wiertsema & Partners on behalf of Groningen Seaports [23].
- On behalf of USACE, FHR suggested modifications to mathematical models for a tanker to simulate approach manoeuvres to the Calcasieu Ship Channel (USA) at the ERDC simulator facility in the frame of a project executed by RPS Group Plc.

7 CONCLUSIONS AND OUTLOOK

This paper intended to give an overview of the research that has been carried out since 1975 on the manoeuvring behaviour of ships in muddy navigation areas.

Despite the numerous research efforts on the manoeuvring behaviour in muddy navigation areas the question still remains how both parts of the nautical bottom definition by PIANC can be linked. It is still hard to tell what the physical limit is, and how it can be measured adequately in situ. Confirmation is needed whether this physical limit is linked to critical issues with the ship's controllability. It is rather doubtful that this critical limit can be summarized in a single parameter such as the mud density, which is however the most common practice to characterize the mud, besides the echo sounding.

Further research is still needed with regards to the measuring tools. At present each tool claims to measure a level which corresponds to the nautical bottom, but a convergence of the different levels is not reached yet.

The manoeuvring behaviour of the vessels in muddy navigation areas also needs further attention, however the limits of physical scale models are reached, as it is hard to address the influence of density and viscosity gradients and thixotropy on model scale. Therefore a start is made to try to implement the rheological behaviour of the mud into CFD. This is a long term project, as for now only the behaviour of a cylinder submerged in mud without water can be predicted [22].

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