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SHIP BEHAVIOUR AND CONTROL IN MUDDY AREAS : STATE OF THE ART

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ABSTRACT

Since 1976, several full scale and model test programs have been carried out in order to investigate the effect of mud on ship behaviour. A review of and a critical comparison between test results is given, as well as an indication of possibilities for further research in this field. Aspects of special importance to manoeuvring and control (resistance, propulsion, rudder forces) are emphasized, but closely related topics (interface deformation, squat effects, rheology) are mentioned as well.

Keywords: nautical bottom, navigation in muddy areas.

INTRODUCTION

In access channels and harbour basins where the bottom is covered with a fluid mud layer, bottom and water depth are not clearly defined. In the first place, difficulties may arise in determining the water depth, as measurements with echo-sounders may result into different values for depth: acoustic signals of high frequency reflect on the water-mud interface, while low frequency waves penetrate into the sediment deposit and give a higher value for water depth. Besides this problem, the question arises whether it is not possible to allow ships to navigate with a smaller keelclearance (KC) relative to the interface than in the case of a solid bottom, or even with negative KC, which means that the ship's keel penetrates into the fluid mud layer. As a matter of fact, the upper part of a mud layer can be considered as "black water", characterised by low density and weak shear strength, so that the ship's hull suffers no damage in case of contact. On the other hand, safety of navigation must be guaranteed, which implies that the ship must be able to overcome possible effects of the presence of mud layers on her controllability and manoeuvrability by means of either her own controls, or external assistance such as tugs. Moreover, physical properties such as density (ρ_2) , dynamic viscosity (η) and - as mud cannot be considered as a Newtonian, but rather as a Bingham fluid (figure 1) - yield stress or rigidity (τ_y) increase gradually with increasing depth, so that at a certain level a transition between "fluid" and "solid" mud must be defined.

Navigation into mud deposits must not be considered as a new problem, and is common practice in several harbours and waterways. During the last two decades, however, efforts were made towards a scientific approach. The research on this topic can be separated into two subjects:
- investigation of the physico-chemical characteristics of mud deposits, including the development of field survey and measurement techniques;
- study of the influence of the presence of fluid mud layers on a ship's navigational response.

The final purpose of this kind of research consists of:
- selecting a theoretical definition and a practical determination method for the *nautical bottom*;
- defining a value for the KC allowing safe navigation;
- acquiring knowledge about the behaviour of the ship in these situations.

As a result of such research programs, the nautical bottom concept is nowadays applied in access channels to several ports: Rotterdam, Zeebrugge, Nantes - Saint-Nazaire, Bordeaux, Emden, Maracaibo. The definition of nautical bottom in all these areas is based on a critical density: 1150 kg/m^3 in Zeebrugge (access channel and outer harbour), 1200 in the Europoort area, the Loire and Gironde estuaries and Maracaibo, 1220 to 1240 in sections of the river Ems.

This variety can be explained as follows. Principally, a definition of nautical bottom should be based on the rheological characteristics, which determine whether the sediment behaves as a fluid or as a solid material. On the other hand, nowadays techniques are available for continuous density measurement, while rheological gauges are only suited for static measurements. Therefore, it is more practical to base a definition on a critical density, which on its turn must be related to some rheological property. As the relationship between density and rheology depends on several parameters (particle diameters, sand content, presence of minerals and organic material, etc.), the critical density depends on the location and can even be time variable.

Most of the density values are based on the so-called rheological transition level, which separates the density ranges for fluid and plastic mud. If all parameters mentioned above are constant, a fixed relationship can be determined between density and rheological properties (figure 2). At low density, the increase of η and τ_y as a function of ρ_2 is slow (fluid mud); at higher density, the increase is faster (plastic mud).

Besides physico-chemical investigations of mud properties, several full scale and model test programs were carried out in order to investigate the effect of mud on ship behaviour. As a general conclusion, the behaviour of a ship navigating above or in fluid mud is mainly affected due to:
- the generation of undulations of the water-mud interface;
- the mud rheology, responsible for additional hull forces.

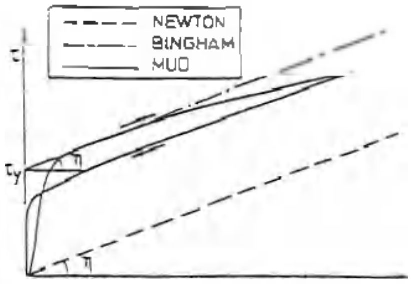

Figure 1. Mud rheology.

All tests have contributed to a better understanding of the physical causes of the influence of the presence of mud. On the other hand, model test conditions were very different. Furthermore, possibilities of comparison between full scale and model tests are also restricted, as full scale tests were usually performed at a limited speed range and a "safe" KC.

The paper intends to give a review of and a critical comparison between test results, and indicates possibilities for further research in this field. Although aspects of special importance to manoeuvring and control (resistance, propulsion, rudder forces) will be emphasized, related topics (interface deformation, squat effects, rheology) have to be mentioned as well.

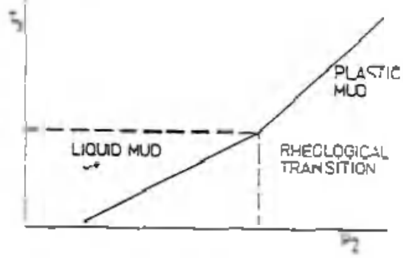

Figure 2. Density-rheology relation.

REVIEW OF TEST PROGRAMS

Model tests

Systematic model tests above mud-simulating materials were carried out in three laboratories:
- MARIN, Wageningen, 1976 (Sellmeijer & Van Oortmerssen, 1983);
- Flanders Hydraulics, Borgerhout-Antwerp, 1986-1989 (Vantorre & Coen, 1988; Wens et al, 1990; Vantorre, 1991; Ferdinande & Vantorre, 1991; Van Craenenbroeck et al, 1991);
- SOGREAH, Grenoble, 1989 (Brossard et al, 1990a, 1990b).

Table 1. Review of model test programs.

Laboratory	Mud simulating material	ρ_2 (kg/m^3)	η (Pa s)	τ_y (Pa)	h_2 (mm)	Ship models	h_1/T	model speed (m/s)
MARIN	chlorinated 1 paraffin 2 - 3 kerosine 4 (CP/K) 5	1140 1240	0.028 0.031	0 0	30 16 47 30 16	Tanker	0.85 - 1.15	0.17, 0.28, 0.40
Flanders Hydraulics (FH)	trichlorethane 1 - 2 petrol 3 (TCE/P) 4	1110 1140 1220	0.002 0.002 0.002	0.135 0.14 0.146 0.146	35 11 35 16	TSHD LNG TSHD TSHD	0.90 - 1.20	0 - 0.5
	natural mud	1089 - 1198	0.005 - 0.024	1.1 - 17.8	140 - 340	inland	1.5 - 5.7	0.16 - 1.25
	artificial mud	1030 - 1196	0.004 - 0.079	0.4 - 32	28 - 40	TSHD	0.85- 1.20	0 - 0.4
SOGREAH	artificial mud	low grad. int. grad. high grad.		low/high low/high low/high	≈ 35 ≈ 30 ≈ 25	Tanker	0.80 - 1.20	.2,.3, .4,.5, .6

Table 2. Ship models.

Laboratory	Ship model	LPP (m)	B (m)	T (m)	CB	Scale
MARIN	Tanker	3.76	0.57	0.23	0.85	1:82.5
Flanders Hydraulics (FH)	TSHD	3.10	0.58	0.20	0.84	1:40
	LNG	3.81	0.59	0.16	0.80	1:70
	Inland	3.95	0.69	0.14-0.34		
SOGREAH	Tanker	2.56				1:100 ; 1:70 ; 1:55

Tables 1 and 2 show that the model tests were carried out under very different conditions:
- Several types of mud simulating material were selected:
  * At MARIN and Flanders Hydraulics, the mud was simulated by means of homogeneous

fluids which were immiscible with water. The material used at MARIN was a Newtonian fluid with rather high viscosity, while most of the model tests at Flanders Hydraulics were carried out with a Bingham fluid with low viscosity and yield stress.

  * A completely different material was selected at SOGREAH, where the tank bottom was covered with artificially composed mud layers, characterized by vertical gradients of density and rheological characteristics. Some experiments were carried out above natural and artificial mud layers at Flanders Hydraulics as well.

- Different test methods were applied at the three laboratories:
  * At MARIN, self-propulsion tests and captive (stationary and PMM) tests were performed.
  * Flanders Hydraulics executed several kinds of straight-line self-propulsion tests above trichlorethane/petrol and artificial mud (acceleration, deceleration, steady-state and rudder angle tests). The test above natural mud layers were carried out with a towed model, but only interface deformation and fluid velocities were studied.
  * SOGREAH made use of a towed model.
- Although the ranges of ship model speeds examined at the three laboratories are comparable, tests were carried out at a limited number of discrete speed values at MARIN and SOGREAH, while a more continuous range of speeds was studied at Flanders Hydraulics.

Due to these differences and the fact that only a limited number of results were published, it is rather difficult to make a clear comparison between the test results of the three institutions.

Full scale tests

The introduction of a nautical bottom approach in Rotterdam, Zeebrugge and Nantes - Saint-Nazaire was preceded by full-scale tests.

In the Europoort area tests were carried out with the 300 000 tdw oil tanker *Lepton* in 1975, navigating with a draught of 20.9 m at a speed of 4 knots over a mud layer of 1.15 m thickness with a KC of 1.60 m (van Bochove & Nederlof, 1979; Sellmeijer & van Oortmerssen, 1983). Similar tests took place in the Loire estuary with the tanker *Alsace* in 1985, with 10% KC relative to the 1200 kg/m^3 density level (Brossard et al, 1990a).

In the outer harbour of Zeebrugge, 17 tests were executed with the trailing suction hopper dredger *Vlaanderen XVIII* in 1986-88 (Kerckaert et al, 1988; Van Craenenbroeck et al, 1991). Three types of tests were carried out: short engine manoeuvres (acceleration-deceleration), constant power manoevres (steady-state) and yawing tests at zero speed by means of bow thrusters. The first and second types of tests were executed with KC from -0.35 to +3.0 m with respect to the interface. Three runs were executed with negative KC, through mud with a density of maximum 1140 kg/m^3.

INTERFACE DEFORMATION

Most effects of the presence of mud layers on ship behaviour are related to the deformation of the interface, causing specific velocity patterns in both the water and the fluid mud. For this reason, some considerations on this topic are required.

Model tests in a two layer system

Model tests with a liquid mud simulating material (MARIN, Flanders Hydraulics) showed that the undulation pattern depends on the ship's speed. At Flanders Hydraulics, test results led to distinction between three speed ranges (figure 3):
- First speed range (SR1): the interface remains practically undisturbed.
- Second speed range (SR2): an interface sinkage is observed under the ship's entrance, which at a certain section changes into an elevation. Oscillations are superposed on the risen interface. The interface jump moves towards the stern with increasing speed. The wave front is perpendicular to the ship's axis of symmetry.
- Third speed range (SR3): the interface jump occurs behind the stern. The angle between the jump and the ship's longitudinal axis increases to approximately 135°.

This relation between speed and interface deformation is less clear at large negative values of KC; at the ship's entrance, a secundary internal wave pattern can be observed.

Similar observations were made at MARIN. As the experiments were carried out in a wide shallow water tank, the lateral propagation of internal waves could be evaluated; it appears that interface deformations generated at lower speeds are located in the vicinity of the ship, while at higher speeds, the influence range is extended to larger distance (figure 4). Furthermore, following conclusions were drawn:
- the height of the internal wave increases with the thickness of the mud layer;
- the wave height reduces with decreasing KC;
- the wave height decreases with increasing density.

Most of these conclusions were confirmed by test results at Flanders Hydraulics and theoretical calculations carried out at the University of Ghent. The latter also led to an expression for the critical speed separating SR2 and SR3:

$$V_{crit} = \sqrt{\frac{8}{27} g h \left(1 - \frac{\rho_1}{\rho_2}\right)} \qquad (1)$$

This value differs from the maximum velocity of propagation of internal waves, which takes following expression for small h_2/h_1 ratio and which is proposed by MARIN to be a critical speed:

$$C_{max} = \sqrt{g h_2 \left(1 - \frac{\rho_1}{\rho_2}\right)} \qquad (2)$$

The experiments at Flanders Hydraulics, however, have shown that the behaviour of neither the ship, nor the interface is modified at C_{max}. As explained by Ferdinande & Vantorre (1991), the transition between the sunken and the risen interface is not an interfacial wave, but an internal hydraulic jump. The oscillations superposed on the risen interface can be considered as waves, but are of minor importance.

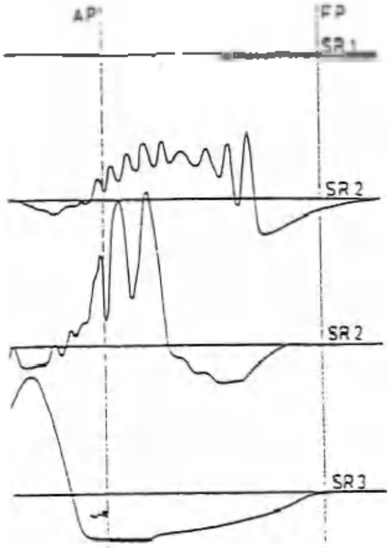

Figure 3. Model tests at FH: interface undulations in TCE/P1, $h_1/T = 1.2$.

Model tests with natural and artificial mud layers

At SOGREAH, observations of interface deformation in artificial mud layers appeared to concur, for the most part, with those published by Sellmeijer & van Oortmerssen (1983), although no interface motion was visible with the most rigid mud at any speed, nor with the least rigid mud at lower speed (0.2 m/s). According to the description given by Brossard et al (1990a), all observed waves have SR3-characteristics. The wave height depends little on the density gradient, and can take values of about 0.5 (KC<0) to 2 (KC>0) times the mud layer thickness.

At Flanders Hydraulics, the test series with self-propelled models above an artificial fluid mud layer revealed interface deformations comparable with those observed in two-layer systems .

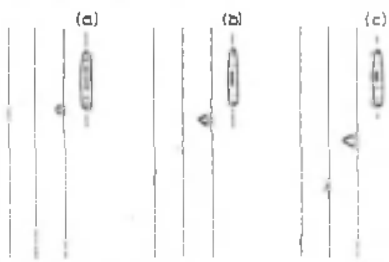

Figure 4. Model tests at MARIN: interface undulations in CP/K1, $h_1/T = 1.03$.

Qualitative tests at Flanders Hydraulics with a towed model above natural mud layers resulted into similar deformation patterns. A comparison with the other test programs is rather difficult, because of the unusual values for KC, h_2/h_1 ratio and blockage. Measurements of fluid velocities confirmed the hydraulic jump character of the interface deformation: mud flows in a opposite sens relative to the ship's speed under the sunken part of the interface, and follows the ship under the risen part (figure 5). Another important conclusion concerns the stability of the interface. At higher speed, mixing of mud with water sometimes occurs, but only takes place behind the ship, so that the fluid velocity patterns around the ship are not affected by this phenomenon. It was also observed that the interface recovered surprisingly fast.

Full scale tests

Sellmeijer & van Oortmerssen (1983) report that the existence of internal waves was confirmed by full scale observations; in addition, the approximate wave height and the position relative to the ship were confirmed. Interface deformations, looking like solitary stern waves, were also observed by survey vessels during the tests at Zeebrugge: Kerckaert et al (1988); Van Craenenbroeck et al (1991).

Conclusions

The fluid velocity pattern around the ship is dominated by a hydraulic jump the position of which relative to the ship is speed dependent. Similar interface deformation patterns are observed in both mud-water and two layer systems.

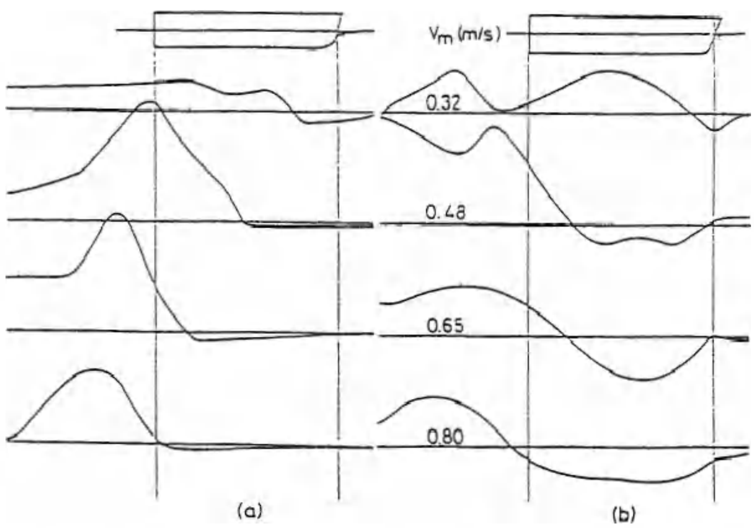

Figure 5. Interface undulations (a) and mud velocity (b) in natural mud layers, Flanders Hydraulics (inland vessel, $h_1/T = 1.5$, $h_2/T = 1.44$, $\rho_2/\rho_1 = 1.09$).

It should be mentioned that in some cases interface deformations in artificial or natural mud layers are only observed at SR3 (SOGREAH model tests, Zeebrugge full scale tests). It is possible that in SR2 the interface deformations are concentrated in a limited area near the ship, as was illustrated by the MARIN observations, but this is subject to confirmation.

SQUAT

Introduction

Sinkage and trim are influenced by the presence of a fluid mud layer due to two effects:

- the interface undulations modify the fluid velocity pattern and, therefore, the pressure distribution on the hull;
- contact between the hull and the mud layer results into an increase of the hydrostatic force acting on the submerged part of the ship due to the higher density of the mud.

Full scale measurements of squat of ships navigating in muddy areas are not available.

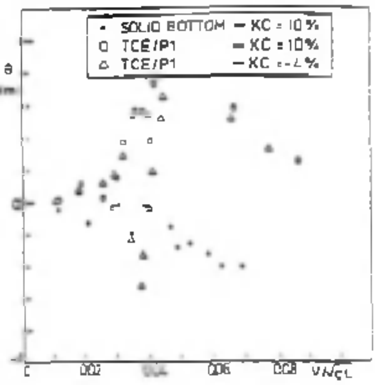

Figure 6. Model tests at FH with TSHD above TCE/P3: trim.

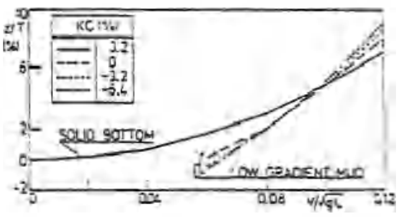

Figure 7. SOGREAH, model tests above artificial mud: sinkage.

Lower speed range

The model tests carried out at Flanders Hydraulics show a clear dependency on speed. The interface jump occurring under the ship in SR2 causes important trim effects (figure 6):

- If the initial KC is sufficiently large so that no contact takes place between the hull and the mud layer, the lower pressures in the vicinity of the run result into a vertical force causing additional sinkage of the stern. The mean sinkage is comparable with, or even slightly larger than in the solid bottom case.
- At small positive and negative KC, a part of the keel is touched by the mud, so that the vertical force acting on the run decreases and even changes its sign, causing an upward motion of the stern. The mean sinkage is practically zero, as squat effects are compensated by the buoyancy effects.
- At relatively large negative KC, buoyancy effects due to the higher mud density dominates so that the ship is lifted.

The results published by MARIN and SOGREAH confirm these observations for mean sinkage, but do not reveal any important trim effects in this speed range.

Higher speed range

At positive or even small negative values of the KC, the interface sinkage occurring over the full length of the ship in SR3 results into an increase of KC; as a result, both sinkage and trim are less compared with solid bottom conditions.

At large negative KC, contact takes place between ship and mud layer, causing two counteracting effects: a hydrostatic buoyancy force, acting upwards, and a hydrodynamic force due to the relatively high velocity between mud and ship, acting downwards. The latter increases with speed, so that at relatively high speed sinkage is larger than in solid bottom conditions, as was observed at SOGREAH with low gradient mud (figure 7), and at Flanders Hydraulics.

RESISTANCE AND PROPULSION

Introduction

A first aspect of controllability concerns the motions of the ship in longitudinal sense: does the presence of mud layers affect the ability of the propulsion to accelerate the ship, maintain the speed at a desired value, and stop the ship within a reasonable time and distance ?

An analysis of this problem requires more insight into the longitudinal forces acting on a ship : resistance, propulsive forces and, in the case of a varying speed, inertia forces, and can only be performed by means of model tests. Full scale tests, on the other-hand, only give an idea about the overall performance, e.g. by means of a relationship between speed and rpm or power.

Unfortunately, neither of the three laboratories have investigated systematically both resistance and propulsion. At MARIN, resistance and propulsion tests only resulted in a speed - rpm curve. As Flanders Hydraulics was not yet equipped with a towing carriage at that time, only self-propulsion tests were carried out. At SOGREAH, resistance was measured, but propulsion was not investigated. This implies that the present state of the art does not contain all elements for a complete evaluation of the effect of mud layers on the longitudinal speed controllability of ships.

Speed - rpm relationship

Results of model tests at MARIN and Flanders Hydraulics show that the speed - rpm relationship, which is approximately linear above a solid bottom, is affected to an important degree in SR2, where a substantially larger rpm is required for a given speed. The transition between SR2 and SR3 is less clear if KC is negative: for a constant rpm, speed decreases with decreasing KC in SR3, while the opposite tendency is observed in SR2. At large negative KC, the speed-rpm curve appears to be more or less linear (figure 8).

Full scale tests carried out at Zeebrugge confirmed the influence between KC and speed at constant propulsive power in SR3: speed appeared to increase by about 20 % if KC varies from -5 to +10% of draught. Comparison between test results of different steady-state runs required elimination of variable parameters such as draught and propulsive power; it was concluded that in the KC range of -5 to +10% of draught, no significant relationship between speed and KC is found, and that there is no evidence that contact between keel and mud would cause a sudden speed loss. Compared with deep water conditions, speed is reduced by 50% at zero KC.

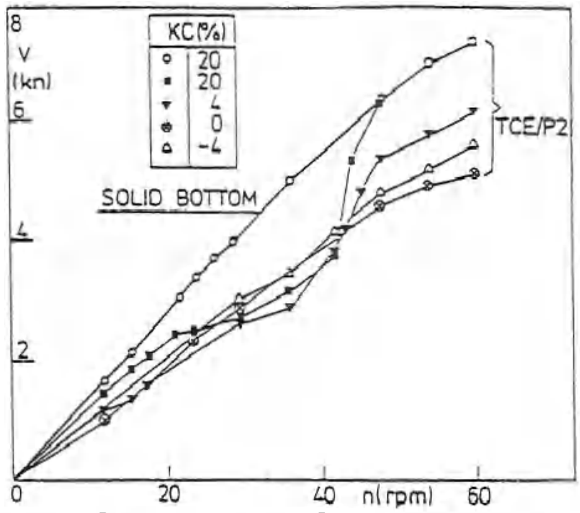

Figure 8. Model tests at Flanders Hydraulics: speed-rpm relationship.

Resistance

The SOGREAH resistance tests revealed an important effect of KC (figure 9):
- for positive KC, the resistance is comparable with a solid bottom situation;
- for negative KC, resistance increases very fast;
- in some cases, a local maximum is reached when the keel is just above the top of the mud.

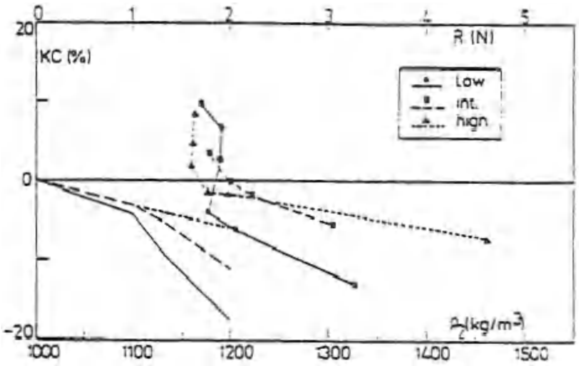

Figure 9. Model tests at SOGREAH above artificial mud: resistance at $V_m = 0.4$ m/s.

Following approximation for resistance is proposed: $R^0 + kV^2$. The initial resistance R^0 depends on KC and mud type, and is zero for positive KC. The values of k are higher by 20 to 50% than these noted for clear water.

The data published by SOGREAH do not allow to obtain a clear idea about the exact shape of the resistance curve, as tests were executed at discrete speed values. Neither is it possible to find a correlation with interface undulation patterns.

Although resistance was not measured at Flanders Hydraulics, a qualitative approximation for the total resistance coefficient C_T was derived from deceleration tests. Conclusions (figure 10):
- At KC>0, C_T is comparable with the solid bottom curve at low and high speed; in some cases, the resistance above mud is even lower.
- In a well-defined intermediate speed range, situated within SR2, C_T increases substantially with increasing speed, and suddenly decreases at a certain critical speed. The latter does not coincide with the transition speed between SR2 and SR3; the sudden decrease appears to take place when, due to squat and interface undulations, contact occurs between the ship's keel and the mud simulating material. This implies that:
  * in spite of the larger viscosity of mud, contact between ship and mud causes a decrease of resistance in this particular speed range;
  * the maximum C_T and the "hump" in the speed-rpm curve do not occur at the same speed.
- At smaller and negative KC, the resistance coefficient curve is smoothened.

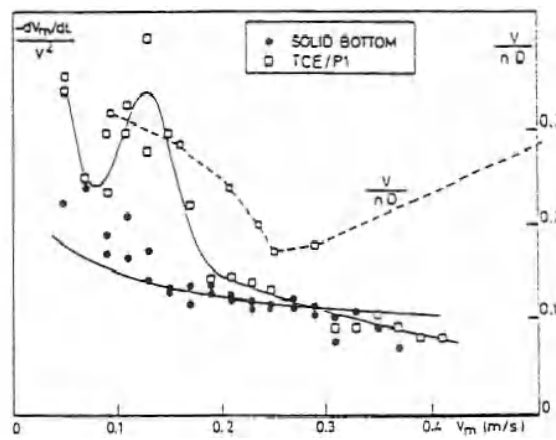

Figure 10. Model tests at FH: deceleration tests (full), speed-rpm ratio (dashed)

Full scale deceleration tests carried out with the trailing suction hopper dredger *Vlaanderen XVIII* were analysed in the same way. At speeds lower than 3 knots, the resistance curve presents some oscillations, but no influence of KC is observed; at higher speeds, contact between keel and mud layer results into an increase of resistance by 50 to 100% (figure 11).

At Flanders Hydraulics, artificial mud with rather high rigidity was used to determine the resistance at zero speed. No relation was found between the test results and the theoretical value obtained by multiplication of contact area with yield stress; the latter overestimates initial resistance at small negative KC, and is too small at large negative KC.

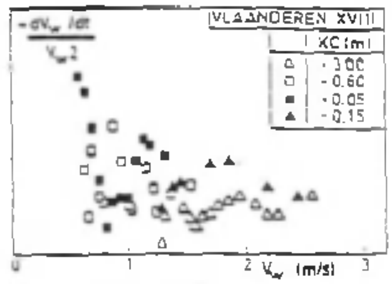

Figure 11. Full-scale tests at Zeebrugge: deceleration tests.

Propulsion

Analysis of propeller thrust and torque measurements during the model tests at FH led to following conclusions (fig. 12):

- The presence of an interface appears to yield higher values for thrust and torque coefficients, except for large advance ratio; this suggests an increase of the wake factor.
- If a steady state is reached in a speed range where the rising part of the interface is situated near the stern, thrust and torque increase to values comparable with bollard pull conditions.
- If the speed range mentioned above is passed during an acceleration phase, oscillations of thrust and torque are observed.

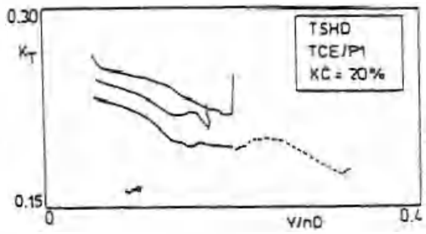

Figure 12. FH model tests: thrust coefficient vs apparent advance ratio (full: SR2; dotted: SR3).

Comparison with the C_T-curves derived from deceleration tests led to some qualitative indications about the thrust deduction factor t in SR2: t decreases if no contact between keel and mud occurs, but increases if the interface jump is concentrated at the stern and touches the keel.

Engine manoeuvres

Full scale tests at Zeebrugge showed that the acceleration characteristics during short engine manoeuvres at low speed are not affected by KC in the range between -5 and +40%.

Discussion

Resistance is affected by the presence of a mud layer due to several causes:
(a) additional wave resistance due to interface undulations;
(b) increase of viscous forces due to the higher viscosity of mud;
(c) initial resistance due to the Bingham character of mud;
(d) changes of relative velocity between ship and water and/or mud due to interface undulations.

The importance of cause (a) is not clear, and can only be evaluated by means of resistance tests combined with registration of internal undulation patterns. It should be born in mind that,

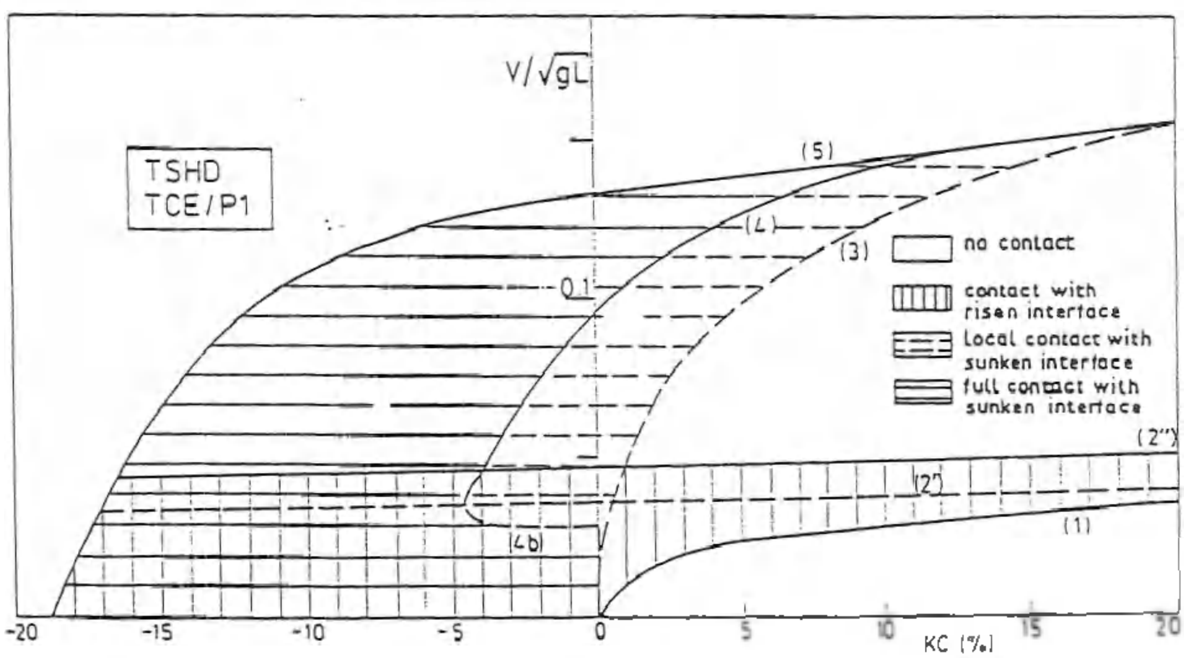

Figure 13. Model tests FH, theoretical calculations UG: position of ship's keel relative to water-"mud" interface as a function of speed and KC.

although relatively high internal "waves" are observed, their energy content is rather low because of the small density difference between both fluids.

(b) and (c) are of importance if contact occurs between the ship and the mud layer; in that case, the effect on resistance is determined by the (negative) KC value, the rheological properties of the mud and the vertical gradient of the latter. The influence is shown by the SOGREAH results.

The importance of (d) depends on the speed range and the initial KC. The speed determines the kind of interface undulation and, therefore, the change in relative velocity: a sunken interface decreases relative water velocity and increases relative mud velocity, while a risen interface has an opposite effect. For a given speed, the initial KC determines whether contact will occur between the ship and the sunken and/or the risen part of the interface. For one particular configuration, all possible cases are given in figure 13:
- SR2, no contact: the relative water velocity is decreased slightly above the sunken interface, but is much increased above the risen interface, which results in an increase of resistance.
- SR2, contact with risen interface: the ship's run is partly in contact with mud, but the relative velocity between ship and mud is small. If the viscosity of the mud is relatively low, resistance can be decreased.
- SR2, full contact: the mud under the sunken interface contacts the ship with increased relative velocity, which results into an increase of resistance.
- SR3, no contact: the relative water velocity and, therefore, resistance is slightly decreased.
- SR3, contact: resistance is increased due to contact with mud at higher relative velocity.

The conclusions of the deceleration tests at Flanders Hydraulics appear to confirm these ideas.

These considerations do not fully explain the aspect of the speed-rpm curve. One possible explanation concerns internal wave resistance at the transition between SR2 and SR3, but measurements of propeller thrust and torque at Flanders Hydraulics indicate that contact between the rising interface and the stern part of the keel obstructs the flow to the propeller, causing a very poor propulsive efficiency.

It can be concluded that KC-speed combinations between curves 1 and 2" are characterized by relatively low resistance and low propulsive efficiency. Further investigation is required in order to check whether speed control and stopping manoeuvres could be affected in these conditions.

MANOEUVRABILITY

Full scale tests

At Rotterdam, the behaviour of the *Lepton* with reduced KC was compared with other ships applying a normal KC. It could be concluded that the *Lepton* did not make significantly different manoevres from the other ships of that size and that the amount of applied steering capacity (rudder, propeller) was about the same as with the other ships.

Full scale zero-speed yawing tests at Zeebrugge showed that rate of turn decreases by 50-60% if KC decreases from 120 to about 0%.

Hydrodynamic derivatives

A full captive manoeuvring test program was executed at MARIN, resulting into a mathematical manoevring model for a tanker in several mud configurations. Conclusions:
- Damping (speed dependent) coefficients are appreciably (2 to 4 times) higher with mud than without. The damping force Y_v increases with increasing mud thickness, decreasing KC and decreasing density. N_v increases with increasing mud thickness.
- rudder action is stronger with mud, but mainly due to the increase of rpm to maintain speed;
- added mass (i.e. acceleration dependent) coefficients are affected more by KC with respect to the bottom than by the presence of mud.

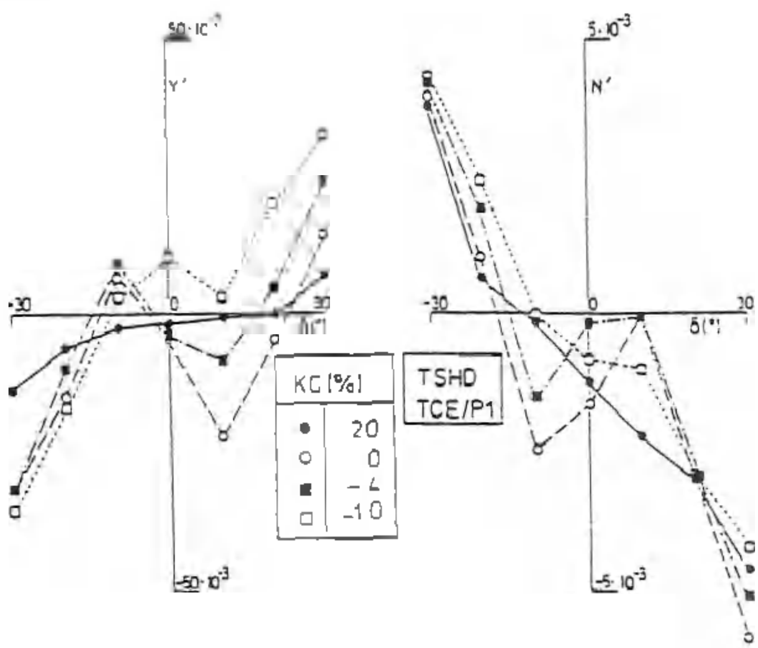

Figure 14. FH model tests, SR2: effect of KC on rudder action.

Rudder tests with self-propelled, beam-guided models at Flanders Hydraulics revealed that in some cases, lateral forces and yawing moments induced by rudder action take the usual sign for large rudder angles, but act into the opposite direction for small angles (figure 14). Such an instable rudder action appears to take place if the keel is in contact with both water and mud (ranges 1-2" and 3-4 in figure 13), especially if the contact zone is located near the stern (range 2'-2"). In case of stable rudder action, forces induced by rudder angles are increased by the presence of the mud.

Standard manoeuvres

Influence of mud on standard manoeuvres (turning circle, zig-zag) was investigated at MARIN by means of simulations. Conclusions:

- The presence of mud has a larger effect on the manoeuvres at low speed (3 knots) and a smaller effect at higher speeds (up to 7 knots).
- In general terms manoeuvres are slower with mud. The ship is most sluggish at small positive KC between keel and mud, but becomes less slow at negative KC. This is particularly the case at small speeds (3-5 knots); at 7 knots the opposite effect occurs in some cases.
- The effect of the presence of a mud layer decreases with increasing mud density.
- The presence of mud generally tends to slacken the steady motions (forward speed, drift, rate of turn are lower) and to accelerate the dynamic motions (overshoot, swept path are smaller).
- The combination of mud thickness and KC causing the most effect on turning parameters result in the highest internal wave.

Controllability of ship in contact with consolidated mud

A ship (intentionally or unintentionally) navigating with the keel in contact with a consolidated mud layer sometimes becomes uncontrollable and chooses the easiest way to follow; at the same time, it is practically impossible to decrease the ship's speed, although the latter is only 1 or 2 knots. These phenomena are not published in any written report or paper, but were observed independently by several witnesses. It is not clear whether there is any relationship between these phenomena and rheological properties, interface undulations, etc.

Discussion

In following situations, manoeuvrability and/or controllability may be affected adversely:

- small positive KC, low speed (according to MARIN tests);
- speed-KC combinations causing contact between the keel and both water and mud (according to Flanders Hydraulics tests);
- keel in contact with plastic mud (according to practical experience).

The third situation needs to be examined more thoroughly. More insight has to be acquired in the forces acting on a ship making attempts to penetrate mud of high rigidity. This can be achieved by means of model tests and/or well controlled full scale tests.

Although the first and second situations may cause problems due to other reasons, it is presumable that a relationship exists between both cases. As shown on figure 13, the first situation can be considered as a particular case of the second one. An analysis of Y_δ and N_δ values published by Sellmeijer & van Oortmerssen (1983) shows that the application point of the resulting force induced by rudder action is situated at about 0.5 L behind midships for the solid bottom situation, but moves to about 0.2 L for KC of 10 to 15%, and even to 0.1 L for KC of +3 to -10%. The Flanders Hydraulics test results lead to comparable values at large rudder angle. This means that the force induced by rudder action applies about midships, which is a less stable situation. It is clear that the rudder angle causes asymmetric flow in both water and mud layers, which results into asymmetric interface undulations, creating lateral forces on the hull. If the latter counteract the force on the rudder, instabilities may occur.

Figure 13 shows that, for a particular KC, problems may be expected in a rather wide speed range at small KC; at larger KC, this range is more restricted. As the MARIN tests were carried out at discrete speed values, it is not clear whether the "worst case" for each condition was selected. With the present knowledge, it would be advisible to choose the speeds according to the several ranges of KC-speed combinations shown in figure 13.

CONCLUSIONS

Harbour and waterways authorities applying the nautical bottom concept have reached a practical compromise between a theoretical definition of nautical bottom, which must be related to the rheological properties of the mud, and a practical determination method, based on continuous density measurement. As no universal density - yield stress relationship exists, a safe critical density value must be selected; the latter is based on a correlation between density and the rheological transition level. This implies that, in principle, the determination of nautical bottom might be optimized if:

- the definition of nautical bottom were based on a critical yield stress value, as the yield stress range corresponding with the rheological transition level is rather low (1-3 N/m^2);

- a device for continuous measurement of rheological properties were available.

The second item lies beyond the scope of this Conference and the author's competence; the first one, on the other hand, is closely related to manoeuvrability and controllability of ships. There is a need for extensive investigation of the influence of mud rheology on ship behaviour; the SOGREAH resistance test program constitutes a very useful reference, but should be extended to propulsion and manoeuvring. Taking account of the poor controllability of ships touching consolidated mud layers, it is not justified to establish a new criterion for nautical bottom without a deeper understanding of ship behaviour in these particular conditions.

Further optimization concerns a well-considered selection of requisite KC, as the ship is not supposed to touch the nautical bottom level. Among other parameters, this KC value must take account of squat considerations; a former chapter shows that many model test results are already available on this topic.

A last but important field of investigation concerns manoeuvrability and controllability of ships navigating with a "safe" KC relative to the nautical bottom. In order to guarantee a safe shipping traffic, pilots should be aware of the modified ship behaviour as a function of speed, KC and mud layer parameters. This requires extensive captive manoeuvring tests above suitable mud simulating layers in order to determine a reliable mathematical manoeuvring model, and training of pilots by means of simulation runs, during which the most critical situations can be evaluated.

A complete investigation program handling all mentioned topics would require a multidisciplinary approach, which can only be successful if experts in measurement techniques, sediment rheology, theoretical and experimental ship hydrodynamics, manoeuvring simulation and nautical science are involved. Taking account of the importance of safe and economic shipping traffic, it is worthwhile to take the challenge.

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NOMENCLATURE (see also Tables 1 and 2)

- B beam
- C wave celerity
- C_B block coefficient
- C_T total resistance coefficient
- g gravity acceleration
- h_1 water depth
- h_2 mud layer thickness
- KC keel clearance
- L ship's length
- L_{pp} length between perpendiculars
- N yawing moment
- r rate of turn
- R resistance
- R^0 initial resistance
- SR speed range
- T draught; thrust
- v sway velocity
- V ship's speed
- V_m model speed
- Y lateral force
- z average sinkage
- δ rudder angle
- ρ_1 water density
- ρ_2 mud density
- η dynamic viscosity
- θ trim angle
- τ_y initial rigidity, yield stress