

NAVIGATION IN MUDDY AREAS:
ESTABLISHING THE NAVIGABLE DEPTH IN THE PORT OF
ZEEBRUGGE

by
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ABSTRACT.

The navigable depth in Zeebrugge, which is actually situated at the 1.15 tm^{-3} density level, was established during an extensive research program, which included:

- laboratory testing of sediment properties;
- in-situ measurements of sediment properties;
- full scale trials with a trailing suction hopper dredger;
- small scale tests modelling the full scale trials and systematic ship model test series.

The paper contains a short description of the laboratory tests, including conventional and newly developed tests for the determination of the structural behaviour of the mud, such as rotaviscometry, and Controlled Stress Rheometry.

Further, a very short description of the equipment developed for the in-situ measurement of sediment properties, such as the towed density gauge Navitracker and the rheometric profiler Rheometer is given.

More attention is paid to the analysis of data recorded during full scale trials with the trailing suction hopper dredger *Vlaanderen XVIII*. Acceleration, deceleration and steady-state phenomena observed in the presence of fluid mud are described. These tests are backed up and placed in a more general framework by model tests, the results of which are also discussed more extensively.

The implementation of the results obtained during the research program resulted in the production of a nautical chart, which is a combined echosounding-density chart, representing:

- the depth of the 210 kHz echosounder in cases where the mud is absent;
- the depth of the 1.15 tm^{-3} density level in muddy areas, this level being a safe criterion for the navigable depth in Zeebrugge.

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NOMENCLATURE

a	acceleration
AP	aft perpendicular
B	ship's beam
C	resistance coefficient
C_B	block coefficient ($= \nabla \div (LBd)$)
d	ship's draught
F_o	Froude number ($= V \div (gL)^{1/2}$)
FP	fore perpendicular
g	gravitational acceleration
h_i	thickness (depth) of layer i
HP	horse power
k	form factor
K	correction factor
KC	keel clearance (in m or in % of draught) relative to interface (210 kHz)
L	ship's length between perpendiculars
m	ship's mass
N	yawing moment
n	number of revolutions of propeller
P	propulsive power
P/D	propeller pitch \div diameter ratio
r	rate of turn (yawing velocity)
R	resistance
S	ship's wetted surface
T	propeller thrust
t	time; thrust deduction factor
TCE/P	trichlorethane/petrol mixture
u_i	relative horizontal velocity of layer i
V	ship's forward velocity
∇	ship's displacement

Y	lateral force component
w_i	percentage by weight
z_i	level of upper boundary of layer i
δ	rudder angle
ζ	ship's sinkage
θ	ship's trim
μ	added mass coefficient
ξ_j	undim'd distance from FP to jump
ρ_i	mass density of layer i
τ_y	yield stress

Subscripts

crit	critical
F	frictional (resistance)
J	(interface) jump
M	model
m	mean
∇	ship's displacement (correction)
PV	viscous pressure (resistance)
R	resistance (correction)
T	total (resistance)
Th	thrust (correction)
w	relative to the water (velocity)
0	reference loading condition
1	referring to fluid layer 1 (water)
2	referring to fluid layer 2 (mud)
∞	deep water condition

Superscripts

'	nondimensional
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1. INTRODUCTION

Zeebrugge is a recently extended sea port on the Belgian Coast (fig. 1). Maintenance dredging operations are carried out:

- in the access channel to the Port of Antwerp, called 'het Scheur',
- in the access channel to the New Outer Harbour, called 'Pas van het Zand',
- in the Central Part of the New Outer Harbour, and
- in the old part of the Outer Harbour.

In the access channels, the bottom generally consists of fine sand, sandy mud and clay. In the Central Part of the New Outer Harbour, the bottom is covered with a fluid mud layer, 1 to 4 metres thick, depending upon the hydrodynamic and sedimentological conditions. The bottom of the old part of the Outer Harbour and the recently constructed docks are covered with rather consolidated mud.

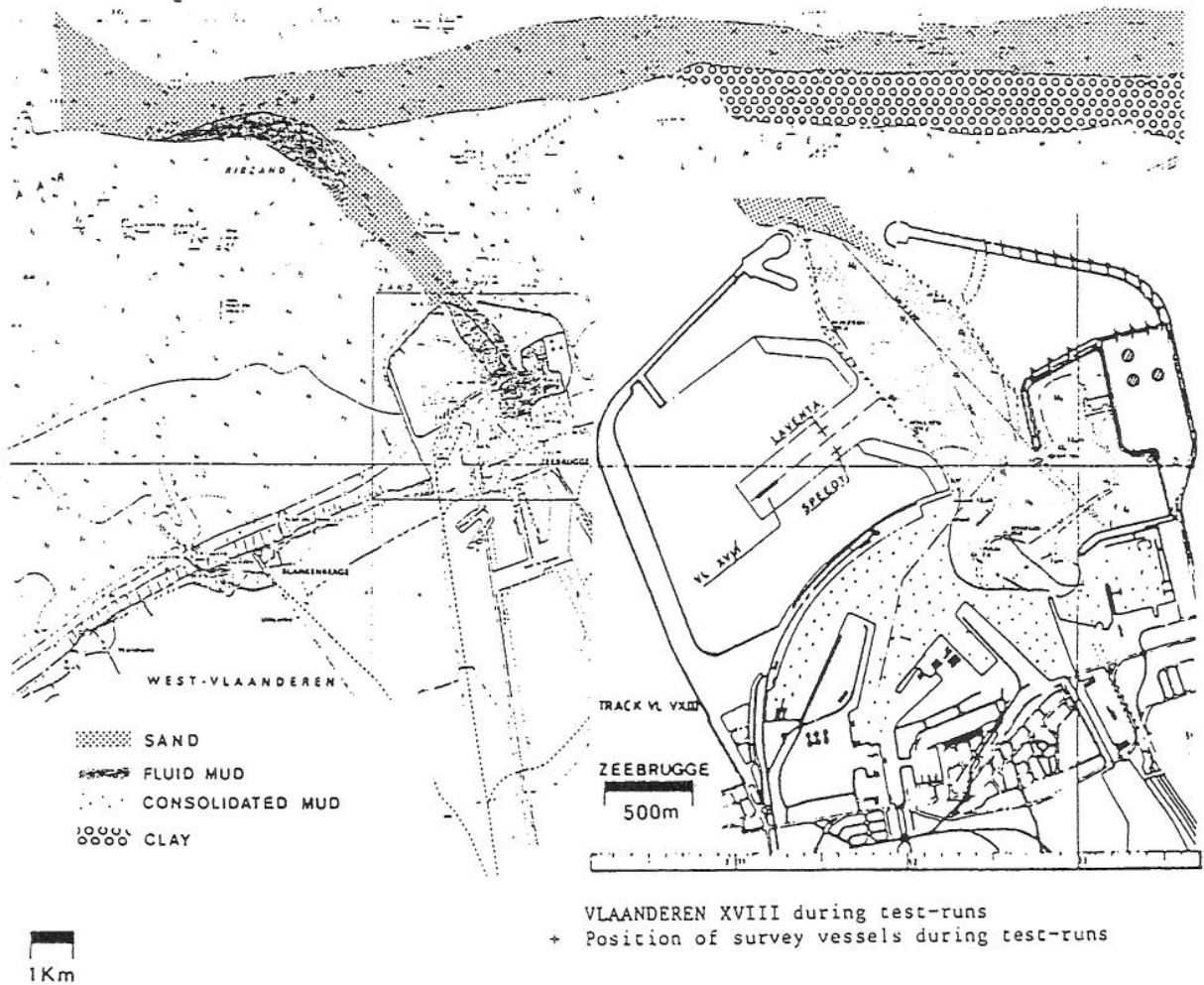


Fig. 1. The Harbour of Zeebrugge and its access channels.

The present paper reviews the efforts in the field of the determination of navigable depth and the production of nautical charts. PIANC, 1983 defines the navigable depth as the maximum depth with respect to chart datum which, for navigational purposes, is

- considered safe to accept as the channel bed. Therefore, two criteria have to be met:
1. The ship's hull must suffer no damage, even if its draught should reach the full navigable depth.
 2. The navigational response of the vessel must not be adversely affected.

2. PHYSIO-CHEMICAL PROPERTIES OF THE ZEEBRUGGE MUD.

Problems of navigable depth in muddy areas are now widely understood and have been discussed in several papers (Kirby et al, 1980; Nederlof & Bockhove, 1981; Sellmeyer & Van Oortmerssen, 1983; Kerckaert et al, 1985; Malherbe & De Wolf, 1986; Kerckaert et al, 1988). Summarising, these problems can be divided in two categories: the first dealing with the physical and chemical properties of the mud, the second with the manoeuvring and navigational behaviour of ships sailing through or just above fluid mud.

The physio-chemical properties of fluid mud influencing navigability are rheological parameters (yield stress, apparent viscosity) and density. These are influenced by sediment characteristics such as mineralogical composition, particle size, organic and carbonate content, by the salinity and the temperature of the water and by the history of the deposition.

2.1. Mineralogy

X-ray diffraction analysis has indicated that the minerals in the clay-fraction of the Zeebrugge mud are predominantly illite, swelling minerals including smectite and vermiculite, calcite, kaolinite, quartz and chlorite.

2.2. Particle Size Spectrum (fig. 2)

The average particle size spectrum of Zeebrugge mud displays a silty material with varying amounts of sand. Individual spectra show a basic silty clay and often an increasing sand content with depth (see also fig. 4).

2.3. Carbonate and organic content (fig. 3)

Fig. 3 displays the consistent and low seasonal variability with carbonate (30-35%) and organic (15-20%) content.

2.4. Density

The density of the medium through which a ship sails influences via buoyancy the hull's displacement. In Zeebrugge, thousands of density-profiles have been measured with a stationary backscatter gauge as well as with the nuclear transmission gauge Navitracker (De Vlioger & De Cloedt, 1988).

2.5. Rheological parameters

In the presence of fluid mud, the degree to which the channel bed participates in the various navigational effects will be affected by whether or not the ship sails above or within the fluid

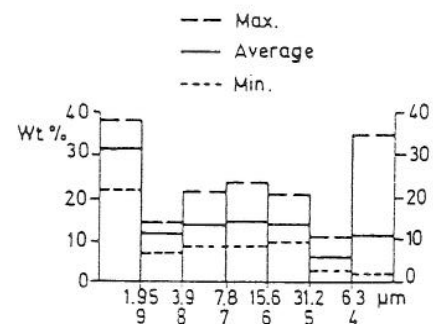


Fig. 2. Zeebrugge mud : particle size spectrum.

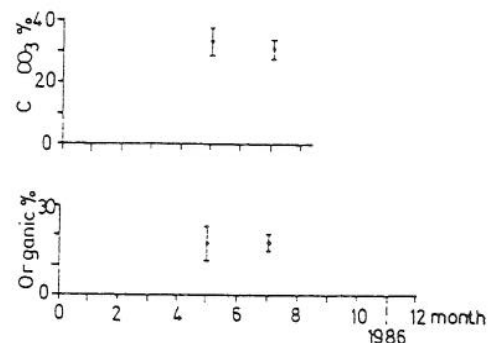


Fig. 3. Zeebrugge mud: seasonal variability of carbonate and organic content.

mud. Sailing above fluid mud, the response of the bed will be influenced by the pressure and flow field around the hull. Failure (flow) of the bed will be limited by its yield stress and apparent viscosity in relation to the pressure gradients and shear stresses caused by the dynamic behaviour of the displaced medium (return flow). Sailing within a fluid mud layer, the ship's manoeuvring and navigational behaviour will be affected by yield stress and apparent viscosity of the mud, the effect of the mud on the hull's drag coefficient and also the change in buoyancy due to the fluid mud density.

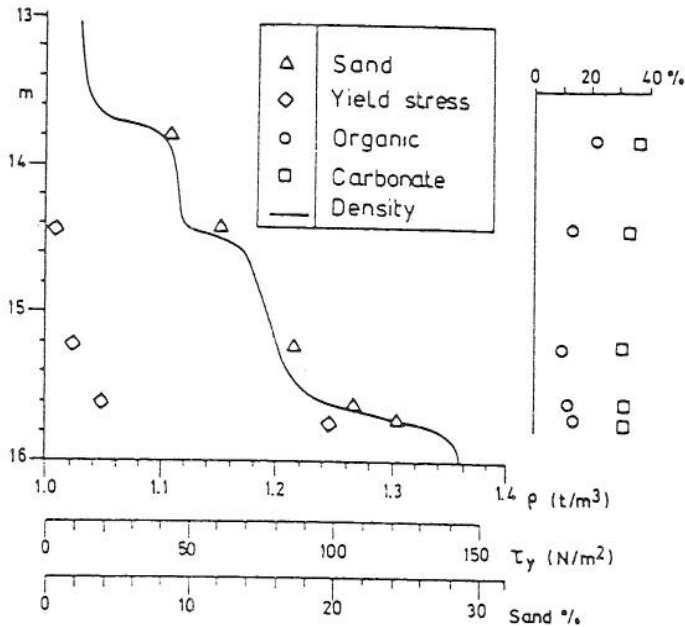


Fig. 4. Zeebrugge mud: sediment characteristic profiles.

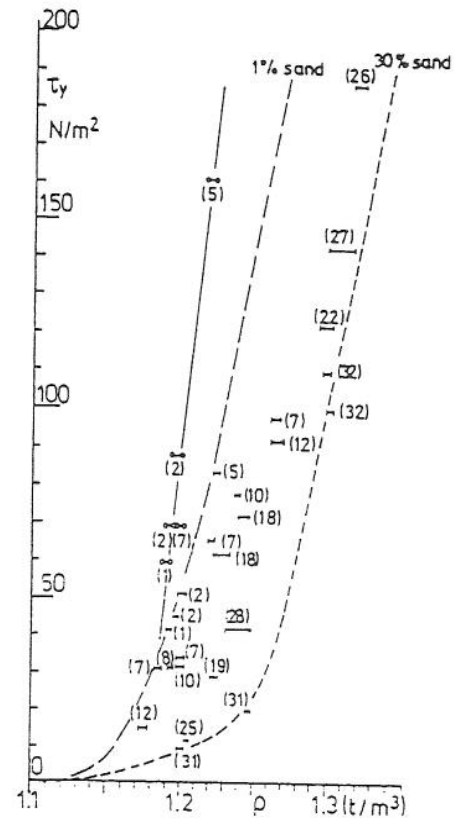


Fig. 5. Zeebrugge mud: yield stress vs. density at different sand contents.

In Zeebrugge, the rheological parameters of the fluid mud have been tested by using conventional rheometrical techniques (roto-viscometer) (Malherbe & De Wolf, 1986) as well as the new developed technique known as Controlled Stress Rheometry (C.S.R.) or Applied Stress Rheometry (A.S.R.) (James et al, 1987; Williams et al, 1988).

A thorough research of the Zeebrugge mud has resulted in the production of sediment characteristic profiles such as the ones shown in fig. 4. This kind of observations also resulted in curves as shown in fig. 5, presenting data on yield stress and density of mud samples with varying sand content, which reveal an exponential relationship between yield stress and density at a particular sand content. From those data it was concluded that the lower limit of measurable yield for Zeebrugge mud corresponds to a bulk density of the order of 1.10 t/m^3 . Above this value the yield stress increases with increasing density. At first, the increase is slow up to about 1.15 t/m^3 , after which it increases more quickly. This change in structural behaviour has been called the Rheological Change-over or Rheologic Transition of the mud (Malherbe & De Wolf, 1986).

3. IN SITU OBSERVATIONS OF THE MUD

For in-situ observation of sediment properties, two innovative measuring instruments have been designed and successfully deployed: the Navitracker survey system and the rheometrical profiler Rheometer.

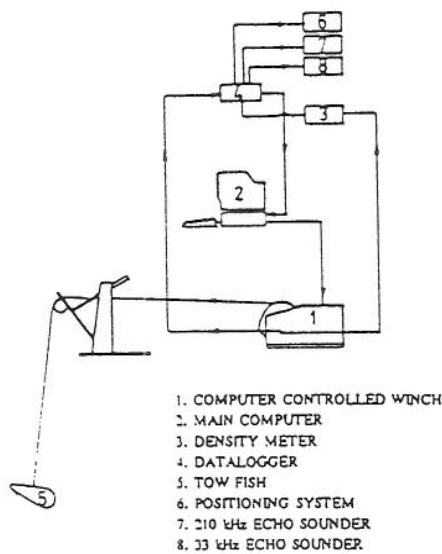


Fig. 6. Navitracker Survey System.

3.1. The Navitracker Survey System (fig. 6)

The Navitracker Survey System was developed for the continuous measurement of sediment density. The central part of the system is an intelligent winch which is controlled by the main computer on board the survey vessel. The winch automatically undulates a tow fish, containing a nuclear transmission gauge and a pressure sensor, between two pre-determined depth, density or echosounding-levels or keeps the fish at a given density-level within the mud. The main computer also integrates with traditional echosounder data (Kerckaert et al, 1988; De Vlioger & De Cloedt, 1988).

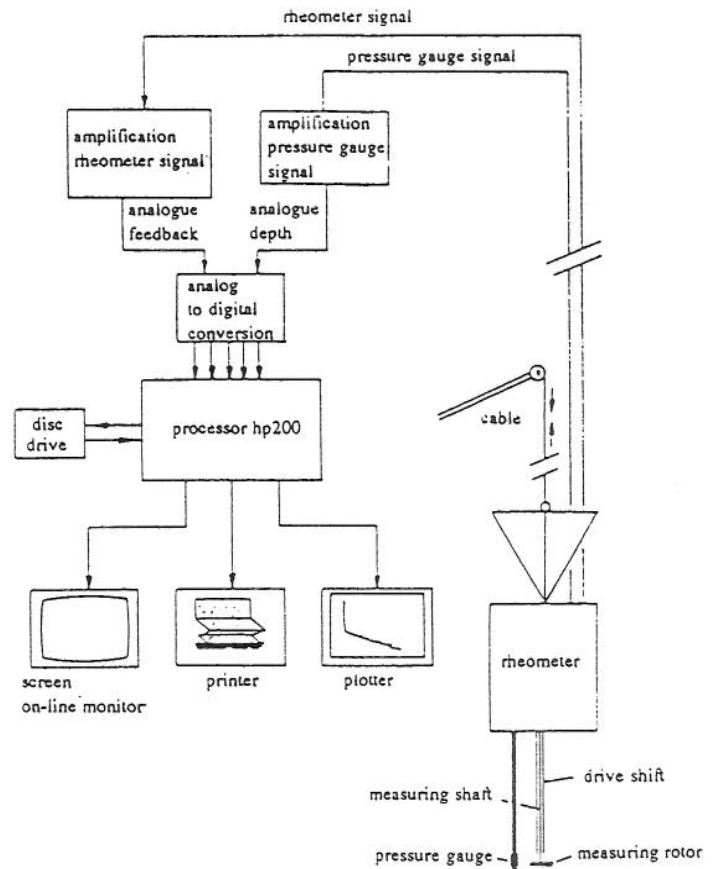


Fig. 7. Rheometrical profiler Rheometer.

3.2. The rheometrical profiler Rheometer for stationary measurements (fig.7).

The Rheometer was developed for the in-situ measurement of the depth of the Rheological Change-Over or Rheologic Transition within the fluid mud deposits. The measuring cell of the Rheometer is an on-line consistency transmitter which has been adapted for in-situ operations (De Meyer & Malherbe, 1987). The Rheometer is deployed simultaneously with a nuclear backscatter gauge, which enables the correlation of the measured rheological transition with density data.

4. FULL SCALE TESTS WITH TRAILING SUCTION HOPPER DREDGER VLAANDEREN XVIII.

4.1. Test Program

Although the analyses of sediment properties gave very interesting results and increased the understanding of the behaviour of the mud, they did not allow the prediction of the actual behaviour of a deep-draught vessel sailing just above or within fluid mud. In order to verify the PLANC criteria and to improve comprehension of a ship's behaviour in muddy areas, it was decided to carry out full scale tests with a large trailing suction

hopper dredger driven by two controllable pitch propellers (*Vlaanderen XVIII*). This type of vessel was selected because:

- draught and keel clearance (KC) can be adjusted very easily and accurately;
- the (water)load can be pumped overboard when trial conditions become critical;
- the vessel is equipped with highly accurate positioning and draught measuring systems;
- the block coefficient ($C_B = 0.82$) is comparable with that of bulk carriers or very large crude carriers (VLCC's).

The following types of tests were performed at different KC:

type 1: after the vessel was positioned, the propellers were put 'full ahead' for 50 to 150 s, before the pitch was returned to zero. Thus the ship underwent an acceleration, followed by a period of deceleration;

type 2: after positioning, the propeller blades were put at a constant forward pitch;

type 3: in order to get an idea of the manoeuvrability of a ship sailing within fluid mud, the ship was rotated at zero speed by means of the bow-thruster.

The first two types of tests took place in February and March 1986, the additional rotation tests (type 3) in June 1988.

4.2. Site description.

The full-scale tests were executed in the western sand dump pit in the central part of the New Outer Harbour in Zeebrugge (fig. 1):

- types 1 and 2 with the ship sailing out of the dock, with KC ranging from -0.35 to +3.0 m with respect to the depth indicated by the 210 kHz echosounder. During these tests, the depth as well as the nature, the sand-content and the density-gradient of the mud was nearly constant. Three runs were sailed with a negative KC, through mud with a maximum density of 1.14 tm^{-3} ;

- type 3 with the ship rotating at the end of the sand dump pit. Table 1, giving the average KC during this kind of tests, shows that the ship was rotated with a negative KC with respect to the level indicated by the 210 kHz echosounder (-0.3 to -0.4 m) and the 1.15 tm^{-3} density horizon (-0.2 m), and with a positive KC of about 0.1 m with respect to the position of the 1.2 tm^{-3} density level, which virtually coincided with the depth of the rheological transition as measured by the Rheometer (see 2.5 and 3.2).

TABLE 1.

LEVEL	Average KC (m)	
	test 1	test 2
210 kHz	-0.3	-0.4
Rheol.Tr.	+0.1	+0.1
1.15 tm^{-3}	-0.2	-0.2
1.20 tm^{-3}	+0.2	+0.1
1.30 tm^{-3}	+0.8	+1.2

During the test runs of types 1 and 2, two survey vessels were anchored along the sand dump pit to observe the behaviour of the mud. This resulted in the registration of a solitary wave at the mud-water interface by means of a 210 kHz echosounder, as depicted in fig. 8.

4.3. Analysis and results.

Comparison between test results required elimination of variable parameters such as draught and propulsive power. For this reason, a reference loading condition has

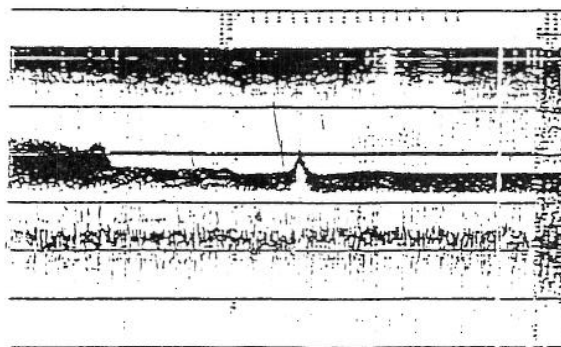


Fig. 8. Internal wave registered by survey vessel *La Venta* during full scale tests with TSHD *Vlaanderen XVIII* (type 1).

been chosen, according to an even keel draught $d_0 = 8.0$ m or a displacement $V_0 = 18$ 000 m^3 . The reference value for propulsive power chosen is $P_0 = 5$ 000 HP.

4.3.1. Acceleration characteristics.

During the acceleration phase of tests of type 1 and 2 the equation of motion yields:

$$(1 + \mu_x)ma = (1 - t)T - R \quad (1)$$

As the acceleration is computed at the initial phase of each test, the vessel's speed and, therefore, the resistance R can be neglected. The corrected acceleration is given by:

$$a_0 = a \frac{m}{m_0} \frac{1 + \mu_x}{1 + \mu_w} \frac{1 - t_0}{1 - t} \frac{T_0}{T} \quad (2)$$

The influence of the loading condition on the added-mass coefficient μ_x and the thrust deduction factor t is neglected as it is impossible to make a reasonable estimation, so that:

$$a_0 = a \frac{m}{m_0} \frac{T_0}{T} = a K_{\nabla} \frac{T_0}{T} \quad (3)$$

Thrust on the propellers was not measured, but results of model test carried out with a model of the *Vlaanderen XVIII* have shown a clear relationship between thrust and power. In fig. 9, $K_{\nabla} \cdot a$ is plotted as a function of propulsive power P ; as spreading of these results is rather limited, it can be concluded that the acceleration is only dependent on power (or thrust), so that the influence of other parameters (such as K_C) can be neglected. The average curve on fig. 9 will be used as a reference, giving a relationship of power vs. acceleration (or thrust).

It was be concluded that short engine manoeuvres at very low speeds are not affected by the K_C . This conclusion is valid for K_C values between -0.35 m and $+3.0$ m.

4.3.2. Deceleration characteristics.

During a deceleration phase (type 1), only inertia and resistance forces act on the vessel:

$$(1 + \mu_x)ma + R = 0 \quad (4)$$

Due to the limited speed, wave making resistance can be neglected, so that only resistance terms of viscous origin, frictional resistance R_F and pressure resistance R_{pV} , have to be taken into account. In a first approximation, R_F is considered to be proportional with $L \cdot (B + 2d)$ (wetted surface), R_{pV} with $B \cdot d$ (midship section). The ratio between R_{pV} and R_F is given by the form factor k , which is estimated to be 0.5 for the *Vlaanderen XVIII* in reference loading condition. In the following expression for resistance, $S \cdot (1 + k)$ can be considered as the geometry dependent part :

$$R = \frac{1}{2} \rho_1 C_F S (1 + k) V^2 \quad (5)$$

Following correction factor is proposed:

$$K_R = \frac{S (1 + k)}{S_0 (1 + k_0)} = \frac{1}{1 + k_0} \frac{B + 2d}{B + 2d_0} + \frac{k_0}{1 + k_0} \frac{d}{d_0} \quad (6)$$

A value for the frictional resistance coefficient C_F can now be derived as follows:

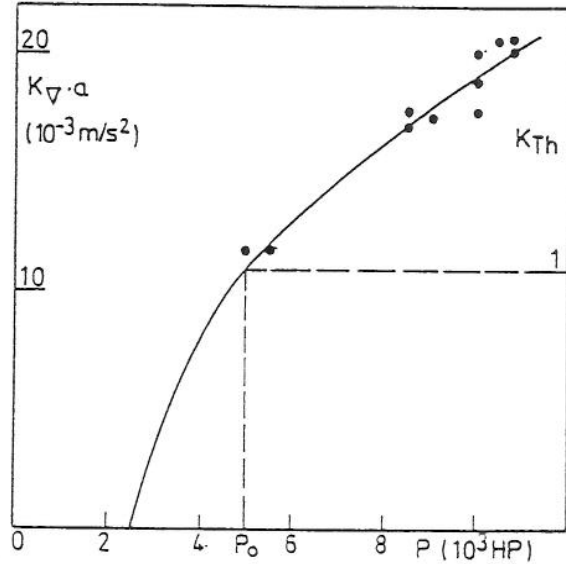


Fig. 9. Full scale trials: acceleration vs. power.

$$C_F = -\frac{(1+\mu_x)ma}{\frac{1}{2}\rho_1 V^2 S(1+k)} = -\frac{(1+\mu_x)}{(1+k_0)} \frac{m_0}{\frac{1}{2}\rho_1 S_0} \frac{K_V a}{K_R V^2} \quad (7)$$

Fig. 10 shows the relationship between a corrected and undimensioned value of $-a \div V^2$ and the vessel's forward velocity. Some conclusions:

- In the lower speed range (0.5 to 1.5 m/s), the resistance coefficient shows some clear minima and maxima; a significant influence of KC cannot be observed.
- At higher speed, resistance increases by 50 to 100% if KC decreases from 45 to -2% of draught.

4.3.3. Steady-state performance.

During the steady-state phase of tests of type 2, (1) is simplified to:

$$R = (1-t)T \quad (8)$$

The speed dependence of the resistance coefficient is eliminated making use of Froude's formula for frictional resistance:

$$R = \frac{1}{2}\rho_1 S(1+k)C_F' V^{1.825} \quad (9)$$

Unlike C_F , C_F' is independent of speed. The steady-state velocity can now be written as:

$$V = \left[\frac{(1-t)T}{\frac{1}{2}\rho_1 S(1+k)C_F'} \right]^{\frac{1}{1.825}} \quad (10)$$

so that steady-state velocities for reference conditions can be calculated as follows :

$$V_0 = \left[\frac{K_{Th}}{K_R} \right]^{\frac{1}{1.825}} V \quad (11)$$

The correction factor K_{Th} for propulsive thrust is displayed in fig.9. Corrected steady-state velocities are plotted as a function of KC in fig. 11. Speed decreases by about 50% if KC is reduced from 100% to about 0% of draught. A fair resemblance is observed with the results of manoeuvres of type 3 (fig. 12).

In the low KC range (-0.4 to 0.5 m), no significant relationship between speed and KC is found. Specifically, there is no evidence that contact between keel and mud would cause a sudden speed loss. Nevertheless, tests executed with constant propulsive power (type 2) reveal a speed increase of 20-25% if the KC varies from -0.35 to +0.70 m (fig. 13). However, similar phenomena are also observed with ships navigating at low KC above a solid bottom, so that the mud does not appear to have a relevant effect on the steady-state velocity in the speed range of the trials (1.5 to 3 m/s).

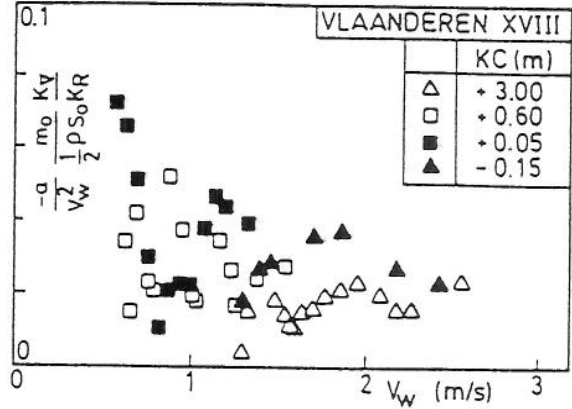


Fig.10. Full scale trials (type 1): deceleration vs. forward speed.

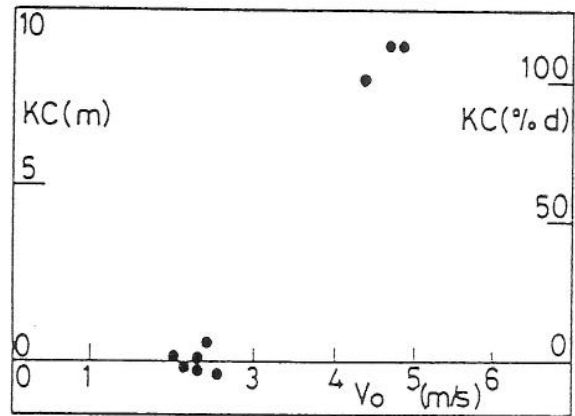


Fig.11. Full scale trials (type 2): steady-state speed vs. keelclearance.

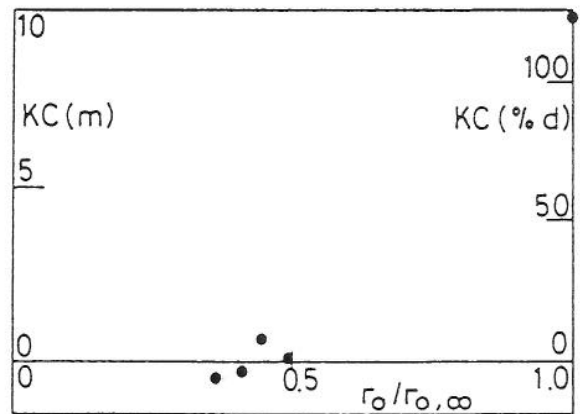


Fig.12. Full scale trials (type 3): steady-state rate of turn vs. keelclearance.

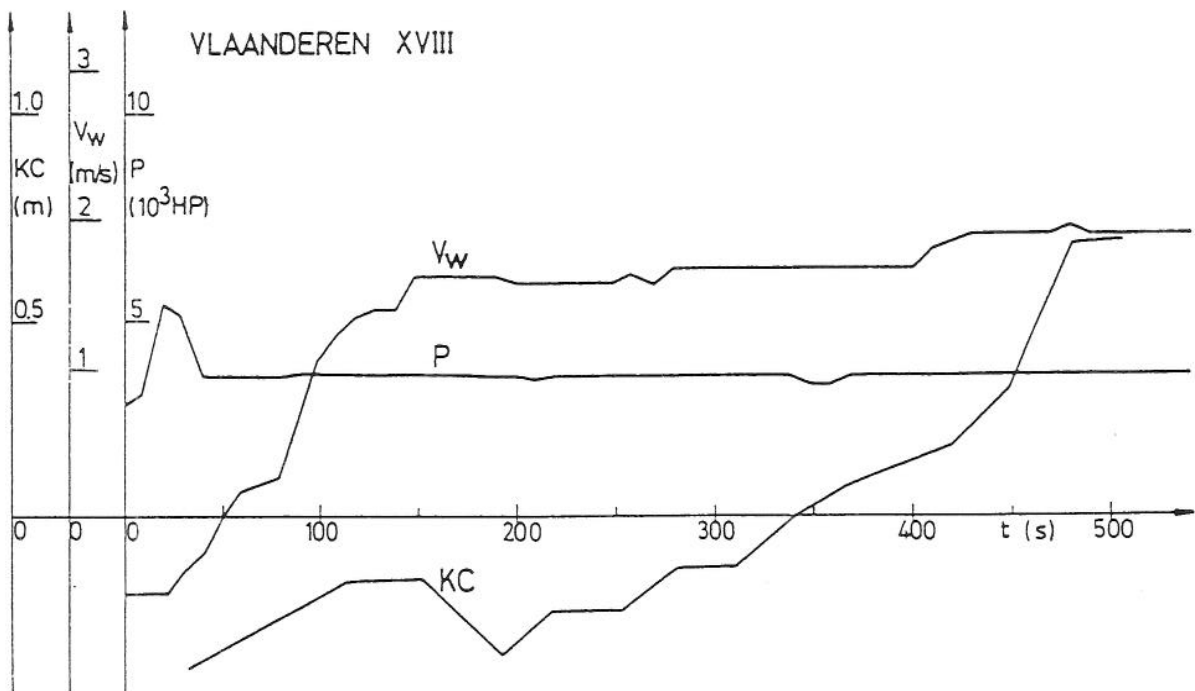


Fig.13. Full scale trial (type 2): influence of keel clearance on velocity at constant propulsive power.

4.3.4. Conclusions.

- There is no obstruction for a vessel to navigate through the top of a mud layer.
- Short engine manoeuvres and, therefore, propeller actions at low speed are not affected by KC.
- Compared with deep water conditions, forward speed and rate of turn are reduced with about 50% at a KC of about 0%. No abrupt transition is observed between positive and negative KC; at the utmost, a speed reduction of 20% is observed in the speed range $V > 3$ knots if KC decreases from +10 to -4%.
- In the range $V > 3$ knots, contact between keel and mud layer results into an increase in resistance of 50 to 100%. In the lower speed range, the resistance curve presents some oscillations, but no influence of KC is observed.
- It should be emphasized that these conclusions are only valid for ships navigating above or in unconsolidated fluid mud with a density not exceeding 1.15 tm^{-3} .

5. SHIP MODEL TEST INVESTIGATION.

5.1. Introduction.

Due to the lack of a theoretical approach and the costs and risks involved with full-scale tests, an experimental program was started at the Hydraulics Research Laboratory (Antwerp-Borgerhout), consisting of following items :

- a. selection of a mud simulating material for physical model tests;
- b. execution of preliminary tests with ship models in a pilot model;
- c. execution of intensive test programs in a towing tank equipped for captive manoeuvring tests with ship models in shallow and muddy navigation areas;
- d. application of model test results for manoeuvring simulator tests.

At present, phases a-b have been completed. This chapter will give a review of the most important conclusions of pilot-model tests (1987-1989) and theoretical investigations.

5.2. Pilot model tests : description and program.

The ship models, equipped with propulsion and rudder(s), were forced to follow a guiding beam at the centre line of a small basin (32.00*2.25*0.30 m³), but were free to move in vertical direction (see fig. 14).

The bottom of the tank was covered with a 1-1-1 trichlorethane - petrol (TCE/P) mixture, which was accepted to be the most suitable mud simulating material. The layer thickness chosen was between 11 and 35 mm, mass density in the range 1.11-1.22 tm⁻³. The vertical interface position was measured at one point of the basin.

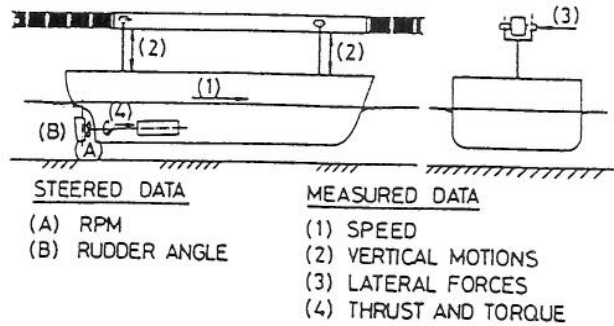


Fig.14. Model tests: experimental setup.

With KC between +20% and -10% of draught, acceleration, deceleration and steady-state tests (with and without rudder action) were carried out with models of a LNG-tanker (267*41.6*0.84 m³; scale 1÷40). The experimental set up and program are also described by Wens et al, 1990.

5.3. Vertical interface motions.

The effect of mud layers on the ship's behaviour mainly depends on the deformation of the interface caused by the pressure field around the moving hull. Model tests have shown that this deformation is related to the ship's speed (see fig. 15) :

- At very low speed, the interface remains practically undisturbed (first speed range).
- At intermediate speed (second speed range), an interface sinkage is observed under the ship's entrance, which at a certain section suddenly changes into an elevation. The interface jump moves towards the stern with increasing speed.
- At higher speed (third speed range), the interface jump occurs behind the stern.

Some insight into the interface behaviour is acquired by means of a simplified theory described by Vantorre & Coen (1988) and Vantorre (1991). The problem of a ship's forward motion with speed V in a canal, the bottom of which is covered with a higher density fluid, is reduced to one of steady flow, in which the ship is fixed while the two layers move with velocity $-V$. Due to the ship's presence, the fluids take velocities u_1 and u_2 , while free surface and interface take vertical positions z_1 and z_2 , respectively.

The unknowns u_1 , u_2 , z_1 , z_2 are determined by a system of four nonlinear equations, expressing continuity of both layers and boundary conditions for dynamic pressure matching on interface and free surface. The number of real solutions depends on the ship's

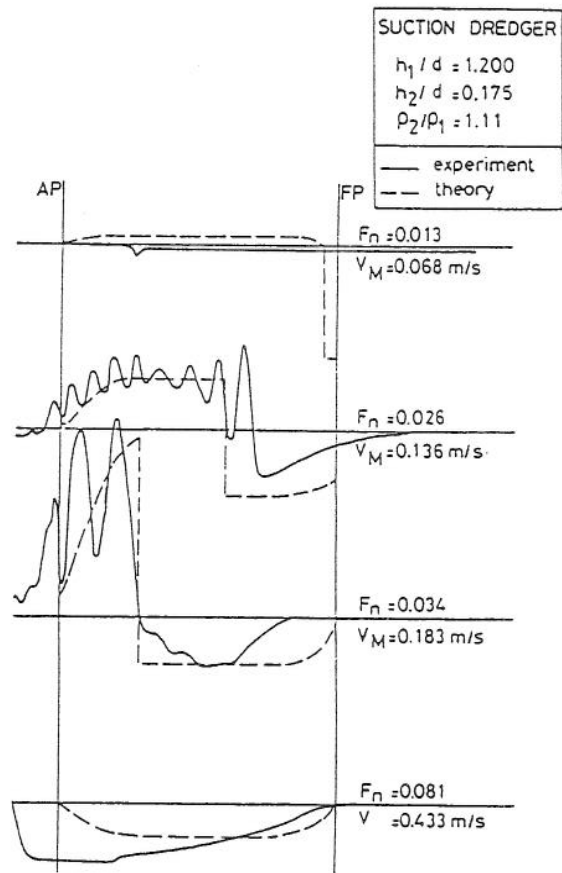


Fig.15. Vertical interface motions: influence of speed (theory and model experiments).

velocity V . At low speed, the system has four sets of real solutions: two of them corresponding with an interface sinkage, the others with an elevation. Beyond a critical speed value, however, no solutions lead to an elevation. A fair approximation of this speed, being the transition velocity between second and third speed ranges, is given by:

$$V_{crit} = \sqrt{\frac{8}{27} g h_1 \left(1 - \frac{\rho_1}{\rho_2}\right)} \quad (12)$$

The theory thus explains why interface elevations under the ship's hull take place at low speed only, and gives possible values for interface elevation and sinkage. An approximation for the jump position is made by supposing that equal volumes of mud are involved in the interface elevation and sinkage, respectively. Substantial differences between measurements and calculations occur only at very low speed, when unrealistically large values are found for the sinkage (fig. 16-17). Viscous effects also cause deviations if the bottom layer is thin (Ferdinande & Vantorre, 1991).

5.4. Vertical ship motions (squat).

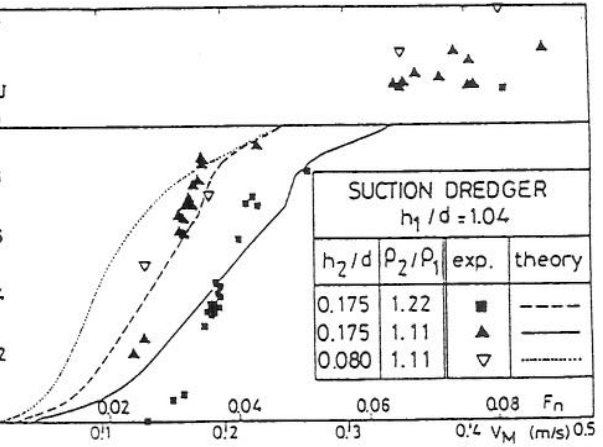
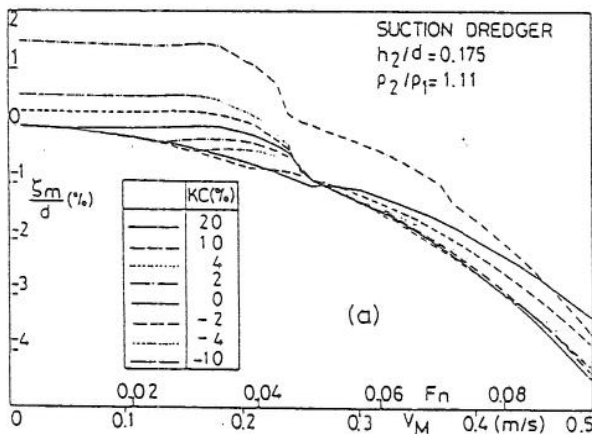


Fig.16. Position of interface jump (theory and model experiments).

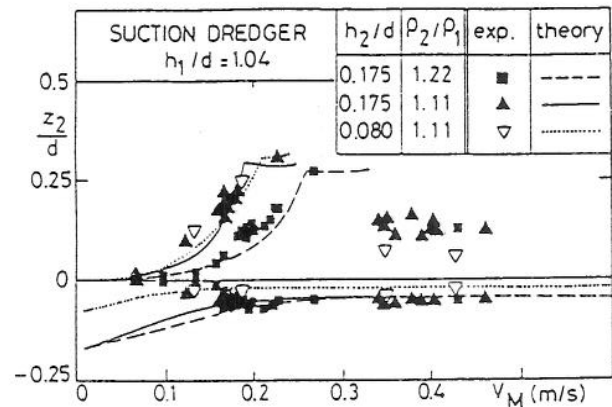


Fig.17. Extremal vertical interface motions (theory and model experiments).

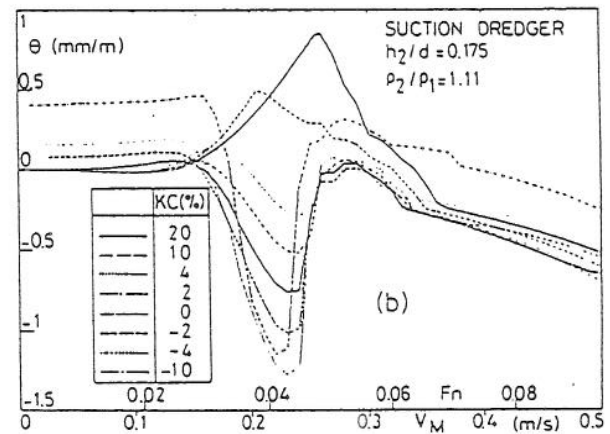


Fig.18. Average sinkage and trim: influence of keel clearance (theory).

Calculation of hull pressures and the static equilibrium condition yield values for the ship's average sinkage and trim. Fig. 18 shows some results of theoretical calculations. If KC is sufficiently large, the interface elevation occurring under the stern in the second speed range will cause trim by the bow. With decreasing KC , contact takes place between keel and interface. The vertical force on the aft part, which is initially directed downwards, decreases in absolute value and even changes its sign, causing the sinkage to change gradually into an elevation, and trimming the ship by the stern. In the third

speed range, squat is generally smoothed as compared with the solid bottom situation, particularly if contact occurs between the mud layer and the keel.

The agreement between experiment and theory is satisfactory. Differences are more important for trim, but comparable trends are observed (see fig. 19).

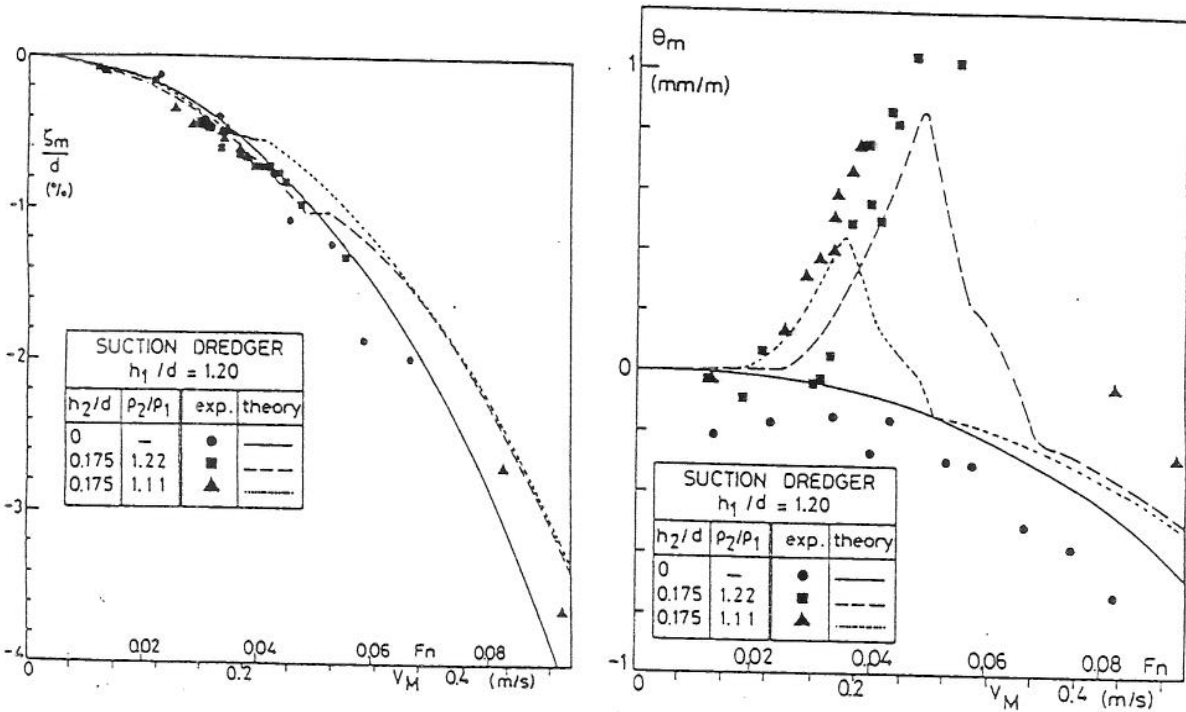


Fig.19. Average sinkage and trim: influence of bottom configuration (theory and model experiment).

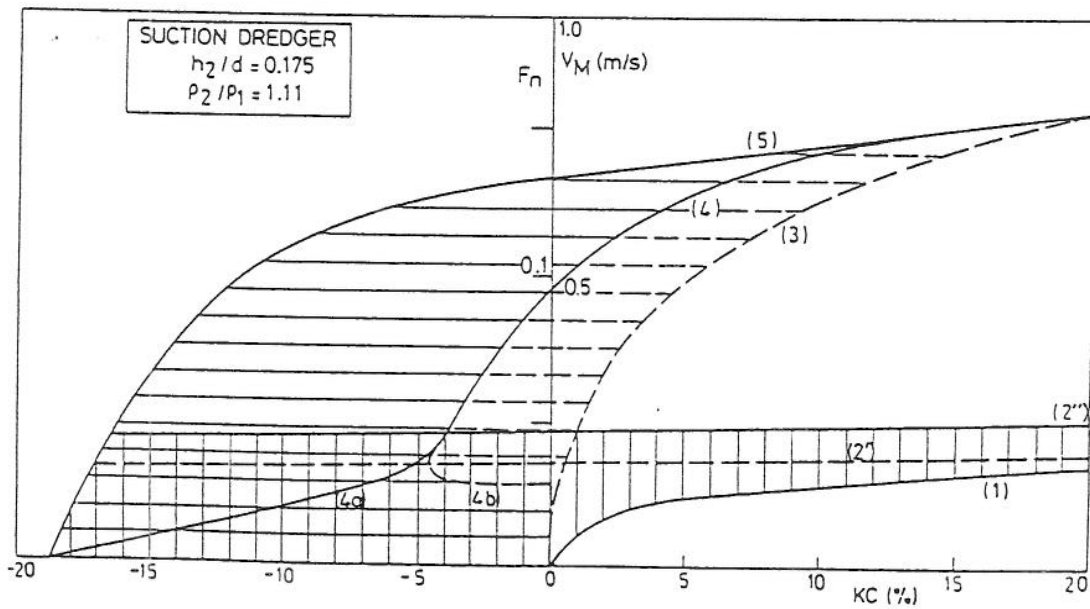


Fig.20. Characteristic velocities vs. keelclearance (theory).

5.5. Characteristic velocities.

Due to vertical motions of interface and ship, the relative position depends on the ship's speed. For each bottom configuration and KC several speed ranges can be defined, separated by a number of characteristic velocities (fig. 20) :

- [1] the speed at which contact occurs between the hull and the rising interface;
- [2'] the maximum speed at which an elevation can occur at the parallel middle body;
- [2''] the maximum speed at which an elevation can occur at any section;
- [3] the speed at which local contact occurs between hull and sinking interface;
- [4] the speed at which the keel is completely flooded by the sinking interface;
- [5] the speed at which contact occurs between the hull and the solid bottom.

Taking account of the difference between theory and experimental results in fig. 16, theoretical curve [4a] should be replaced by experimental curve [4b] at low speed.

5.6. Resistance and propulsion.

The effect of mud on a ship's performance is mainly situated in the second speed range, where a given rpm results into a substantially lower speed compared with a solid bottom situation; this is in accordance with Sellmeijer & Van Oortmerssen (1983). The transition between second and third speed range is smoothed with decreasing KC (fig. 21).

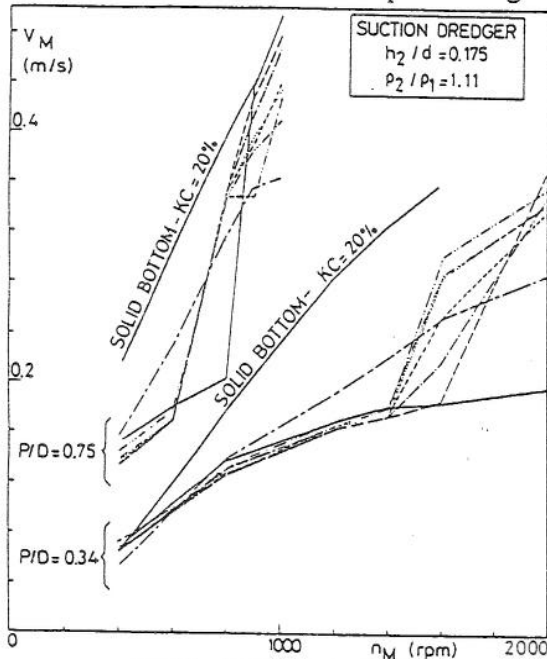


Fig. 21. Speed-rpm relation.

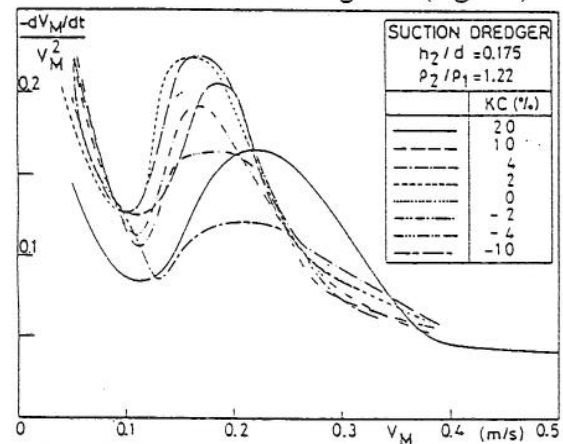


Fig. 22. Deceleration vs. speed (model tests).

The $V(n)$ -curve is the result of both resistance and propulsion characteristics. Deceleration tests (fig. 22) show that the resistance coefficient increases in a well-defined speed range and reaches a maximum at characteristic speed [1] (see fig. 20), at which contact occurs with the rising interface. The effect is smoothed with decreasing KC.

The effect is smoothed with decreasing KC.

The shape of the resistance curve can be explained as follows. An interface sinkage increases the relative velocity of the lower layer, while the ship's speed through the water slightly decreases compared with a solid bottom situation (fig. 23a). Consequently, an interface sinkage only leads to an increase of frictional resistance if there is contact between the keel and the mud layer (fig. 23b). On the other hand, an elevation reduces the relative speed of the mud, and increases the relative water velocity. If no contact occurs (fig. 23c), a jump under the keel increases frictional resistance. In spite of the higher viscosity of the lower fluid, contact of the rising interface with the keel (fig. 23d) can even lead to a global resistance reduction as the relative velocity between the hull and the lower fluid is much smaller.

As the maximum of the resistance coefficient occurs at a lower speed than the value

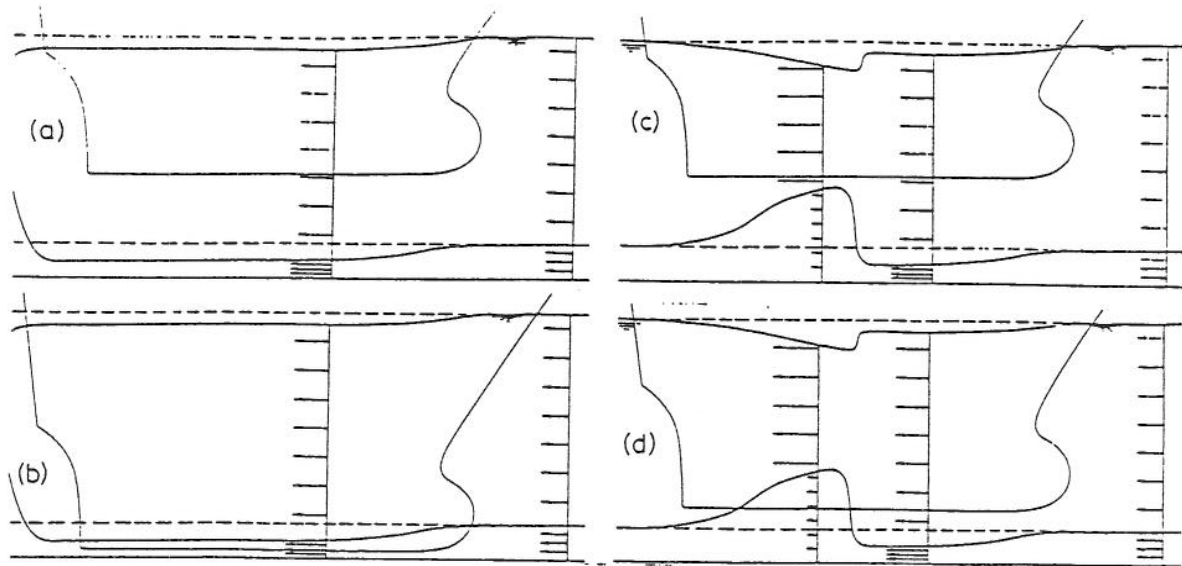


Fig.23. Flow around a ship navigating in a two-layer system.

corresponding with the "hollow" in the $V(n)$ -curve, the latter should not merely be ascribed to an increased resistance, but rather to the influence of interface motions on the propulsion. Thrust and torque measurements have revealed values which are comparable with bollard pull situations ($V = 0$) in cases where a steady state is reached in the speed range $[2']$ - $[2'']$, characterized by a concentration of the jump near the stern. There are indications that contact between the rising interface and the after body obstructs the flow to the propeller, causing an increase of both thrust deduction and wake factors, and a very poor propulsive efficiency. Although practical conclusions cannot be derived in this stage, propulsion control might be affected in these circumstances.

5.7. Rudder forces.

Above a solid bottom, a rudder command to port induces a lateral force Y on the rudder pointing to starboard, resulting into a moment N forcing the ship to yaw to port. Test results above TCE/P do not always follow this pattern. In some cases, Y and N take the usual sign for large rudder angles, but point to the opposite direction for small δ . This phenomenon will be called "instability of rudder action".

A clear relationship is found between interface motions and rudder action stability. I-stable rudder action appears to take place if the keel is in contact with both water and mud (ranges $[1]$ - $[2'']$ and $[3]$ - $[4]$), especially when the contact zone is located near the stern ($[2']$ - $[2'']$): see fig. 24, where instabilities are observed for KC from -4% to 10%.

5.8. Comparison between full scale trials and model tests.

With $h_1 \approx 8$ m and $\rho_2 \approx 1.15$ tm^{-3} , critical speed (12) is about 3 knots, which means that all full scale steady-state tests have been performed in the third speed range. Model tests have shown that the influence of mud layers is inferior to the usual shallow water effects in these circumstances, which is in accordance with the results of the full scale trials.

There is also a qualitative conformity between the results of full and reduced scale deceleration tests, where a distinction has to be made between two speed ranges. The lower range is characterized by a sharp maximum; for the higher velocity range the conclusions of the steady-state tests can be repeated.

5.9. Conclusions.

Definitive, quantitative conclusions about the effect of the presence of mud layers on ship behaviour can only be based on captive resistance and manoeuvring tests performed in a well-equipped model basin. Nevertheless, the present results yield some clear indications. A strong relationship is observed between the modifications which ship behaviour and controllability may undergo when navigating in muddy areas and the relative motion between interface and ship hull. This reaches a maximum in a restricted speed range, the upper limit of which is given by (12), if the initial KC is small enough to allow contact between the hull and the mud layer. There are strong indications for changed controllability of both rudder and propulsion in these circumstances.

6. CRITERIA FOR DETERMINATION OF THE NAVIGABLE DEPTH.

From the rheological evaluation of the Zeebrugge mud and the above discussed full scale trials, it was concluded that the 1.15 tm^{-3} density-horizon represents a safe criterion for the navigable depth in Zeebrugge.

7. PRODUCTION OF NAUTICAL CHARTS.

From the above mentioned results, the following procedure to produce nautical charts has now been established, making optimal use of the various techniques developed. Twice a month, the Central Part of the New Outer Harbour is surveyed simultaneously by the BEASAC (Belfotop Eurosense Acoustical Survey Air Cushion) platform and the Navitracker survey system. Twenty four hours after the data-collection, a first chart is delivered by each survey team:

- The beasac chart represents the echosounding data, with shaded areas where two different echoes (210 kHz and 33 kHz) have been detected.
- The Navitracker chart comprises three sub-charts:
 - (a) a chart indicating the level of the 210 kHz echosounder data;
 - (b) a chart depicting the depths of the surveyed density horizon;
 - (c) a differential chart representing the differences in depth between the 210 kHz reflections and the surveyed density horizon.

Twenty four hours later, i.e. 48 hours after the survey, the actual nautical map can be distributed (fig. 25). This nautical chart is a combined Beasac/Navitracker map, in which the 210 kHz echosounder data in the muddy area are replaced by the Navitracker collected depth data of the 1.15 tm^{-3} density-horizon.

8. CONCLUSIONS AND RECOMMENDATIONS.

The use of the 1.15 tm^{-3} density-horizon as the navigable depth in Zeebrugge has proved to meet the first criterion prescribed by PLANCO: intensive physio-chemical research of the sediment under concern as well as full scale trials have shown that a ship navigating

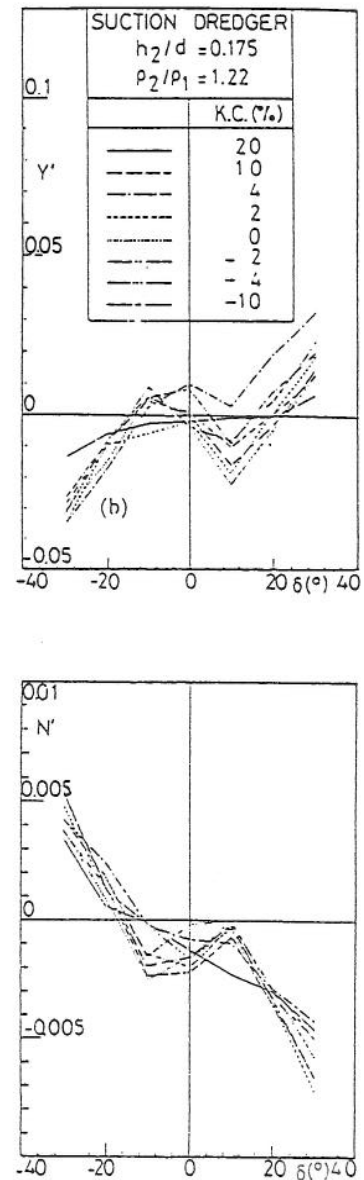


Fig.24. Rudder action instability in 2nd speed range ($U_M = 0.16 - 0.20 \text{ m/s}$; $\xi_J = 0.62 - 0.88$).

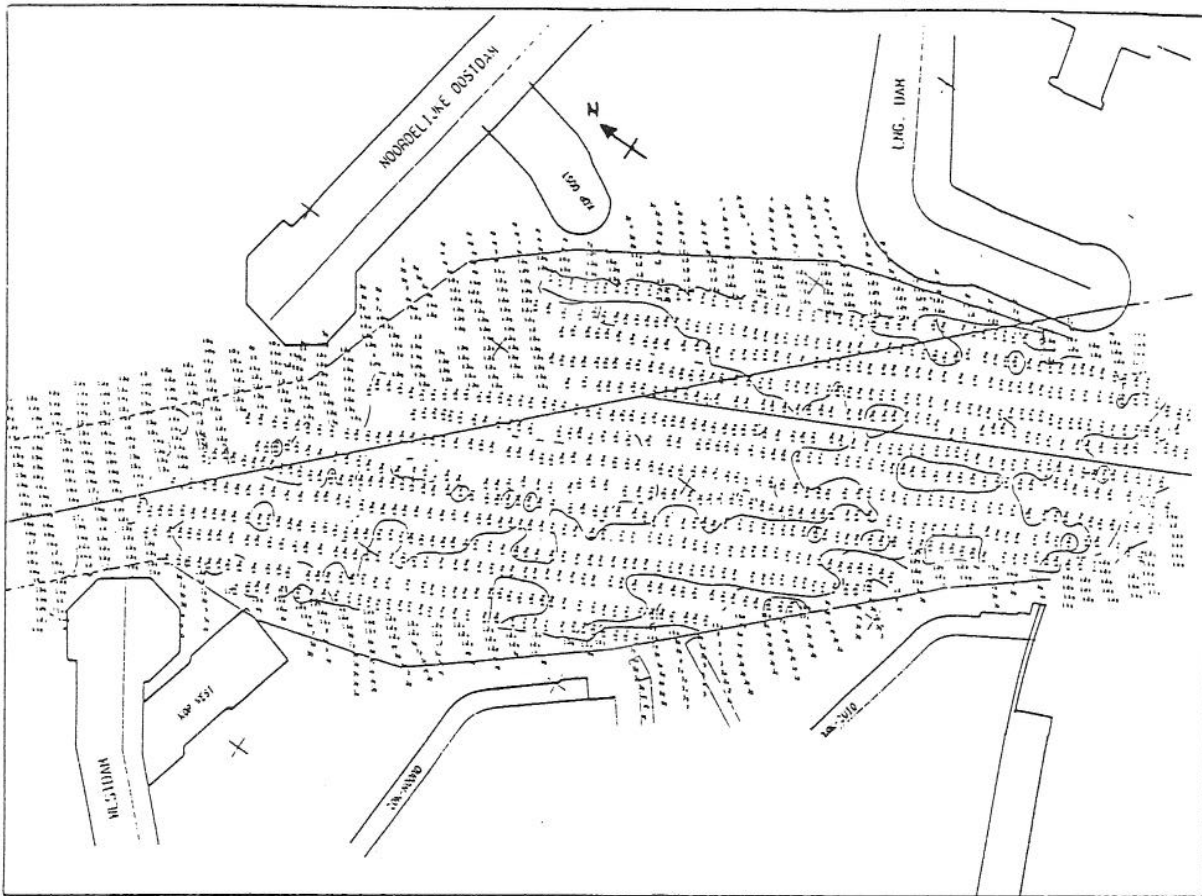


Fig.25. Outer Harbour of Zeebrugge: nautical chart (combined Beasac/Navitracker map).

even with zero keel clearance relative to this level does not suffer any damage.

Full scale tests and practice with deep-draught ships indicate that the second criterion is met as well. However, preliminary ship model tests have given clear indications that a ship's controllability might undergo modifications in a very limited speed range. As it is necessary for pilots to be aware of the effects of the presence of an interface and with the aim of possibly shifting the navigable limit to higher density values (e.g. 1.2 tm^{-3}), the results obtained today can be refined by additional full scale tests, which in combination with systematic model tests which will be executed in the shallow water towing and manoeuvring tank under construction at the Hydraulic Research Laboratory (Antwerp). It is intended that the results should be used as input data for real-time manoeuvring simulator tests.

It should be emphasized that the density level mentioned is only suitable for the Zeebrugge mud, and in no way represents a universal value for nautical depth.

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