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AUTHORS	:	ir. B. Malherbe, Haecon N.V., Ghent ir. P. De Wolf, Ministry of Public Works, Ostend ir. B. Paquot, Baggerwerken Decloedt & Son, Zeebrugge
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Nautical Bottom Research and Survey for Optimization of Maintenance Dredging in Mud Areas

B. Malherbe, Project Manager, Geological Engineer, *N. V. Haecon*,
P. Dewolf, Principal Engineer, Civil Engineer, Ministry of Public Works, Coastal Service, Ostend, Belgium
and *B. Paquot*, Project Engineer, Civil Engineer, Baggerwerken Decloedt & Son

There is a definite need to better define a uniform and exact nautical bottom within loose mud deposits, characterized by low shear strengths in their upper parts. This chapter presents a better approximation of a mud nautical bottom definition, based mainly on the rheological characteristics of the mud considered. From the results it will be clear that a direct application of this theory in the field is possible. Maintenance dredging can be optimized in two ways, by introducing such a definition of the nautical bottom:

- a better definition of the target depth for piloting the dredging works;
- the possiblity of better and more uniform production work.

Additionally, intensive mud survey allows a better understanding of the behaviour of the deposit and may form a programming tool for maintenance dredging; this will be illustrated by some practical examples.

INTRODUCTION

In 1984 the Coastal Service of Ostend, of the Administration of Waterways (Ministry of Public Works, Belgium), ordered a research program wherein, amongst other items, special research is to be carried out on the definition and the detection of the so-called nautical bottom in mud. This chapter presents some of the research results obtained so far.

A nautical bottom as determined by an echo-sounder or a lead wire does not seem to form a basis for discussion, since the hydrographer wants to define the bottom according to safe navigability and manoeuvring capacity, and will thus use for this bottom the level where the medium changes its behaviour drastically, i.e. the water-sediment or water-rock interface. From there on, all calculations can be executed to determine the nautical depth (including keel clearance, sedimentation, tide reduction, etc.), for the programming of maintenance dredging works and for the description of the navigability and manoeuvrability of the access channel or waterway considered.

Loose mud deposits in waterways are characterized by:

- a sharp water-mud interface;
- very low mud shear strengths in the upper parts of the deposit.

These considerations lead to the conclusion that a nautical bottom in mud is not necessarily determined by the water-mud interface, but may be located within the deposit itself. The problem is what level to indicate and what unit to use for the characterization of the nautical bottom, and thus safe navigation also.

Previous work and investigations tend to define the nautical bottom as a density level within the mud deposit. Some relevant work can be summarized here. Extensive investigations have been made in Bangkok and along the coast of Surinam, where ships sail in mud with negative keel-clearance; in Bangkok a volume-mass value of 1.230 t/m^3 of mud is still considered as a safe value in which vessels can sail. On the basis of these investigations and a literature search, it was found that densities up to 1.2 had only a slight influence on manoeuvrability (Kirby and Parker, 1979; Van Bochove, 1979; Nederlof, 1979). Actually in the Rotterdam Europoort, the so-called "nautical bottom" has been set at the 1.2 t/m^3 density limit to be on the safe side (Nederlof, 1981). The question remains whether similar density values are applicable in all cases to define the nautical depth.

From the research results presented in this chapter, an exact and uniform definition of the nautical bottom can only be given when the deformation characteristics (stress - strain relation) of the channel bottom sediments are taken into account. This seems logical, since navigation and manoeuvring capacity are mainly determined by friction, eddy and wave-making resistance, all of these being forces influenced by the viscosity and thus the shear strength of the medium.

In the next section, an attempt will be made to illustrate some typical behaviour features of mud deposits. This mud deposit survey allows better guidance of the research on the nautical bottom and a better understanding of the general behaviour of mud for programming maintenance dredging.

In a further section, the special concept of the nautical bottom definition derived from basic rheological research on mud will be discussed. Also, the universality of this concept will be shown to allow the development of efficient detection techniques.

Finally, the results will be summarized and evaluated with regard to the optimization of maintenance dredging in similar mud deposits.

THE BEHAVIOUR OF "LOOSE MUD" DEPOSITS

The first indication of the presence of "loose mud" deposits is the indication, by a high-frequency acoustic echo-sounder (frequency higher than 10 kHz), while navigating, of a flat sub-horizontal weak reflector (Fig. 1).

Simultaneously, depending upon transducer emission power or coupling of a lower-frequency transducer, deeper penetration is sometimes achieved, revealing a so-called "second reflector or echo", usually interpeted as the hard bottom (see Fig. 1).

The basic questions about detected mud deposits remain:

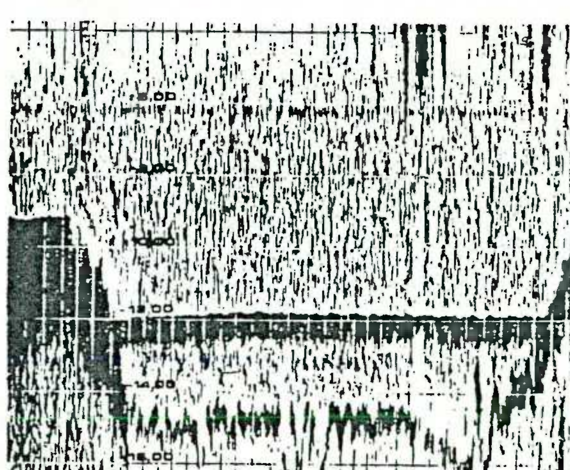

Fig. 1 Cross profile over the access channel to Zeebrugge, showing double echo (top. roof of mud deposit)

- What is the physical significance of these echoes or reflectors, and can they be related in a certain way and with some degree of accuracy to a nautical bottom?
- What is the physical occurrence and behaviour of the deposit, what is his time-dependent variation and what are the factors influencing it?

Physical Significance of Echoes in Mud Deposits

To understand the physical significance of these echoes, one has to realize that reflection of emitted acoustic waves is determined by the reflection coefficient of the two layers encountered by these waves. The reflection coefficient is given by:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

where: R = reflection coefficient; subscript 1 refers to the upper layer; subscript 2 refers to the lower layer; and Z = acoustic impedance, dependent upon wave travelling velocity and medium density.

The greater the difference in acoustic impedance between two layers, the greater R will be, and the better a contrasted reflector will be shown on the echogram. Compared to water, the best reflectors are obtained with rock, sand or compacted sediments and gas.

Loose mud, with typically high water content values, will ovbiously not show a large "acoustic impedance" difference with water and will, in this way, give a weak reflector.

To illustrate these considerations better in Fig. 2 several recorded density profiles in the mud deposits of the access channel to Zeebrugge (Belgium) are compared to the levels of the first and second echo. From this illustration it is obvious that, when mud deposits reach several metres thickness:

- the first echo seems to occur at the water-mud interface, i.e. the first signifi-

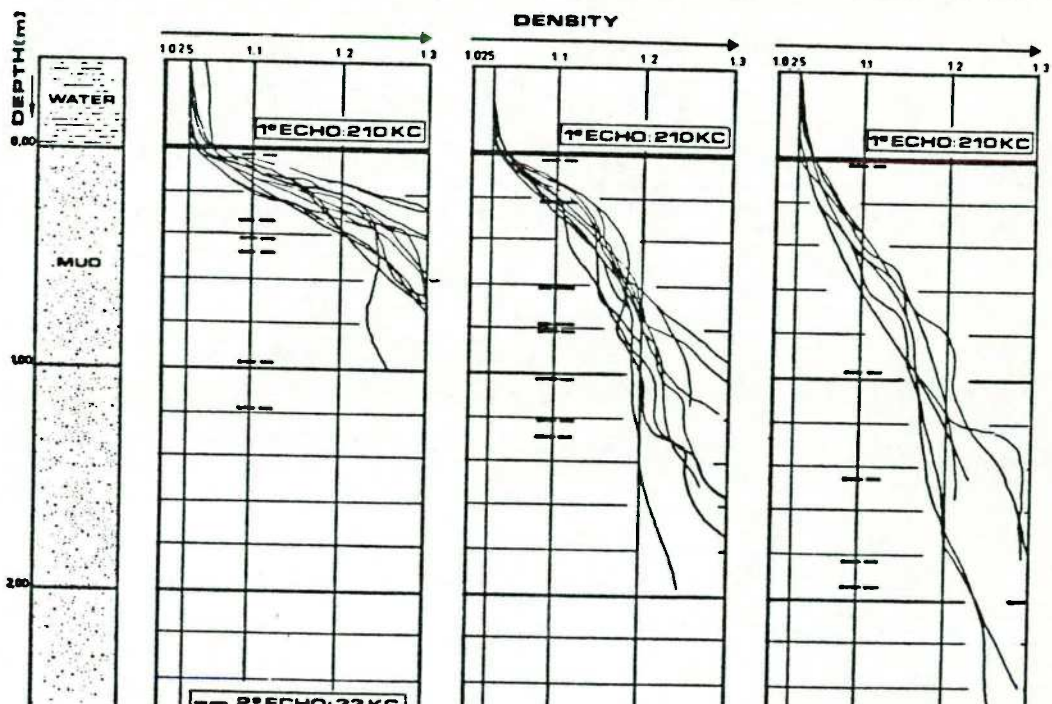

Fig. 2 Comparison of recorded density profiles in Zeebrugge harbour (radioactive back-scatter gauge) with double echo reflections (Atlas Deso 10)

cant "acoustic impedance" changeover;

- the second echo does not seem to correspond to a well defined density value; however, penetration depths of acoustic waves are greater when mud deposits are less consolidated (profile C).

Experience reveals that, when compacted sediments or sand occur at small depths (1–2 m) under the loose mud, this will mostly give a clear reflector. In those cases, the term "hard bottom" can, of course, be considered appropriate for this second echo.

Physical Occurrance and Behaviour of Mud Deposits

To obtain a better knowledge of the physical occurrence and the behaviour of mud deposits, other field-measuring devices become necessary.

With the help of lightweight gravity corers, it is possible to sample several metres of such loose mud deposits at one time. Either freezing in or rapid sampling of the highly loaded fluid core, allow us to distinguish the vertical distribution of physical parameters of the mud deposit, such as:

- water content and concentration;
- sand mixture (proportion of sand in the mud);
- rheological parameters.

Some results of such mud corings are illustrated in Fig. 3. Usually, research pays much attention to the determination of the water content and the granulometric distribution; rheological characteristics are deduced from these two parameters (see next section).

Results of analyses of some mud corings in the access channel to Zeebrugge lead to the following conclusions:

- the sand content (fraction greater than 0.063 mm) may vary within a broad range between 0% and 35% even in this loose mud;
- the sand content within the mud generally increases gradually with depth in the mud;
- the water content or concentration profile in the mud deposit generally shows a rapid

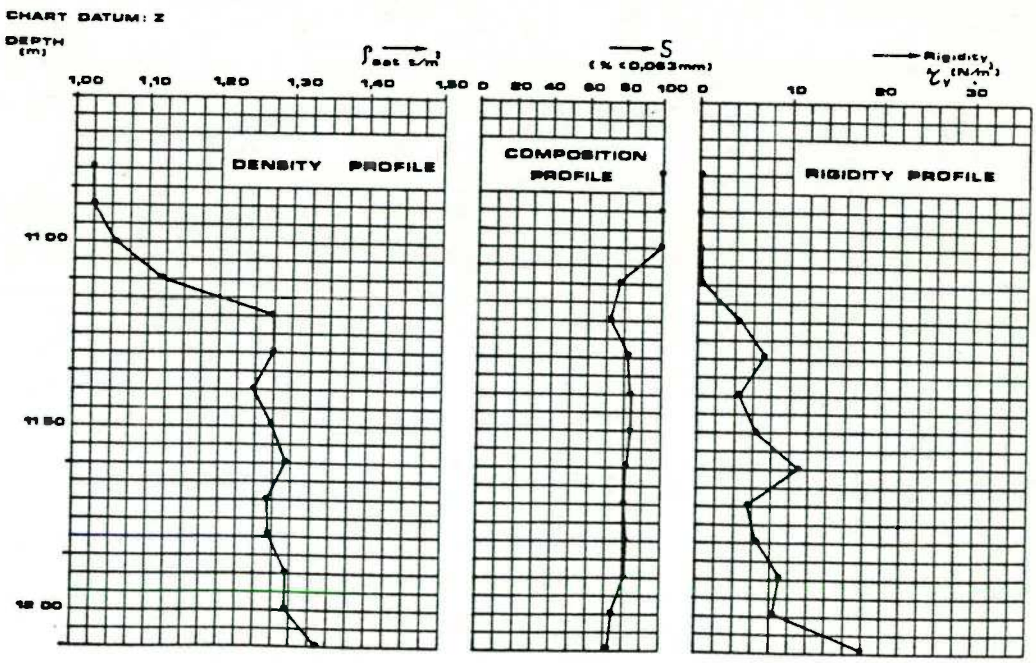

Fig. 3 Mud coring analysis results (mud core no. 8 in access channel to Zeebrugge, Belgium, 11 October 1979).

growth at first (strong density gradient) followed by a weak density gradient.

Radioactive density-measuring devices can be particularly well adapted to the water or marine environment, and allow an operational profiling of the mud density (either horizontal or vertical). Therefore, these kinds of gauges have been developed extensively over the past 10 years (Anguenot, 1972; Kirby and Parker, 1979; Caillot *et al.*, 1984).

Radioactive density gauges may function either by:

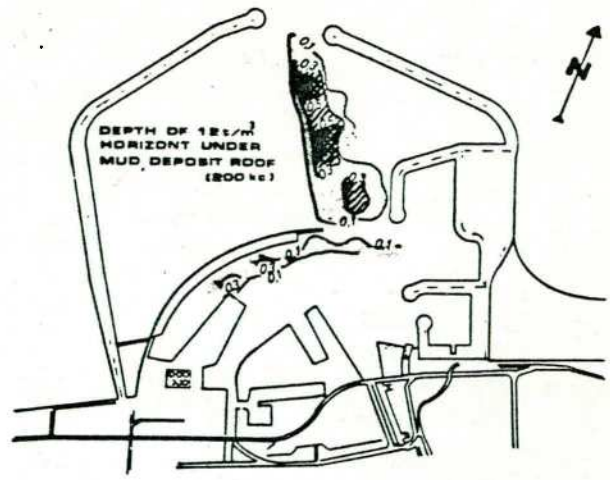

Fig. 4 Example of mud deposit thickness map as recorded in Zeebrugge harbour

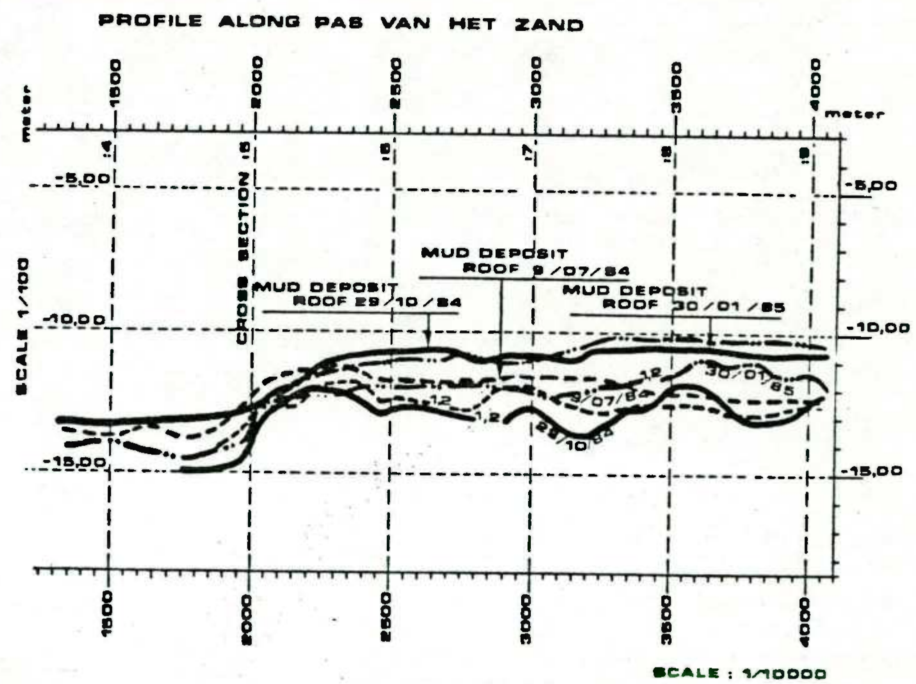

Fig. 5 Profiles along the access channel to Zeebrugge, showing the variation with time of the mud deposit roof and the 1.2 density level

- retro-diffusion or back-scattering of gamma rays;
- transmission of gamma rays.

Both systems have their own measuring characteristics, but can be mounted in hydrodynamically profiled supports to achieve minimum disturbance of the mud.

In this way it is possible to draw so-called "density maps" illustrating either the absolute level of density values, or the layer thickness of mud between the deposit roof and a certain density value horizon (see Fig. 4).

An operational high production survey of the mud deposit density build-up, allows us to recognize the behaviour of the deposit; therefore, an operational fully automatic vertical profiling density gauge was developed.

Figure 5 shows profiles, recorded with this gauge, along the axis of the navigation channel to the harbour of Zeebrugge; the profiles are computations of the results of simultaneous echo-sounding and density profiling measurement campaigns.

It is interesting to observe the time variation of the levels of both the first echo (210 kHz) and of the 1.2 density value in the mud deposit. On the figure these levels are indicated for three distinct campaigns: when the first echo of the top of the mud deposit rises, the level of the 1.2 density goes down, and vice versa. This can be interpreted as a "swelling" and a "shrinking" of the mud deposit, in which the swelling implies an increase of the deposit's volume coupled with a relative dilution (weaker density gradient). Factors influencing this temporary dilution of the mud deposit can be considered to be:

- navigation of deep-draught vessels, and trailing of suction dredgers;
- high wave activity (pore-water pressure build-up);
- gas development due to fermentation.

The direct conclusion of these considerations is that a rise in level of the first echo does not necessarily mean a rise of the nautical bottom (or a decrease in nautical depths).

When measuring the deposit for different tidal coefficients (spring, mean or neap tide) and for approximately the same conditions of maintenance dredging season and wave activity, other features do appear. Figure 6 illustrates two longitudinal density profiles along the access channel within the new harbour of Zeebrugge: one is taken at spring tide while the other is at neap tide; the long profiles are recorded with a time interval of about 1 week. Figure 6 shows a significant difference in the global density build-up of the deposit:

- at spring tide, the deposit seems to be more dilute than at neap tide (stronger density gradient);
- the different density levels and the roof of the mud deposit rises at neap tide.

Both effects seem to indicate a greater net sediment supply in the access channel during neap tide periods.

DETERMINATION OF THE NAUTICAL BOTTOM WITHIN LOOSE MUD DEPOSITS

Introduction

The definition of the nautical depth in mud areas is complicated both by problems of how to define this depth and how to measure it. The nautical depth in mud is not necessarily the water-mud interface, since the upper part of the mud-deposit is characterized by low shear strength. This low shear strength in the upper mud layers is as important for navigation with negative keel-clearance as with restricted keel-clearance (less than 10% above the mud-water interface).

Navigation and manoeuvring with restricted keel-clearance above a hard bottom will be influenced mainly by the underflow; navigating and manoeuvring with restricted keel-clearance above loose mud deposits will additionally be influenced by the deformation characteristics of the bed (Sellmeijer and van Oortmerssen, 1983). The mud bed will be deformed according to the applied shear stress and the rheological characteristics of the mud. From model results with ships sailing with restricted keel-

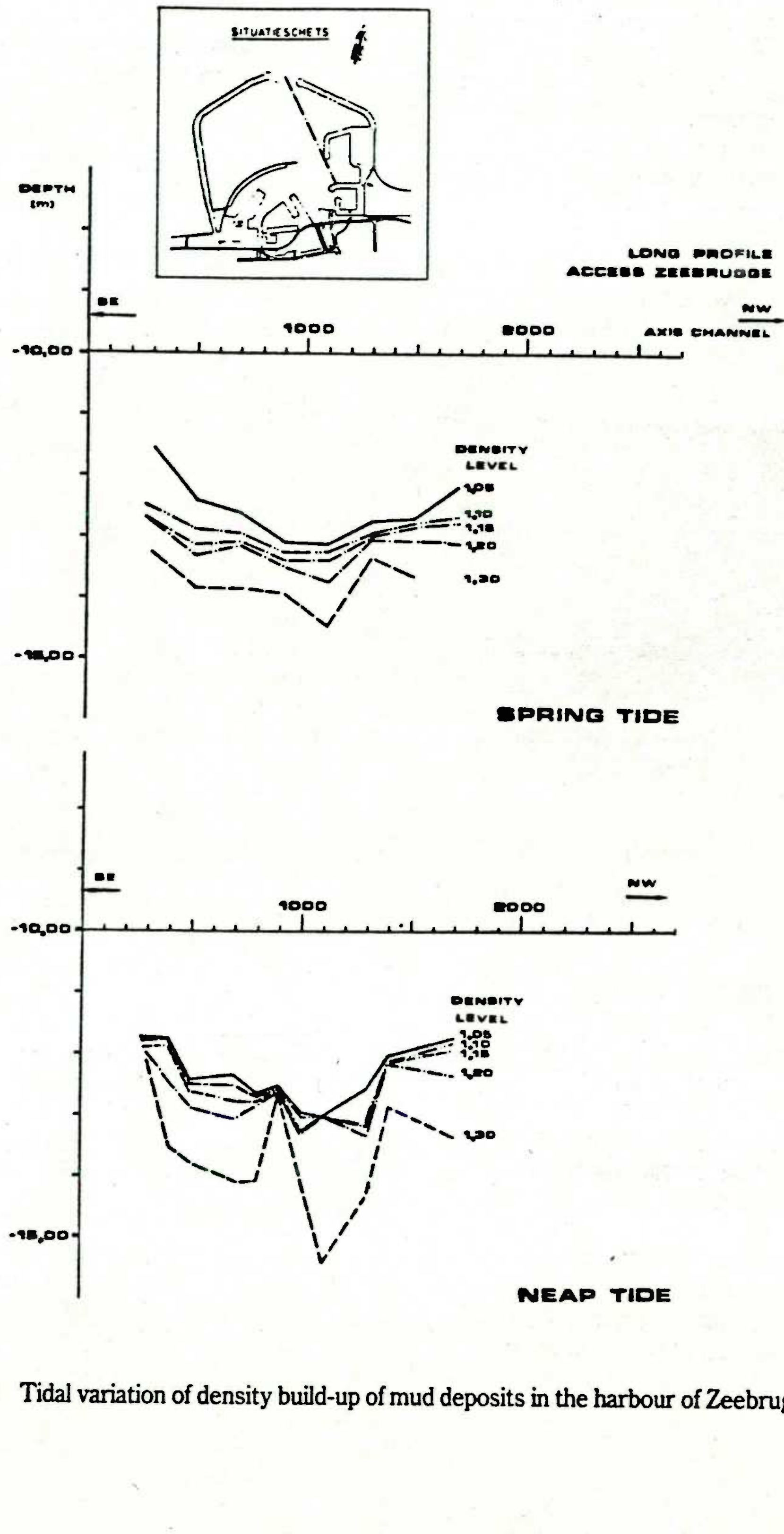

Fig. 6 Tidal variation of density build-up of mud deposits in the harbour of Zeebrugge

clearance, it appeared that in some cases internal waves may form at the water-mud interface (van Bochove and Nederlof, 1979); those internal waves enhance the total wave, causing resistance to the passage of the ship and thus affecting its manoeuvring behaviour. The formation of these waves is, of course, also completely dependent on the deformation characteristics of the mud considered or the mud simulation product.

As mentioned clearly in an earlier publication on physical mud properties (Malherbe, Bastin and De Putter, 1982; PIANC Working Group, 1982–3), the rheological characteristics of mud are mainly determined by:

- the specific gravity or concentration of dry sediment;
- the composition and the sand content of the mud;
- the physico-chemical properties of the mud considered.

Knowing the rheological relationship of the mud, it is possible to deduce theoretically, for instance, the energy absorbed by shear stress when navigating at 0% keel-clearance (to the mud-water interface) above a loose mud bottom (Malherbe *et al.*, 1982); some results of these calculations are illustrated in Fig. 7.

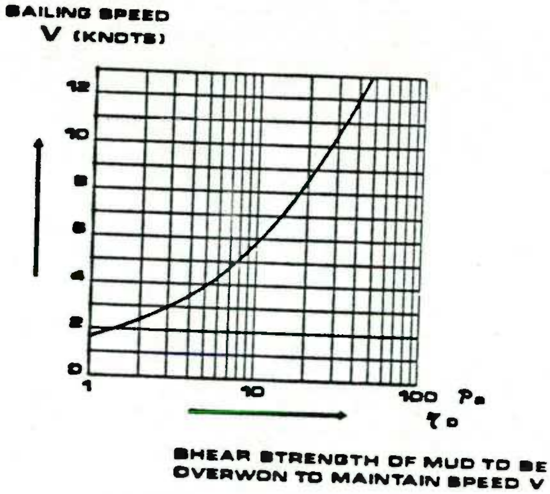

Fig. 7 Navigation above mud at 0% keel-clearance; shear stress exerted by ships' keels at different speeds

Rheological Properties of Mud

The most important rheological characteristics of mud sediments for the definition of the deformation behaviour (stress-strain relation) and the shear strength of the deposit are (see Fig. 7):

- the initial rigidity (or yield strength), τ_y (defined at low shear rate or deformation);
- the dynamic viscosity, η (defined at high shear rate or deformation).

This was first mentioned by C I. Francis-Boeuf in 1941, in his work upon mud properties; therefore his terminology has been used here.

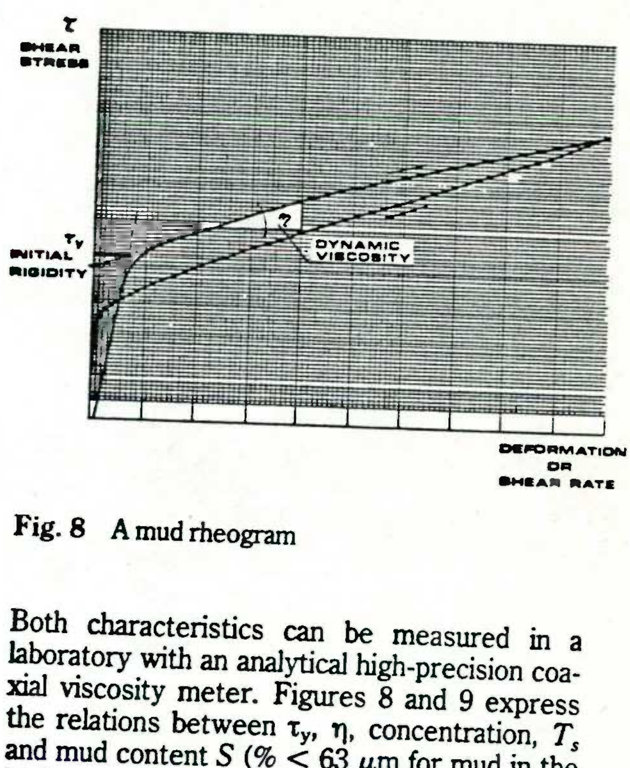

Fig. 8 A mud rheogram

Both characteristics can be measured in a laboratory with an analytical high-precision coaxial viscosity meter. Figures 8 and 9 express the relations between τ_y, η, concentration, T_s and mud content S (% < 63 μm for mud in the harbour at Zeebrugge (Belgium).

Zeebrugge forms a direct access to the North Sea and, due to the high wave activity, mud sediments are mixed in very different amounts with fine marine sand, depending upon the season and the wave activity.

One can deduce from these relationships that two distinct mud behaviours occur:

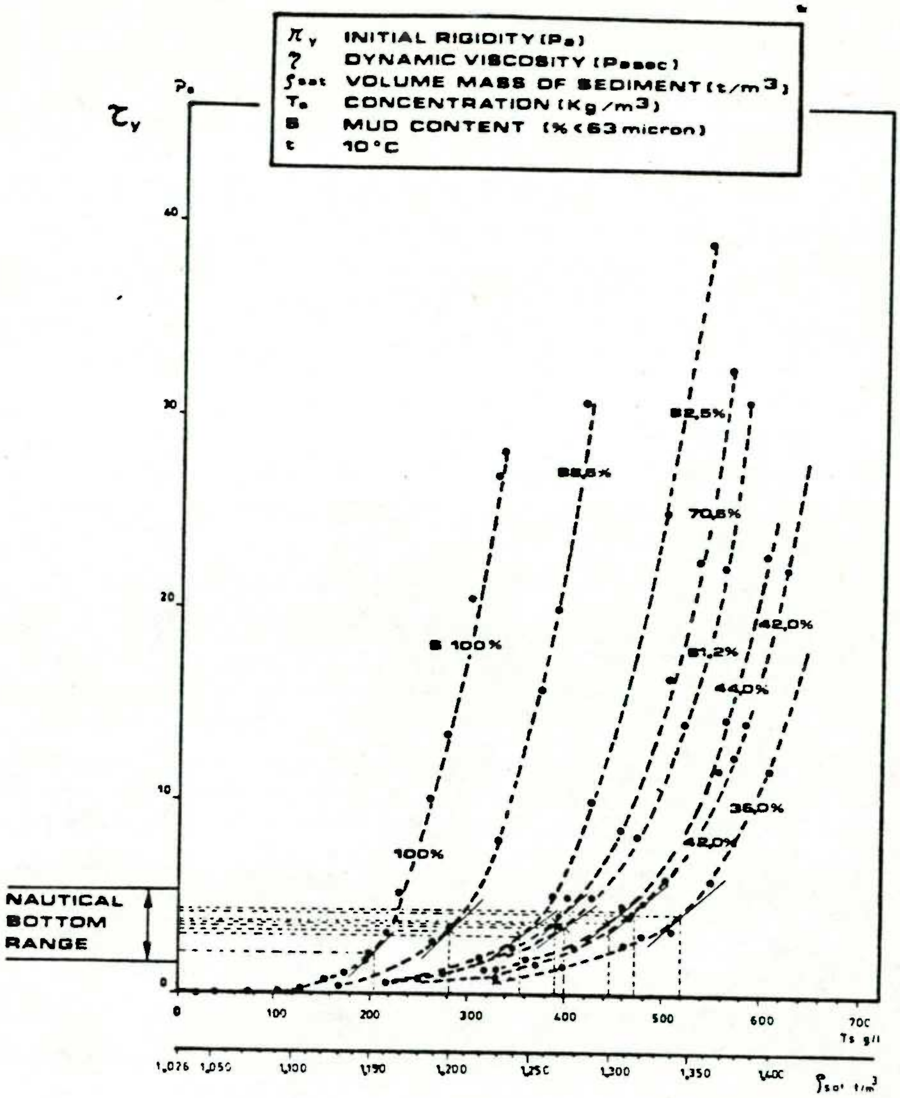

Fig. 9 Initial rigidity τ_y as a function of concentration and mud composition (Zeebrugge mud)

- a first behaviour region where initial rigidity τ_y and dynamic viscosity η are less dependent on the concentration and remain very similar to the values for pure water (first part of curves, small slope);
- a second behaviour region where initial rigidity τ_y and dynamic viscosity η are strongly dependent on the concentration and also very different from the values for pure water (second part of the curves, steep slope).

To illustrate this further, the mud from the Maasmond, Europoort (the Netherlands) was analysed in the same way (see Fig. 11: relation of initial rigidity to concentration); the figure shows a similar kind of relationship as in Fig. 9. The comparison of the relationships of different mud types leads to the following conclusions (Malherbe, 1985):

- From zero up to a certain concentration value, depending mainly on mud type and

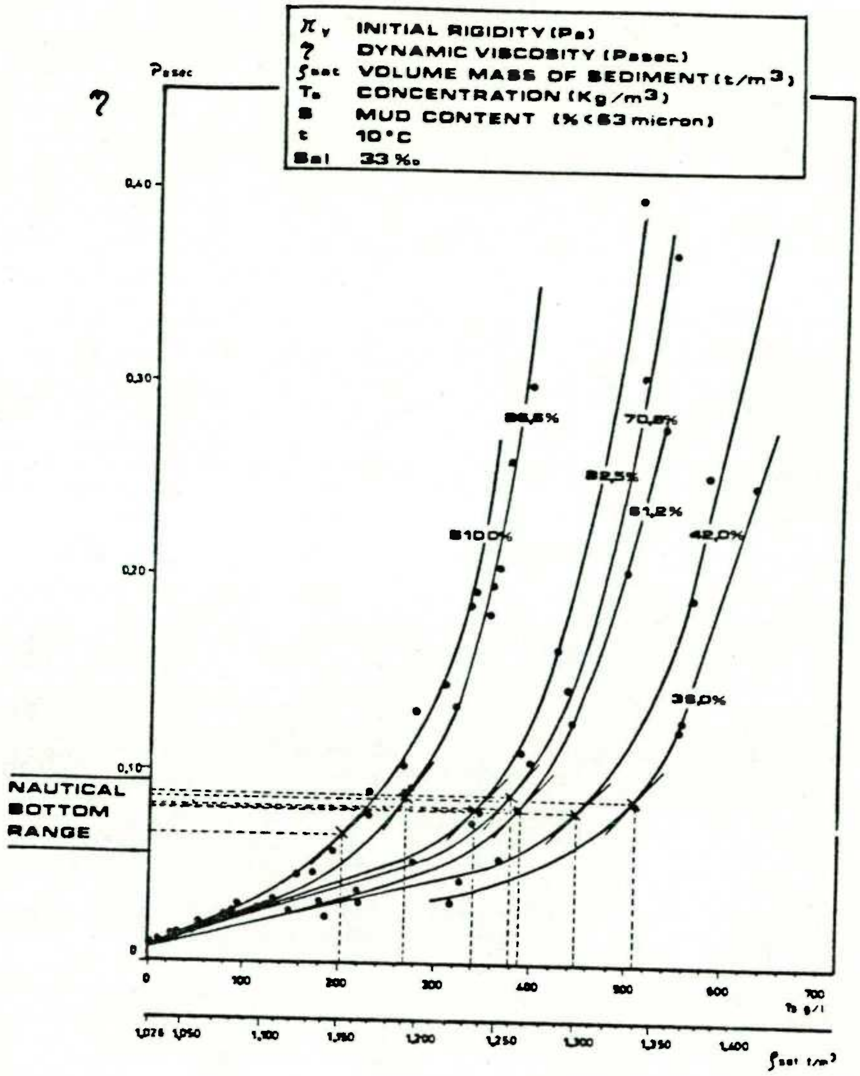

Fig. 10 Dynamic viscosity η as a function of concentration and mud composition (Zeebrugge)

mud composition, the shear strength and the rheology of the mud is not, or is weakly, affected by the mud concentration; for concentrations higher than this certain value, the shear strength and rheological characteristics will increase rapidly with concentration;

- The influence of the composition (sand mixing) is obviously important, but can be very different depending upon the mud type; for mud from the Maasmond, for instance, this influence is stronger than for mud from the harbour of Zeebrugge; also it appears that the effect of the sand content in the mud is most important for low sand content values (0–30%).
- The influence of the mud type particularly affects the rheological characteristic values for a given concentration: depending upon the origin, for a given concentration value, shear strength, initial rigidity or dynamic viscosity can differ by a factor of 10, but the rheological behaviour changeover seems to occur around the same rheological value (for instance, rigidity between 2 and 5 Pa or viscosity between 0.06 and 0.09 Pa s).

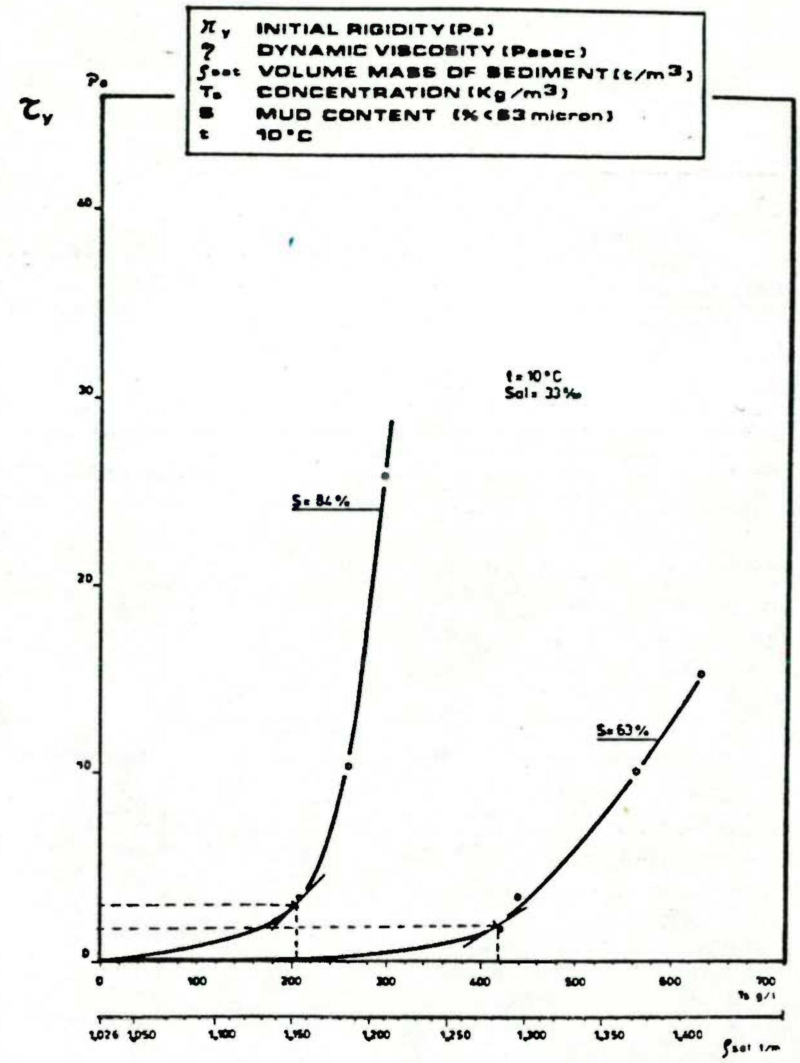

Fig. 11 Initial rigidity as a function of mud concentration (Rotterdam harbour)

The influence of sand content (S = 100%) on the rheological properties seems obvious: the higher the sand content in the mud, the lower the initial rigidity and the dynamic viscosity will be at the same concentration value.

Physically, this can be explained by the fact that rheological properties of cohesive sediments are mainly influenced by the properties of the colloids in it (clay minerals, amorphous clays, biocolloids, etc.). An increase of the proportion of non-colloidal substances (sand, for instance) will decrease the typical values of the mud shear strength.

The Definition of Navigable Depth Based Upon Rheological Properties

Since harbour authorities want to indicate a navigable depth with a certain degree of safety, this depth has to indicate the minimum level at which the medium in which navigation occurs drastically changes its behaviour.

For sandy bottoms it will be clear that the navigable depth will be defined by the water-sand interface.

For muddy bottoms, however, such an interface exists also but a significant change in stress-strain behaviour occurs within the mud deposit itself (see Figs 9, 10, and 11); the level where this significant changeover in shear within the mud deposit occurs will be defined both by:

- the density profile of the deposit; and
- the composition profile (sand content) of the deposit.

From the point of view of navigation and manoeuvring, the presence of two rheological behaviour regions indicates the validity of the following interpretation:

- a first behaviour region where navigation and manoeuvring is not, or is weakly, affected by the concentration of the deposit (navigation rather similar to that in water);
- a second behaviour region where navigation and manoeuvring is strongly affected by the concentration of the deposit (navigation different from that in water).

The rheological behaviour changeover is not very sharply defined. Using an intermediate value between those two behaviour regions to define the nautical bottom will include a certain safety margin, since the second behaviour region of affected navigation will not yet have been reached. Therefore, the determination of the behaviour changeover is done with the help of the point on the curves where the minimum radius of curvature occurs (Kerckaert, Malherbe, and Bastin, 1985).

In this way, it is possible to determine, for Zeebrugge harbour mud, the nautical depth values in terms of volume-mass (abscissa) from the experimental rheological relationships shown in Figs 3 and 4.

The nautical bottom values expressed as volume-masses are summarized in Table 1.

From the results in Table 1 it appears that the behaviour changeover in mud occurs at approximately the same volume-mass value (for a given sand/mud proportion) independent of low shear rates (initial rigidity) or for high shear rates (dynamic viscosity).

TABLE 1

Deduced Nautical Bottom Volume-mass from Different Mud Compositions

	Nautical bottom volume mass (t/m^3)		
Mud content (<63μm) S (%)	*Determined with initial rigidity*	*Determined with dynamic viscosity*	*Mean values*
100	1.151	1.153	1.152
86.6	1.199	1.194	1.197
82.5	1.242	1.238	1.240
70.6	1.267	1.260	1.263
61.2	1.271	1.268	1.270
42	1.316	1.301	1.309
36	1.347	1.340	1.344

Rheological analyses provide only relative values of shear stresses since the values are dependent upon the system being used. Volume-mass measurements give absolute values and, in this way, provide the link between relative and absolute measurements.

On the other hand, the changeover rheological value (initial rigidity or dynamic viscosity) seems to lie within a small range and is only slightly affected by the mud composition S (% < 63μm) and the mud concentration (see Figs 9 and 10).

Table 1 shows that the nautical bottom criterion, expressed as a volume-mass of the sediment, varies in a broad range from 1.151 t/m^3 to 1.347 t/m^3 for the mud compositions tested; using a single volume-mass value in all cases is thus a risky operation and this seems to be valid for all types of mud where sand may mix with the mud.

A test program, using small-scale model experiments and full-scale tests in the field, has been set up to evaluate in which way the inclusion of a mud layer in the keel-clearance of a sailing ship affects the manoeuvring characteristics. These experiments will ascertain the similarity between the changeover in rheological and manoeuvring characteristics. As a part of the whole program, these investigations must lead to the definition of the nautical depth in terms of both mud characteristics and manoeuvring behaviour.

Measuring the Nautical Depth in the Field

From the definition of a nautical bottom as a rheological changeover level and from the considerations mentioned above, it will be clear that a "nautical depth measuring device" should simultaneously measure volume-mass and a rheological property (or a characteristic proportional to one or two rheological properties) to give maximum information about the mud considered.

Volume-mass measuring systems (such as radioactive gauges) can provide all the absolute values needed to draw the density profile within the mud.

On the other hand, rheological measuring devices allow the localization of the nautical depth; the combination of both volume-mass and rheological properties gives all necessury further information about the absolute values to be detected.

Indeed, it seems that measuring rheological properties is always relative: the definition of navigable depth as a mud behaviour changeover is not sensitive to the rheological measuring system as long as these measurements can be calibrated to volume-mass and sand/mud proportions. Of course, measurements of volume-mass and rheological properties have to be reproducible.

OPTIMIZATION OF MAINTENANCE DREDGING

An optimization of maintenance dredging with the aid of rheological knowledge of the mud considered can be performed in two ways, as mentioned in the introduction.

A better Definition of Dredging Level

This allows port authorities to program maintenance dredging according to the changes in the nautical bottom, instead of changes in the top of the mud layer (echo-sounding); the top of the mud layer can vary much more rapidly and strongly than the density levels within the mud deposit.

Intensive mud survey programs reveal a periodical change in the density build-up of the mud deposits in the harbour of Zeebrugge; this results in changes of the mud top layer without a significant need of dredging.

Optimization of Dredging Production

A mud deposit survey based on nautical bottom detection provides a new approach to hydraulic maintenance dredging. It is obvious that a rheological changeover of the mud is also a production changeover; trailing with drag-heads within the mud will give an optimal ratio of gained production/developed power when the head is positioned as close as possible to the *in-situ* detected rheological changeover ("hunting" the rheological changeover).

CONCLUSIONS

1. The detection of loose mud deposits with the aid of echo-sounders is possible, but an exact interpretation of the echograms in terms of density levels remains difficult to achieve. The first echo corresponds mostly to the sharply defined mud-water interface, while the second echo does not seem to correspond to a well defined density level; the reason for this can be found in all the features that can occur within such a mud deposit and that can change the acoustic impedance significantly (gas bubbles, sandy horizons, etc.).

2. The sand content (fraction finer than 0.063 mm) within the profile of these mud deposits may vary within a broad range of values between 0% and 35%, this can be explained by the fact that mud flocs can hold sand grains within their structure.

3. Intensive mud density survey provides a better understanding of the behaviour of this kind of deposit:

- mud deposits are characterized by a weak density gradient versus depth;
- the time variation of this density build-up shows the existence of "swelling" effects (dilution of the deposit) and "shrinking"

(consolidation of the deposit);

- variation of the density build-up of the deposit as a function of the tidal coefficient reveals a net supply of sediment and a general consolidation of the deposit allowed during neap tides.

4. Navigation with restricted keel-clearance in muddy areas requires a better definition of the nautical depth than the obtainable by echo-sounding. The definition of the nautical depth has to take into account both volume-mass and deformation behaviour of the mud.

5. Rheological or deformation behaviour of mud is determined by:

- the volume-mass of the sediment (or the concentration);
- the composition (sand/mud proportion, specially for sand contents between 0% and 30%);
- the physico-chemical properties of the mud (the origin).

Nautical depth within the mud deposit can be defined as the level where the mud changes its rheological behaviour drastically (Kerckaert, Malherbe, and Bastin, 1985). This behaviour changeover occurs at approximately the same volume-mass value for both low and high shear rates (Figs 3 and 4).

6. Nautical depth values defined by rheological properties occur within a small range of initial rigidity or dynamic viscosity, independent of sand/mud proportions, and density or concentration (for the considered mud types, the nautical bottom can be defined with a rigidity ranging from 2 to 5 Pa or a dynamic viscosity ranging from 0.06 to 0.09 Pa s).

7. As the behaviour changeover level is not sharply defined, such a definition of the nautical bottom does include a safety margin: the shear characteristics of the mud are not yet strongly dependent on the concentration value, i.e. the second behaviour region with:

- different rheological concentration relationships;
- different and dangerous navigation characteristics;
- different and strongly varying trailing productions.

8. Recent work has led to the development of a great many instruments capable of measuring either volume-mass or a rheological value. As rheological measurements are dependent upon the system being used, nautical depth sensors should measure both volume-mass (absolute values) and rheological properties (relative values) to get the maximum information about the mud deposit considered.

9. Maintenance dredging in mud can be optimized in two ways:

- better definition of the changes in nautical depth and more efficient steering of maintenance dredging;
- trailing in mud (drag-head within mud deposit) can be done with better ratios of gained production/developed power when "hunting" the in-situ measured rheological changeover.

ACKNOWLEDGEMENTS

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REFERENCES

Anguenot, F. 1972. Jauges radioactives pour la mesure des turbidites. Rapport CEA — CEN

Caillot, A., de Meyer, C., Chambeller, D. and Tanguy, J. C. 1984. *A New Nuclear Density Gauge to Measure Directly High Turbidities in Muddy Areas*. Saclay: ORIS-CEA, October.

Francis-Boeuf, C. L. and Bourcart, J. 1942. *La Vase Actualites Scientifiques et Industrielles*. Paris.

Granboulan, J., Fourcassies, C. and Chaumet-Lagrange 1984. Measuring the navigable depth in a muddy channel. Presented at the 2nd International Hydrographic Technical Conference, Plymouth, September.

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

Kirby, R. and Parker, W. 1979. Definition of the seabed in navigation routes through mud areas. *Report IOS*. Taunton.

Malherbe, B. 1985. The determination of the nautical bottom in muddy areas. Presented at MARINTEC China '85 Shanghai, December.

Malherbe, B., Bastin, A. and De Putter, G. 1982. Physical properties of sand and mud sediments. *Symposium on Engineering in the Marine Environment,* Koninklijke Vlaamse Ingenieursvereniging, Brugge (May).

Migniot, C. 1984. Mesures des caracteristiques mecaniques des vases deposees dans les chenaux de navigation. *XVIIIe J. Hydraul. Soc. Hydrotech. France*, Sept.

Nederlof, L. 1981. Sailing through water rich in floating silt: a vessel behaves differently, but remains manageable. Rotterdam Europoort Delta.

Report of PIANC Working Group no. 3a 1982-3. Navigation in mud areas. Report in *PIANC Bulletin* 43.

Sellmeijer, R. and van Oortmerssen, G. 1983. The effect of mud on tanker maneouvres. Presented at The Royal Institute of Naval Architects spring meeting.

van Bochove, G. and Nederlof, J. 1979. Vaargedrag van diepstekende schepen in slibrijke gebieden. *De Ingenieur* 30/31 (July).