NAUTICAL DEPTH SOUNDING - THE RHEOCABLE SURVEY METHOD

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Abstract

Since 1984, research and development activities have been undertaken in Belgium comprising in situ measurements and sea trials with TSHD ‘Vlaanderen 18’ in Zeebrugge. Towing tank experiments and sludge test tank experiments have also been performed in the laboratories of the Flanders Hydraulic Research. This work has enabled the authors to conclude that mud on the seabed consists of two different physical states occurring in the same configuration - fluid mud on top of solid (consolidating) mud.

Fluid mud is navigable, solid mud is not. The interface between both is characterized by a drastic increase of rheological parameters, in particular, the yield stress. However, for the time being, this phenomenon cannot be fully interpreted scientifically.

The Rheocable sounding method is designed to detect the interface between fluid and solid mud. A towed object, when kept in a velocity window, is always positioned at this interface between fluid and solid mud. This method makes it possible to develop a new maintenance dredging strategy - leave/ignore the fluid mud and remove only the solid mud.

The dredging of fluid mud is therefore unnecessary – it is navigable (!) – and extremely uneconomical. Solid mud on the other hand is not navigable, is immobile and will absolutely maintain its position on the seabed unless removed by dredging action. Furthermore, the deployment of the Rheocable implies many operational and contractual advantages, including transparency of dredged quantities etc.

The Rehocable cable sounding method allows for a considerably improved focus, smaller quantities and easier planning of the maintenance dredging activities, resulting in lower budgets and improved safety for shipping traffic.

Résumé

Depuis 1984, des activités de recherche et de développement . entreprises en Belgique, qui comprennent des mesures in situ et des essais à la mer sur le TSHD ‘Vlaanderen 18’ à Zeebrugge. Des expériences dans des bassins d’essais de carène et des expériences dans des bassins de boue ont également été réalisées dans les laboratoires de la Flanders Hydraulic Research. Ces travaux ont permis aux auteurs de conclure que la boue du fond marin consiste en deux différentes compositions physiques qui se présentent sous la même configuration – boue fluide sur un sommet de boue solide (en consolidation).

La boue fluide est navigable, la boue solide ne l’est pas L’interface entre les deux est caractérisée par un accroissement drastique des paramètres rhéologiques, en particulier le seuil d’écoulement. Toutefois, pour le moment, ce phénomène ne peut pas être entièrement interprété au niveau scientifique.

La méthode Rheocable de sondes est destinée à détecter l’interface entre la boue solide et la boue fluide. Un objet tracté lorsqu’il est maintenu dans une fenêtre de vélocité est toujours positionné à l’interface entre la boue fluide et la boue solide. Cette méthode rend possible le développement d’une nouvelle stratégie de dragage d’entretien. – de laisser/ignorer la boue fluide et d’enlever seulement la boue solide.

Le dragage de boue fluide n’est donc pas nécessaire – c’est navigable – et extrêmement peu économique. D’un autre côté, la boue solide n’est pas navigable, est immobile et dragage. En outre, le déploiement du Rheocable implique des avantages opérationnels et contractuels incluant la transparence sur les quantités draguées, etc.

La méthode de levés Rheocable permet une mise au point considérablement améliorée, de plus petites quantités et une planification plus aisée des activités de dragage d’entretien, ce qui a pour résultat une réduction des budgets et l’amélioration de la sécurité du trafic maritime.

Resumen

Desde 1984, se han emprendido en Bélgica actividades relacionadas con la investigación y el desarrollo, comprendiendo medidas *in situ* y pruebas en el mar con el TSHD ‘Vlaanderen 18’, en Zeebrugge. Se han llevado a cabo también experimentos en canale de pruebas hidrodinámicas y experimentos de canales de prueba para sedimentos en los laboratorios de Investigación Hidráulica de Flandes. Este trabajo ha permitido a los autores concluir que el lodo del fondo marino consta de dos estados físicos diferentes en la misma configuración - el lodo fluido en la parte superior del lodo sólido (que se consolida).

El lodo fluido es navegable, el lodo sólido no lo es. La interfaz entre ambos está caracterizada por un aumento drástico de los parámetros reológicos, en particular la elasticidad. Sin embargo, por el momento, este fenómeno no puede ser interpretado del todo científicamente.

El sondaje empleando el método de flujo ha sido diseñado para detectar la interfaz entre el lodo fluido y el sólido. Un objeto remolcado, cuando se mantiene en una ventana de velocidad, está siempre posicionado en esta interfaz entre el lodo fluido y el sólido. Este método hace que sea posible desarrollar una nueva estrategia de mantenimiento del dragado - dejar/ignorar el lodo fluido y retirar sólo el lodo sólido.

El dragado del lodo fluido es pues innecesario - es navegable (¡!) – y extremadamente costoso. Por otra parte, el lodo sólido no es navegable, es inmóvil y mantendrá absolutamente su posición en el fondo marino a menos que sea retirado mediante el dragado. Además, el despliegue del método flujo dependiente implica muchas ventajas operacionales y transaccionales, incluyendo la transparencia de las cantidades dragadas etc.

El sondaje empleando el método de flujo permite un enfoque considerablemente mejorado, cantidades inferiores y una planificación más sencilla de las actividades de mantenimiento del dragado, dando como resultado presupuestos inferiores y una mejora en la seguridad del tráfico marítimo.

Introduction

The problem of the determination of the Nautical Depth in mud environments is illustrated in ***Figure 1*** which represents a classical vertical bathymetric section across a channel using a dual-frequency echosounder with two different acoustic sounding frequencies: 210 kHz and 33 kHz. In the port of Zeebrugge, the difference between both can vary between approximately 2 and 4 m. Such a marked difference between 210 and 33 kHz signals is characteristic for the presence of mud.

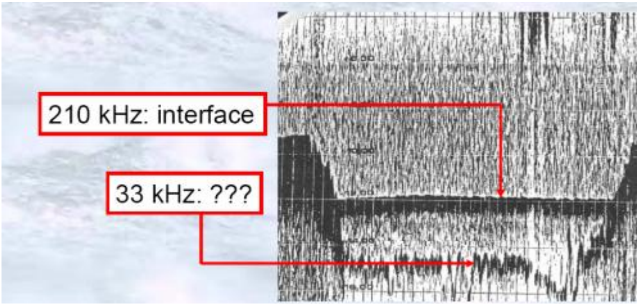

Figure 1. [1]

The following questions arise from these observations:

Which depth has to be communicated to a captain or pilot of a deep draft ship?

Which depth is meant by the PIANC definition of the Nautical Bottom (PIANC-IAPH 1997)? [16]

'The level where physical characteristics of the bottom reach a critical limit beyond which contact with a ship's keel causes either damage or unacceptable effects on controllability and manoeuvrability'

In Zeebrugge, this problem received much attention during the period 1984 – 1988 [2]

An ongoing extensive research programme revealed two important facts:

The existence of a transition zone in terms of rheological behaviour in the mud layer, implying the presence of two different physical states of the same sediment: fluid mud for the top layer and consolidating mud (soil) or solid mud for the lower layer. This transition zone more specifically expresses itself as a very sudden and drastic increase of the mud yield stress.

Trials with the TSHD 'Vlaanderen XVIII' in Zeebrugge, navigating with an under-keel clearance close to zero with respect to the rheological transition zone, showed a stark decline in maneuverability and steerability of the ship [3], totally unacceptable in terms of safe navigation.

Two different physical states

1.1 Initial observations

The existence of a rheological transition implies the presence of two different physical states of the same material: fluid mud and solid mud (soil). This can be experienced on board of any trailing suction hopper dredger carrying out dredging operations. At a certain point when lowering the draghead, the mixture velocity will be drastically reduced within a depth interval of a few decimetres when the draghead passes the interface between fluid and solid mud. ***Figure 2*** shows pump – and pipe resistance curves where the mixture velocity drops from 5 m/s to 2 m/s when passing through the transition zone.

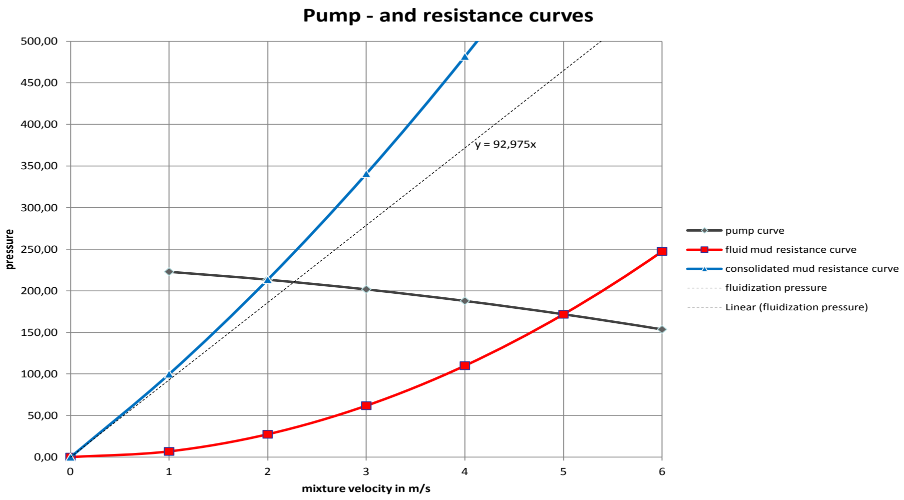

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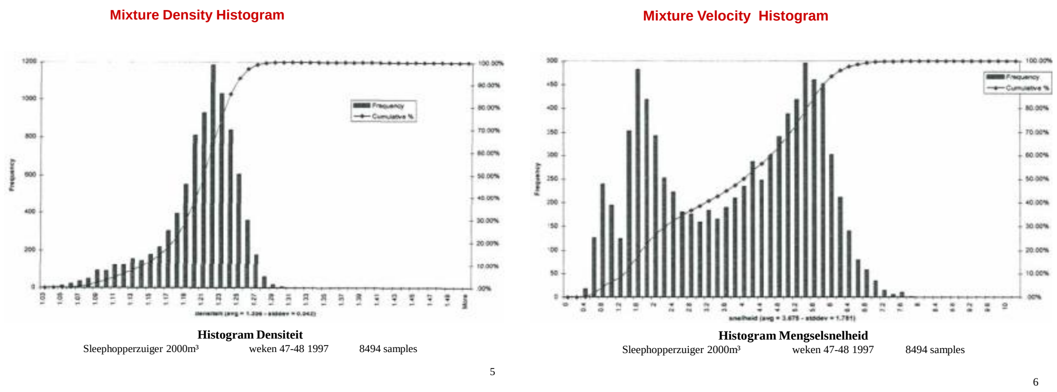
Figure 2.

Another observation also confirms the existence of mud in two different physical states. Figure 3 shows the mixture density and the mixture velocity histograms of the same dredging operation. While the density histogram shows a single density population, the mixture velocity histogram clearly shows two different populations.

1.2 Further Research and Development

Since these early observations, more facts and details have become known. Ongoing research carried out by Malherbe et al [14] provided the important discovery of the rheological transition in mud as early as 1986.



Histogram Densiteit
Sleephopperzuiger 2000m³ weken 47-48 1997 8494 samples

Histogram Mengselsnelheid
Sleephopperzuiger 2000m³ weken 47-48 1997 8494 samples

Figure 3.

At that time (1988), the interface between the fluid state of the mud and the solid state was called the **rheological transition zone**.

This transition from a watery suspension into a soil structure with measurable shear stress, is influenced by density, water content, and by the sand content of the mud (Figure 4). This occurs at any location where sedimentation / flocculation of fine grained material takes place.

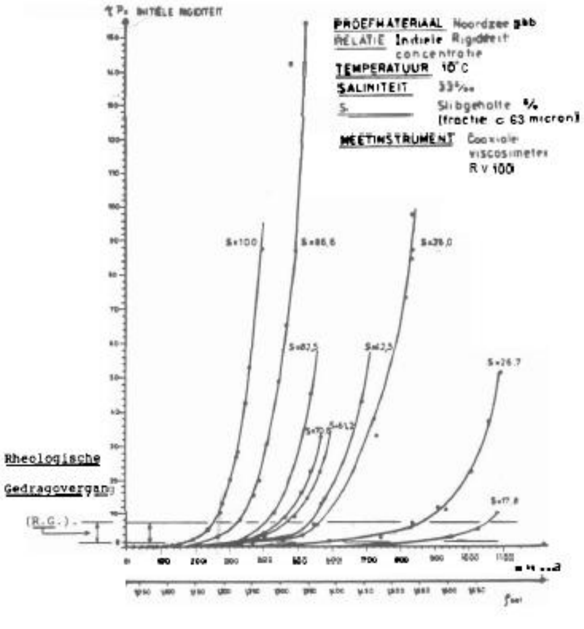


Figure 4.

In more recent years, reference has also to be made to the research and experiments of Wurpts [4]. He describes the phases in the process of mud formation and shows the different properties of fluid mud and solid mud (soil):

- aerobic versus anaerobic
- organic versus inorganic
- absence of gas versus presence of gas
- difference in colour
- process of flocculation versus process of consolidation
- fluid dynamics versus soil mechanics
- low yield stress (25 Pa) versus high yield stress (1000Pa)

An extremely important observation by Dr. Wurpts is that in a navigation channel, it is inefficient and useless to dredge fluid mud - only solid mud needs to be dredged (or treated). Hence the importance of locating, or sounding the interface between fluid and solid mud in relation to maintenance dredging activities. This interface can be made visible as shown in the Figures 5, 6 and 7, taken in the DEME harbour at low tide along the river Scheldt at Antwerp.

As soon as 'decantation' process is accomplished, the fluid mud is gone with the tide and the solid mud shown in the pictures will stay and not move unless removed eventually by some dredging process.

An exhaustive description of the sedimentation process and the consolidation process of cohesive sediment has been made by Toorman [5]. Significant research in this field has also been carried out by the Waterway Experimental Station (WES) of the US Army Corps of Engineers. [6] They reported that, at the end of the sedimentation process or at the beginning of the consolidation process (meaning the interface between fluid mud and solid mud), the water content is equal to the liquid limit (Atterberg), multiplied by 2.5.

Figure 5

Figure 6

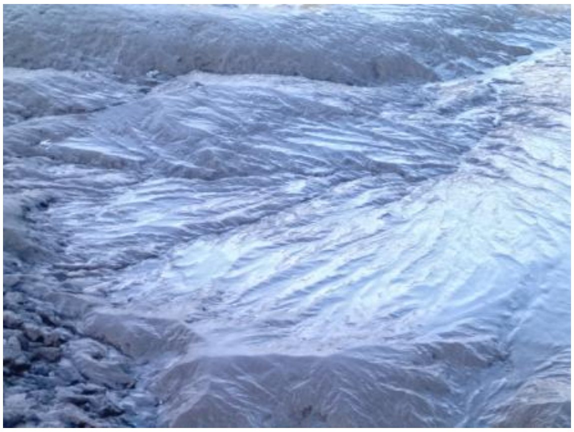


Figure 7

This observation is significant. It relates the density at the fluid / solid interface to the nature of the mud: silt, clay [15]. It shows that density as a parameter for the Nautical Depth is basically inappropriate, because it depends on the mud composition (refer to Figure 4: the influence of sand content on the density at the rheological transition). Furthermore, it was found that in the upper layer of 30 cm in the fluid mud, the water content is about 5 times the liquid limit.

1.3 Rheological transition / discontinuity: some examples

In the laboratory, during the Rheocable and Accelero probe tests [8], the rheological profile in the sludge test tank (SST) was measured with great accuracy (***Figure 8***). The transition / discontinuity can be observed between a depth of 85 cm and 97.5 cm. The part of the profile lower than 100 cm, did not allow in situ measurements. The measuring instrument is unable to penetrate in the solid mud.

The density profile shown in ***Figure 9***, shows a similar transition at the same location. This is unlike the in situ situation where the density transition is normally positioned in a position lower than the rheological transition. Figure 10 shows the shear stresses versus depth, at the shear rates of 0.1 and 1000 (1/s).

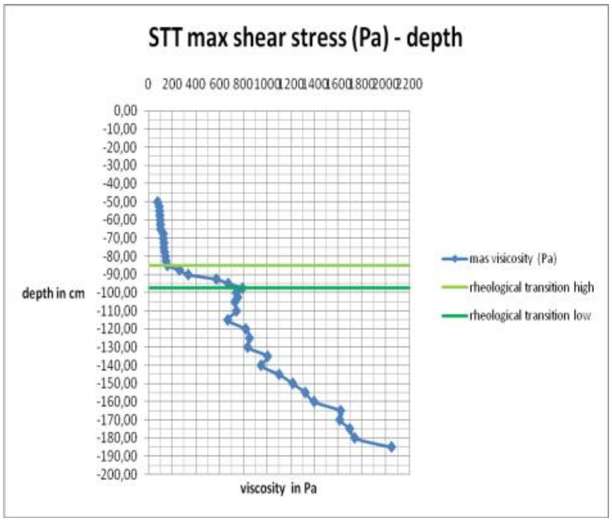


Figure 8

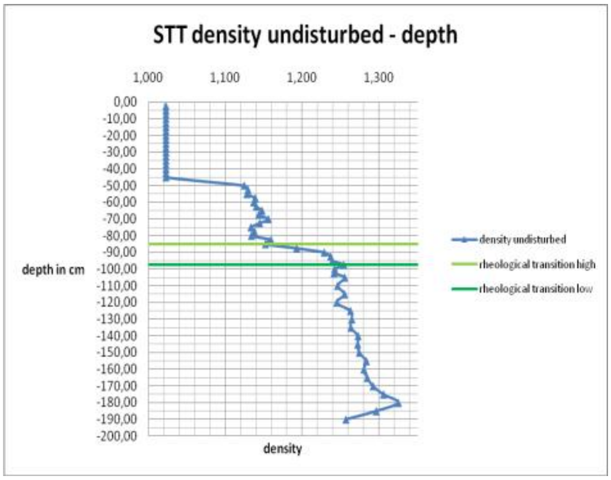


Figure 9

Both profiles have different values above and below the discontinuity, but in both cases the discontinuity occurs at the same level. In an interval of 12.5 cm, the shear stress increases drastically with a factor of about 10: from about 50 Pa up to 500 Pa for the 0.1 shear rate, and from about 80 Pa up to about 800 Pa for the 1000 shear rate.

The rheological transition from fluid mud to solid mud is therefore perfectly detectable. The difference will show up, independently from the applied shear rate, even at varying shear rates.

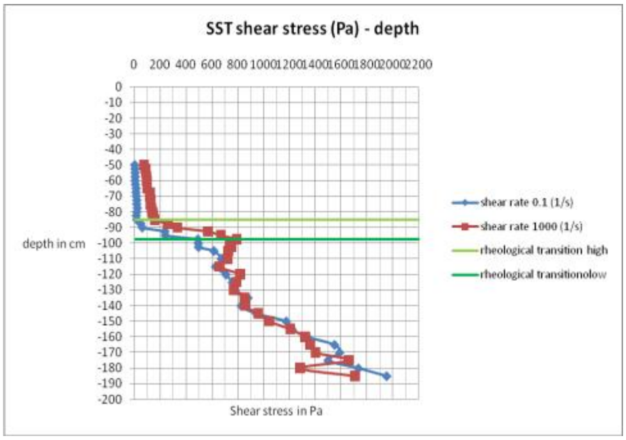


Figure 10

The existence of two different physical states of the mud is also confirmed by the relation yield stress – density. ***Figure 11*** shows this relation density – shear strength at an applied 0.1 1/s shear rate. At this low shear rate, the stresses measured are as close to the yield stress as possible. (See also the similarity with the laboratory results reported by Haecon in 2008 [7]).

It confirms and illustrates the existence of two different physical states: a fluid mud state and a solid mud state. At the interface, the yield stress increases very quickly. In situ, this will be recorded as a discontinuity in the yield stress profile.

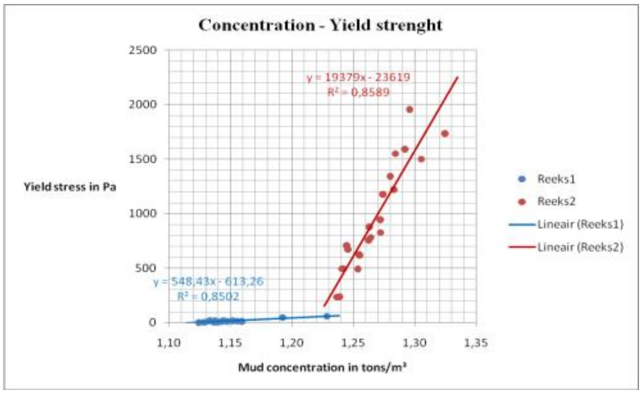


Figure 11

Figures 12 and ***13*** illustrate the rheological discontinuity that has been picked out of a series of prick soundings in the Central Part of the New Harbour in Zeebrugge, carried out for the Department of Flemish Hydrography on the 8 of June 2009 using the Rheotune (Stema).

The interface between fluid mud and solid mud is easy recognizable: observe the fact that the interface has a density of 1180 g/l.

1.4 Rheological transition/discontinuity - (absence of) scientific background

During the Rheocable and Accelero probe tests in laboratory conditions [8], the rheological profile was measured with great accuracy (see ***Figure 14***), where shear stress is recorded versus shear rate at different depths in the SST.

The rheological difference between the levels of 85 and 95 cm depth – the red (above the discontinuity/transition zone), respectively the green line (below the discontinuity/transition zone) – is striking. Both lines are to be associated with Bingham fluids, but the line at a depth of 95 cm reveals an initial yield stress which is about 10 times higher.

At the level of 105 cm and further down in the solid mud, the relation shear rate / shear stress changes its profile: the yield stress is higher, but the shear stress falls with increasing shear rate, reaches a minimum and continues like a Bingham fluid. In this case, the yield stress is named ‘static’ yield stress, the minimum is called ‘dynamic’ yield stress.

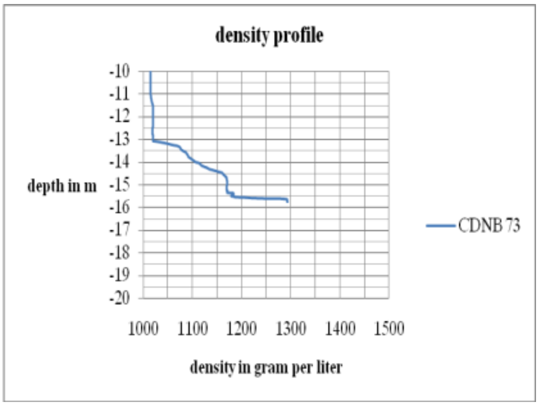


Figure 12

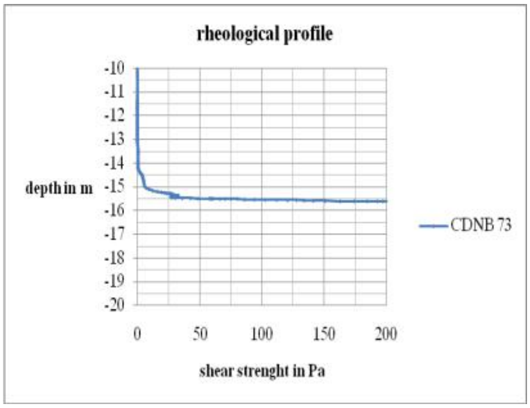


Figure 13

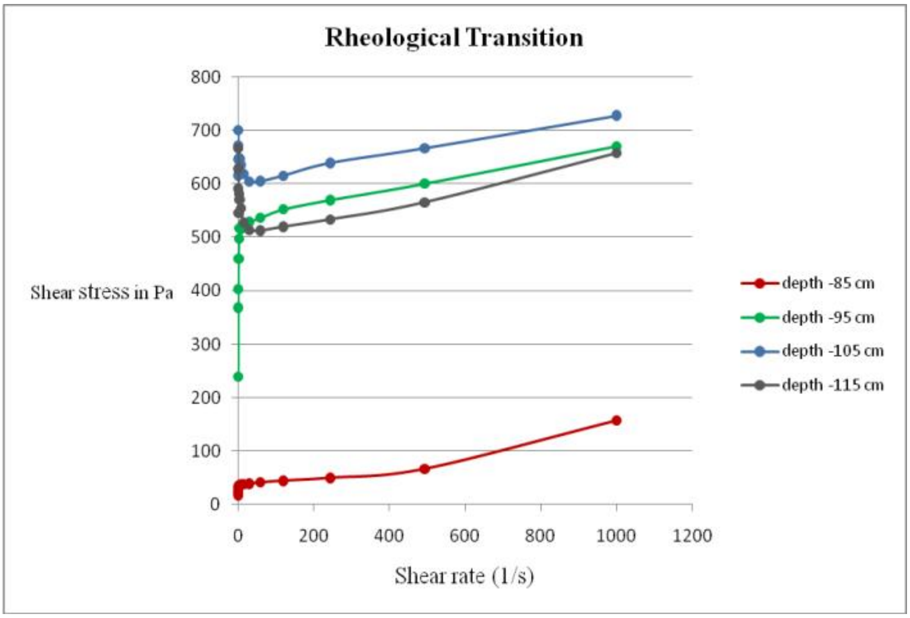


Figure 14

This phenomenon widens the already existing rheological gap. Toorman [13] describes this phenomenon (see ***Figure 15)*** and makes reference to a secondary structure in some cases. But an explanation for its occurrence in some clay suspensions is unknown.

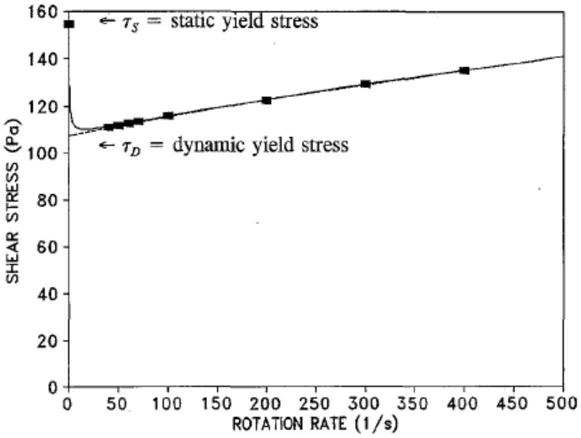


Figure 15

Apparently, the mud in the test tank is part of this category of clay suspensions showing static and dynamic yield stresses. The mud is a direct sample from the seabed which implies that potentially all mud in our harbours and shipping channels belongs to this category. This wide rheological gap between fluid and solid mud lacks a satisfactory scientific explanation.

This is further evidence for the existence of two different physical states of the mud, with very different rheological properties and separated by a small transition zone, which in situ is recorded as a discontinuity.

1.5 Summary and discussion

Figure 16 represents schematically the properties of the two different physical states of the mud as known.

Figure 16

The corresponding average density and rheological profiles (in Zeebrugge) are represented in ***Figure 17*** [7].

With regard to the relation between both, following details are important to notice:

- The lines AB and EF are positioned near the 210 kHz level
- The point of articulation G in the density profile is situated below the point C (= rheological transition point)
- The point of articulation G is positioned above the 33 kHz level.

In section 4.1, the Rheocable soundings in Zeebrugge exactly show and repeat these observations.

In Emden a yield stress of 70 Pa is momentarily used as the definition of the Nautical Depth, with the perspective / hope of changing the definition to 100 Pa in the future - density definitively has been put aside. We agree with Wurpts to choose the parameter of the yield stress to define the Nautical Depth, but for different reasons. We will not use a particular value of the yield stress, but rather the discontinuity of the yield stress between fluid and solid mud as the main criterion defining the Nautical Depth.

2. A ships behaviour: TSHD ‘Vlaanderen XVIII’

Trials with the TSHD ‘Vlaanderen XVIII’ in Zeebrugge (***Figure 18***), navigating with an under-keel clearance of about zero with respect to the rheological transition, showed a very stark decline in manoeuvrability and steerability of the ship [3], totally unacceptable with respect to normal and safe navigation. The vessel kept moving on, but was unmanageable!

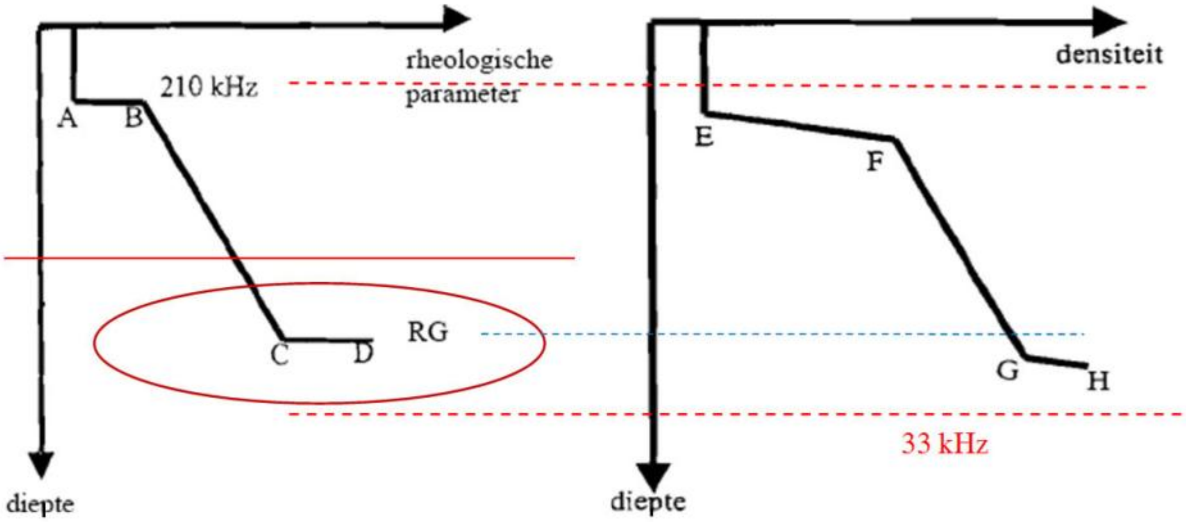


Figure 17

Conclusion

As reported by Wurpts [4], and confirmed by the laboratory observations, the yield stress shows a major discontinuity in the transition between fluid mud to solid mud and he proposes the yield stress as the parameter to specify the Nautical Depth.

The yield stress is a measure of the force needed to start the fluidisation of the mud: 25 N per m² (2.5 kg) in the fluid mud state, 1000 N per m² (100 kg) in the solid mud state. Wurpts [4] characterizes the fluid mud as ‘navigable’ (i.e. a vessel is able to navigate in a sea of homogenous fluid mud) and the solid mud as ‘not navigable’.

Figure 18

With the ship's bottom in contact with the solid mud at the interface level, the normal flow of water / mud to the propellers is severely hindered and quasi interrupted due to the high yield stress of the solid mud. Consequently, the propeller's thrust is significantly reduced, including its effect on the rudder: the ship completely loses her manoeuvrability and steerability.

On the other hand, the contact of the vessel's keel with the interface generates quasi no frictional forces: the vessel keeps going her own way, completely out of control.

It is clear that the under-keel clearance with respect to the rheological transition of the mud is an important parameter when analyzing the behaviour of a deep draft vessel navigating above a seabed of mud. However, the position of the Nautical Depth and the properties of the fluid mud layer are not the only parameters influencing the behaviour of a deep drafted vessel. Ship related parameters have to be considered as well such as speed, keel clearance, squat, type of manoeuvre etc.

The interaction between ship and fluid mud layer has been investigated extensively by Vantorre and his team in the specially build towing tank in Flanders Hydraulic Research, Borgerhout Antwerp [9].

An important result of this research is that although the keel clearance relative to the Nautical Depth is extremely important, keel clearance relative to the water/fluid mud interface has significant effects as well.

For safe and fluent navigation, pilots, captains and ship's officers need to know both levels: the 210 kHz level and the level of the rheological transition zone, meaning the yield stress discontinuity level in the mud. As the 33 kHz and the 1.2 density signals fail in providing the latter level, there is an urgent need to find a valid sounding method capable of detecting the Nautical Depth!

3. The Rheocable Method

3.1 Principles

Any object, towed on a cable through water, will meet resistance. The depth of the object will depend on the towing speed through the water. The same applies for a Bingham or Herschel–Bulkley fluid, with this difference that an extra force is required to overcome the yield stress and extra energy for the liquefaction of the mud displaced by the object.

For a fluid mud, with low yield stress, friction forces are low, the energy for liquefaction is low, therefore the resistance and towing force are low, and the corresponding position of the object, when towed in an homogenous fluid mud environment is low (Figure 19).

For a solid mud, with high yield stress, friction forces are high, the energy for liquefaction is high, therefore the resistance and towing forces are high, and the corresponding position of the object, when towed in a homogenous solid mud environment is high (Figure 20). In reality, the object will come out of the solid, gel-like mud.

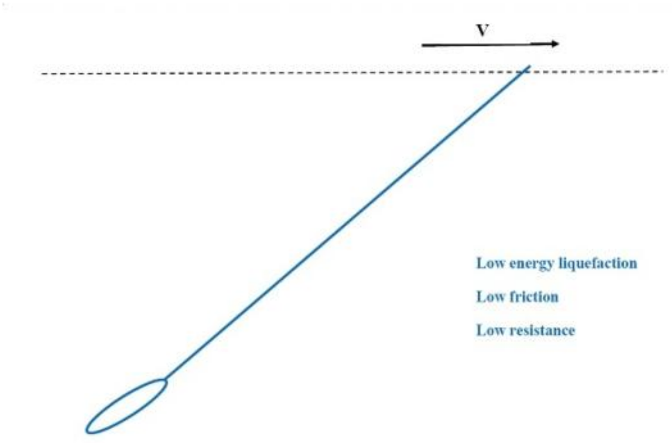


Figure 19

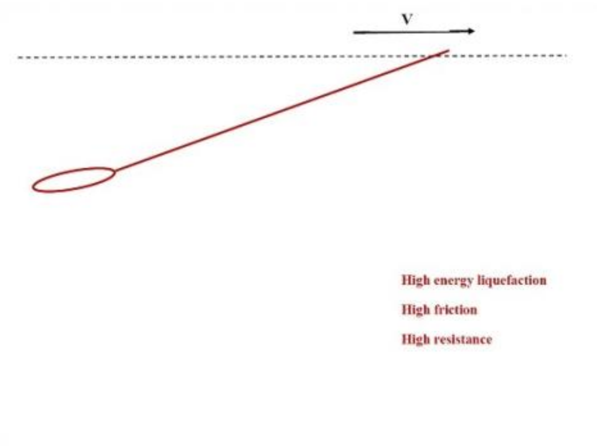


Figure 20

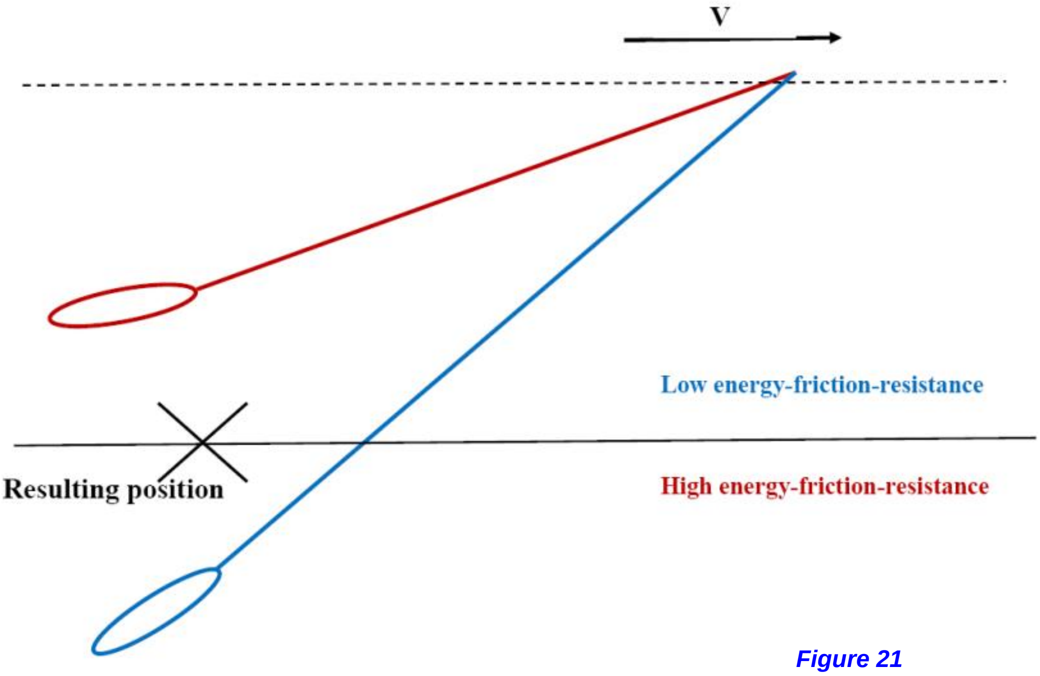


Figure 21

A second principle used by the Rheocable sounding method is the fact that fluid mud and solid mud have different electrical resistivity values. The resistivity of the fluid mud layer is low (especially higher above the transition zone), compared to the resistivity of the solid mud layer. By measuring resistivity of the towed object whilst underway, the Rheocable method is able to verify (and record) continuously whether or not the towed object is in contact with the solid mud, i.e. that the towed object is not floating. If the object leaves the fluid/solid mud interface and starts floating above it, this results in an instantaneous decrease of the measured resistivity value.

Finally, the depth of the towed object is recorded by measuring the hydrostatic pressure – with measures in place to compensate for variable density values within the fluid mud layer – and by measuring the density of the water column at different levels.

3.2 Measuring array

The towed object consists of a weight and a pressures sensor, tightly wrapped in a protective rubber hose, and a resistivity cable attached to it (***see Figure 22***). The resistivity cable includes 4 electrodes, used to measure the resistivity. This combination is connected to the survey vessel by an umbilical cable. It has several functions: towing the combination, bringing DC current to the resistivity cable, and transmitting signals to the computers on board the survey vessel.

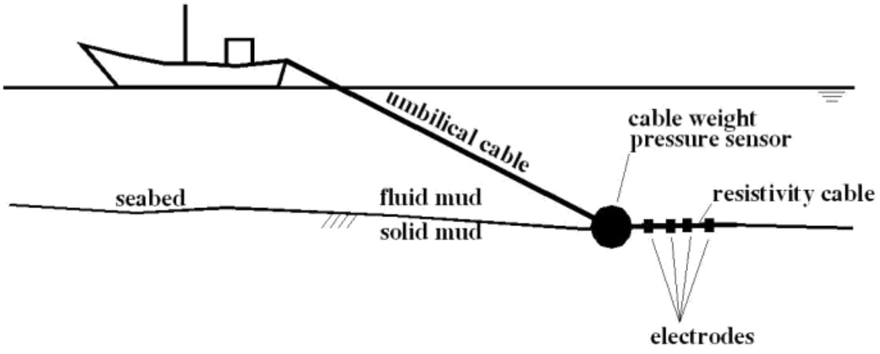


Figure 22

Figure 23 shows the resistivity cable attached to the towed object. ***Figure 24*** shows the complete towed object with the umbilical cable. ***Figure 25*** shows the AC/DC Converter and the attached computer for monitoring and recording the resistivity values. Measurements and recordings are carried out with a frequency of 1 Hertz.

The length of the cable is approximately 3 times the depth to be surveyed - for a channel depth of 20 m, a 60 m long umbilical cable will be used at velocities up to 4 knots.

During a working day of 8 hours, a length of about 30 to 50 km can be surveyed. This is about 3 to 6 times more than would be possible with a prick probe, taking a prick every 100 m - 70 pricks per working day being a standard for this kind of activity. Consequently the cost of the Rheocable method versus prick probe survey – ship, surveyors, etc. can be estimated at 1 versus 3 to 6. Furthermore, considerably more information and detail will be available with the Rheocable method of sounding because every second a depth sounding is recorded.

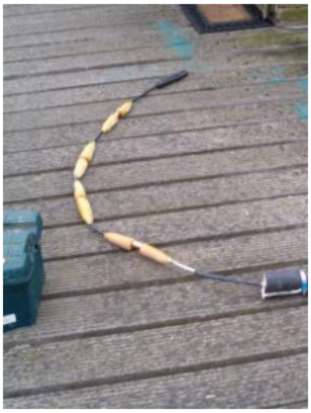


Figure 23

Figure 24

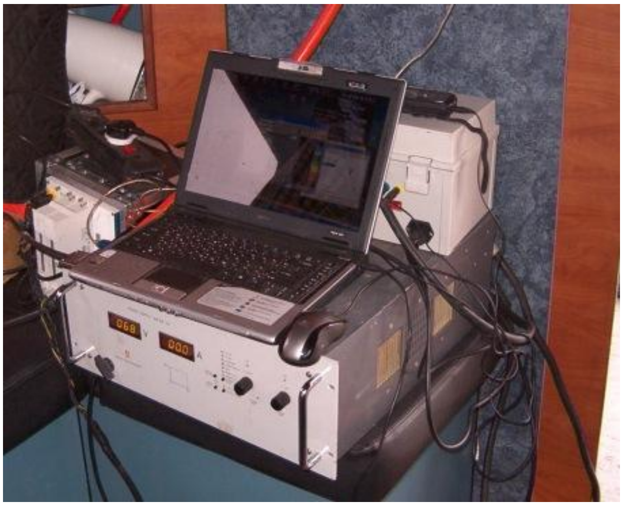


Figure 25

Any vessel can be used as a platform for the survey. The Rheocable equipment is self sufficient, including generator, positioning system, 210 kHz survey system, etc. A well equipped survey vessel, handled by a survey crew, is the ideal platform. Moreover, after 1 or 2 surveys and with some instruction and assistance, the crew will be able to carry out a Rheocable survey without any assistance from the THV Nautic.

3.3 Analytical model

In order to investigate the behaviour of the cable combination during towing, an analytical model was developed. This model enables the study of the different parameters – cable length, cable diameter, cable weight, additional weights etc. and their influence on the 'performance' of the cable. Performance in this context is defined as the ability of the cable to keep its 'tail' on the seabed and in contact with the solid mud, at a towing speed as high as possible.

The model can be calibrated easily by towing the cable in a floating condition at different velocities whilst recording speed and depth. ***Figures 26*** and ***27*** show two examples of such a calibration carried out in IJmuiden and Zeebrugge.

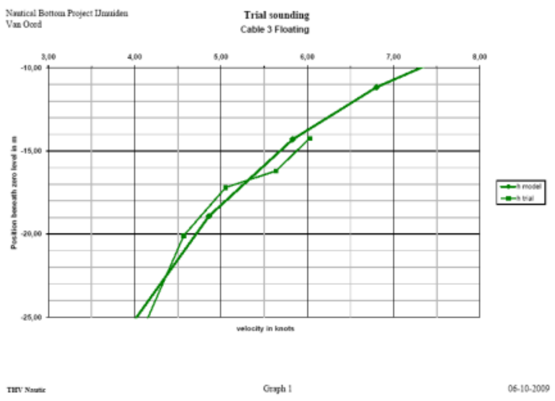


Figure 26

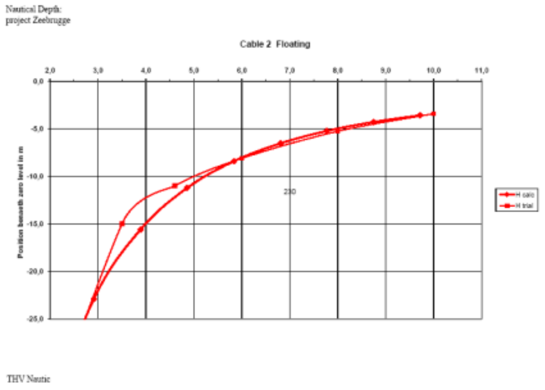


Figure 27

The model is sufficiently accurate to assist with the clarification of some questions and problems put forward [10].

3.4 Resistivity

Resistivity is a key feature of the Rheocable system to ensure the cable is effectively in contact with the fluid/solid mud interface. During the survey trials in October 2009 in Zeebrugge, a resistivity test was carried out. The same survey line was run with different speeds in order to determine the velocity beyond which the cable started floating and losing contact with the solid mud.

Figure 28 shows the frequency distribution of the survey velocity values recorded. With each velocity recorded, a resistivity value is associated, measured and recorded at the same time. ***Figure 29*** shows the frequency distribution of these resistivity values and clearly indicates, contrary to the Figure 28, two different sets of resistivity values, sharply separated at a resistivity value of 0.300. ***Figure 30*** shows the frequency distribution of two sets whereby the velocities are associated with resistivity values lower than 0.300 and higher than 0.300.

Both are apparently normally distributed, with medians respectively 2.6 knots and 4.4 knots. The 2.6 knots set is associated with resistivity values higher above 0.300 Ohmm whilst the 4.4 knots set has resistivity values lower than 0.300 Ohmm.

For this particular type of cable used and for the given depth range, the velocity of 3.6 knots appears to be the limit between both sets and is the difference between the rheocable being in contact with solid mud or floating.

There is an area of overlap around the 3.6 knots interface: this is due to the fact that with increasing velocities, the Rheocable ‘sticks’ somewhat longer to the solid mud and with decreasing velocities, the Rheocable takes more time to re-establish contact with the solid mud.

Figure 29 proves that the parameter resistivity (ρ) can be used to establish, unequivocally, the fact that the Rheocable is in contact with the solid mud and therefore indicating the Nautical Depth. Figure 30 indicates that this contact can be guaranteed / secured by keeping the survey velocity below a certain level.

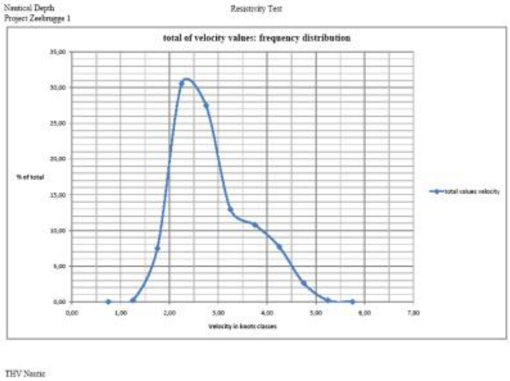


Figure 28

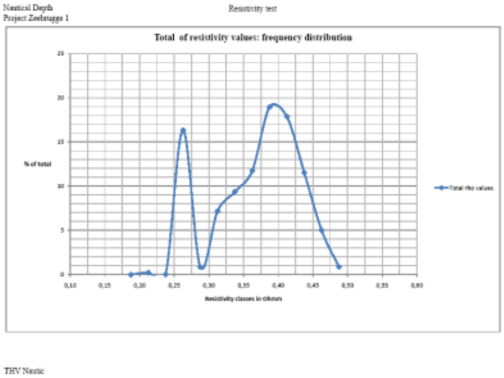


Figure 29

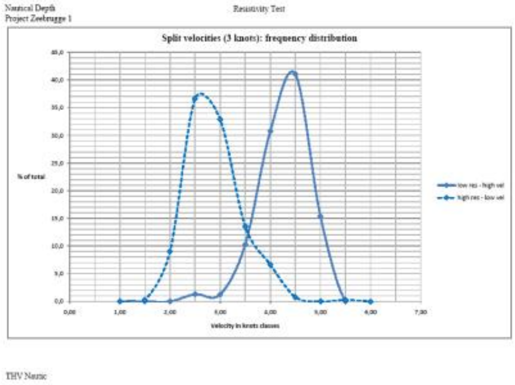


Figure 30

All sounded depths, associated with resisitivity values lower than 0.300 Ohmm, will be deleted when producing survey charts. This eliminates all ‘false’ sounded depths (associated with a floating cable situation) and guarantees true Nautical Depths to be represented in the charts.

4. Rheocable method results

4.1 In situ Nautical Depth surveys

Figure 31 shows an example of a Nautical Depth survey carried out in Zeebrugge with the Rheocable [11]. The survey took about 6 hours to complete – mobilization and demobilization excluded, and was otherwise simple, transparent and straight forward.

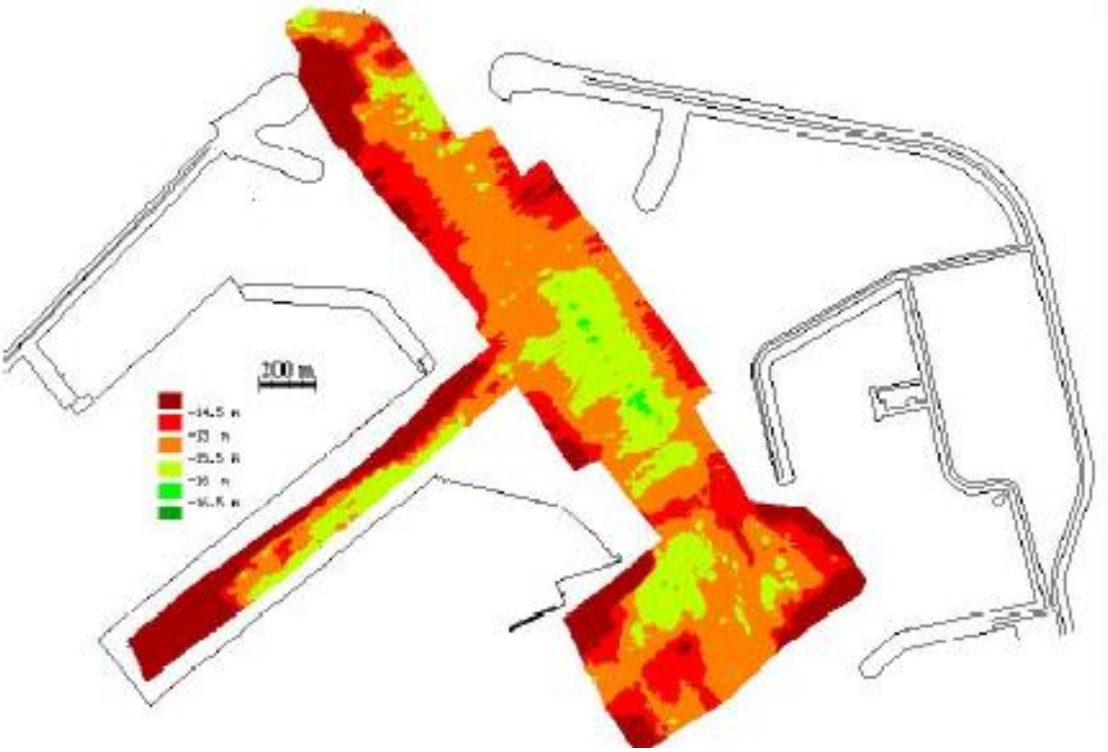


Figure 31

The results of other survey techniques using acoustic methods at 210 kHz and 33 kHz and the density pricks, with reference to the Rheocable survey are shown in ***Figures 32*** and ***33***. Figure 32 relates to the area ZP1 which is the most southern area of the port whilst Figure 33 relates to the central part of the new outer port (CDNB).

The blue graph is the frequency distribution of the depths measured using the Rheocable. The grey graph is the 33 kHz frequency distribution, the green graph shows the 210 kHz and the red graph represents the 1.2 density depths by the prick probe.

In the area ZP1, the distributions have roughly the same characteristics, only that the modes are significantly shifted. The most important is the shift between the Rheocable (interface fluid/solid mud) and the 1.2 density distribution (official Nautical Depth). The interface fluid/solid mud is shallower than the 1.2 density by 0.5 m, meaning that the 'real' nautical depth is 0.5 m shallower as compared to the 'official' nautical depth. The distributions in the CDNB have a considerable higher variance and the difference between Rheocable and 1.2 density modes is smaller.

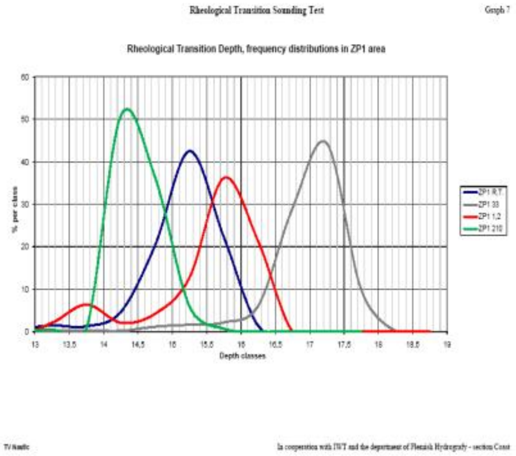


Figure 32

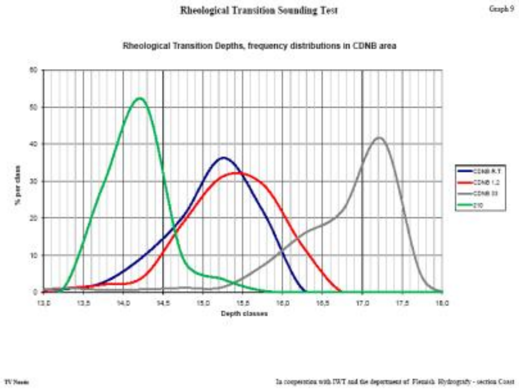


Figure 33

It can be seen in both areas, that the Rheocable result is positioned at shallower levels as compared to the 33 kHz results as was already recorded in the Haecon study [7] (see Figure 17).

The same observations were made during survey trials in the Port of IJmuiden (***Figure 34***) and also during further surveys in the Port of Zeebrugge.

The observation that the position of the fluid/solid mud interface is situated at shallower levels as compared to the ‘official’ and nautical depth surveys is significant and could help to explain some difficulties of ships trying to manoeuvre in these areas.

4.2 Laboratory Tests

In June 2011, Rheocable tests were carried out in the Sludge Test Tank (STT) of Flanders Hydraulic Research (FHR) [12]. The dimensions of the STT did not allow tests to be performed with the original Rheocable. Therefore an adapted Rheocable model was used. The weight and dimensions were reduced and the resistivity function renounced. This adapted Rheocable was towed in the tank with various velocities. The result of these tests is shown in ***Figure 35***.

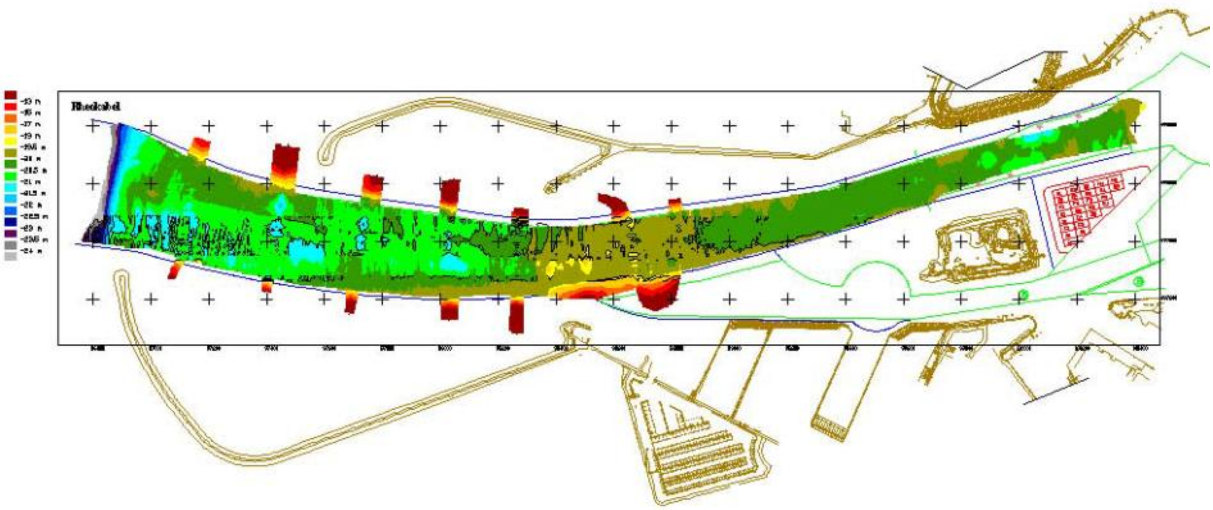


Figure 34

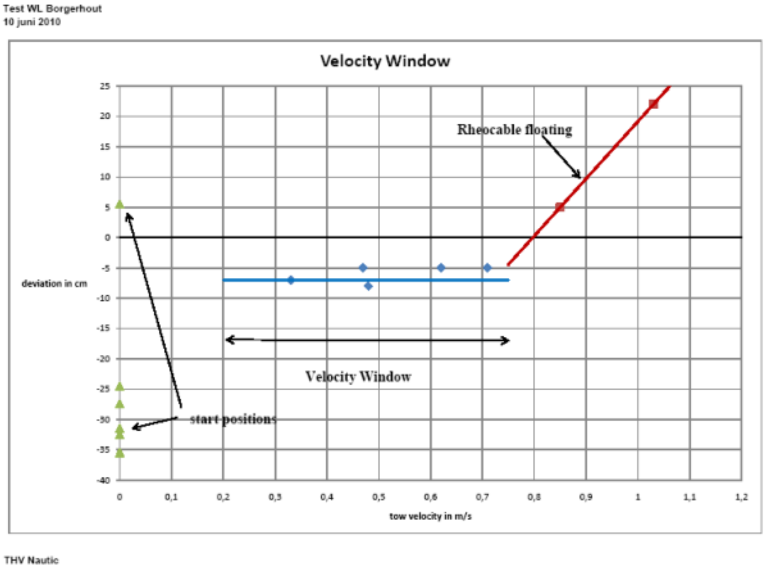


Figure 35

The tests confirmed the existence of a velocity window. The towing velocities in the window generate the same depth position of the Rheocable with regard to the interface between fluid mud and consolidating mud. At the lower end of the window velocity, all test runs, except one, show that the Rheocable sinks into the consolidating mud at zero tow velocity and that already at a minimal towing velocity, the Rheocable moves up to its fixed liquid/ solid mud interface position.

Once completed the acceleration phase, the position of the Rheocable remains fixed (within 2 to 3 cm) – fully independent of the varying tow velocity up to a velocity of about 0.75 m/s. At higher velocities, the Rheocable starts to float as experienced in both test runs with higher velocities. This proves that the cable stays on a rheological transition level for a determined speed window.

In a real environment the width of the speed window naturally depends on water depth, umbilical cable length, cable design and cable weight.

5. Maintenance Dredging: a new strategy

The procedure of sounding the Nautical Depth, as applied by a majority of maritime and port authorities, uses the method of sounding a density horizon in the mud, 1.2 in many cases. Today, it is generally accepted that this procedure is far from accurate and leaves much to be desired when used to control/ quantify the necessary maintenance dredging works. More specifically it is recognized that problems exist concerning the quantification of quantities dredged and quantities to be dredged. Notwithstanding these deficiencies, most authorities are fully capable of running a safe operation, due to their vast experience and careful approach, albeit with a relatively high budget.

However, with the availability of the ‘Rheocable method’ a new sounding method capable of accurately defining the true Nautical Depth, different dredging strategies for the handling of maintenance dredging works can be introduced, leading to improved safety and reduced costs.

5.1 The Principle

The measurement of the Nautical Depth, as made possible by the Rheocable method of THV Nautic, produces the position of the interface between fluid mud and consolidated mud (***Figure 36***).

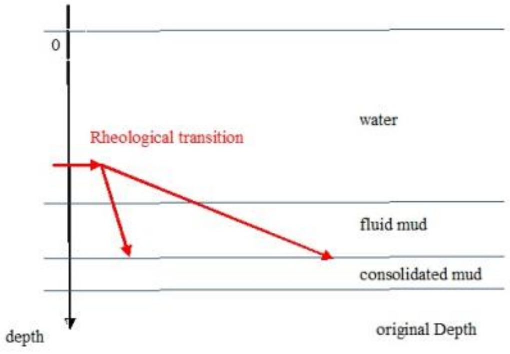


Figure 36

This distinction between fluid mud and consolidated mud, made possible by this sounding method, is very important in that principally, fluid mud doesn’t need to be removed from the seabed as it is navigable. Furthermore, fluid mud is mobile and when driven by wind, tide and currents, can travel considerable distances. It may even disappear from the area to be dredged under the effect of outgoing tidal currents. The dredging of fluid mud is therefore unnecessary and very uneconomical.

Consolidated mud on the other hand is not navigable, is immobile, will absolutely maintain its position on the seabed and is not affected by wind, tide or currents. If the guaranteed water depth is situated below the rheological transition zone (in the consolidated mud), this mud needs to be removed.

Solid mud needs to be removed

The under-keel clearance of a ship with reference to the interface fluid / solid mud and the under-keel clearance with reference to the 210 kHz level, are the critical parameters with regard to the behaviour and the safety of the ship.

Whilst the 210 kHz level cannot be influenced by dredging, the interface fluid/solid mud can, by dredging the solid mud. Therefore, the new dredging strategy proposed in this paper supposes the implementation of two important elements:

- The rheological transition between fluid mud and consolidated mud is the real Nautical Depth and must be accepted and specified as such. (Density horizons must be removed as definitions of the Nautical Depth)
- ignore the fluid mud and remove only the solid mud when necessary.

5.2 Operational Advantages

Control of the dredging activities can be carried out independently of the dredger, simply and efficiently:

Dredged quantities are calculated in m³ using in– and out-surveys

The measurement of dredged quantities on board of the dredger, such as hopper density and /or TDM (tons of dry material) in case of a trailing suction hopper dredger, is unnecessary. Systems, automatic or not, developed for this purpose, have become superfluous.

Any dredging equipment

Abstraction made from environmental and contractual elements (such as shipping traffic, contaminations etc.) means the nature of the dredging equipment is no longer relevant - water injection dredger, cutter suction dredger, hopper suction dredger, bucket dredger, plow (with or without jets), etc. As long as the out-survey shows nautical depth levels obtained to meet the specifications, any dredge technique is acceptable.

Therefore, different dredging techniques can be used in one dredging area without consequences/ complications for the control and measurement of the dredge quantities.

Contractors can be charged to carry out intermediate soundings. It is only necessary for the Principal to carry out the in- and out-survey.

Limited or no supervision on board.

The limitation of the ‘suction tube depth’ is obtained by not paying, or even, by fining the quantities dredged below the target depth plus tolerance. ‘Overdepths’ can easily be detected and quantified using the Rheocable method. The tendency of dredging contractors to dredge deeper than required, when hopper densities are used for the calculation of dredge quantities can be avoided by the contractor, because they know it will not be paid for or even be fined. Consequently, supervision on board of the dredger is no longer required.

Dredge quantities located outside the dredging area, when made non- payable or fined can easily be detected using the Rheocable method - contractors will try to avoid this.

The disposal of dredged material within the specified areas can be checked using registrations of the existing positioning systems on board, controlled eventually by existing radar facilities ashore.

Dredge overflow, in the case of suction hopper dredgers, is not critical with the new dredging strategy and can be left to the discretion of the contractor.

Supervision on board with the purpose of ensuring a tight control of the maintenance dredging activities is no longer required.

5.3 More or less maintenance dredging activities?

Comparing dredged mud quantities, measured in tons of dry material (TDM) with dredged in situ mud quantities measured in m³, is never a simple exercise. During the dredging process, mud continually changes density and volume on its way from the seabed up into to the hopper, during the stay in the hopper, and unless the changing densities together with the changing volumes can be measured and recorded - quod non – the exercise of comparing m^3 of in situ mud with tons of dry material remains uncertain. Furthermore, a distinction between fluid mud and solid mud cannot be made.

Another imponderable element is overflowing.

The confusion, caused by the presence of fluid mud, in terms of ‘classic’ sounding data and in terms of quantities dredged, disappears when using the Rheocable.

The same applies when the contract uses a density horizon: for example 1.2. This inadequate criterion leads inevitably to more quantities dredged and paid for than strictly necessary.

For ongoing dredging contracts, which have not been based on Rheocable determined strategies, the Rheocable method can be used to determine the real efficiency of ongoing maintenance dredging activities and also to prepare for contracts based on Rheocable soundings.

It is reasonable to anticipate a considerable reduction of the dredging effort and the related budget.

The Rheocable sounding method allows for a much better focus and planning of the maintenance dredging activities.

Conclusion

The use of the **Rheocable sounding method,** capable of measuring directly the transition between fluid and consolidated mud, allows for a much better focused approach and control of maintenance dredging activities involving mud. The superfluous dredging of (navigable) fluid mud is avoided and the necessary dredging is limited to the (not navigable) solid mud.

Start, finish and quantities of the dredging campaign will be determined correctly using an accurate sounding method. This has considerable beneficial effects upon:

- The safety and fluency of shipping traffic
- The planning of the dredging campaigns
- The quantities to be dredged
- The production and efficiency of the individual dredgers
- The budget of the maintenance dredging works

The introduction of the Rheocable sounding method, measuring directly and accurately, the interface between fluid and consolidated mud, will provide the competent authorities with an adequate tool to support their decisions and will significantly improve cost savings and safety for shipping traffic.

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Biographie of the Authors

ir. Marc Druyts has been a part of the Belgian dredging company Decloedt, later called DEME NV, for years.

He achieved an engineering diploma for naval architecture at the State University of Gent, and started working at the company Decloedt in Zeebrugge in 1985, where he initially led the technical department. Between 1991 and 2001, he led the dredging operations on the Belgian coast in the function of Executive Director of the TV (temporary company) Noordzee & Kust. This TV is still performing dredging operations on the Belgian coast to this day.

Since May 2001 he is a self-employed consultant through his company MDCE bvba. (http://mdce.be)

Dr. ir. Peteralv Brabers has done geo-technical surveys for years with his own company all over the world, mainly on water but also on land, primarily for dredging companies, but also for harbour authorities and management boards. His unique specialty is the execution and processing of resistivity measurements, a geophysical method capable of accurately defining the seabed geology.

P. Brabers is CEO of his company DEMCO nv. (http://www.demco-surveys.com)

Marc and Peteralv founded THV Nautic as a partnership, to give a home to their combined activities related to sounding the nautical bottom.

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