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# HOW NAVIGABLE ARE FLUID MUD LAYERS?

by

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## ABSTRACT

This paper gives an overview of the research that has been conducted to get a better understanding of the navigation in ports and waterways with fluid mud layers. In particular, the up-to-date review of reported full scale experiments that involve real vessels is provided. To study physical processes, the full scale experiments are accompanied by scaled experiments and numerical modelling. This combination provides a valuable insight into ship behavior with respect to different navigation conditions and physical properties of fluid mud. Another aspect of this paper are the surveying methods that can localize the fluid mud layers and potentially provide information about the strength of these layers. Some of these methods were tested on fluid mud produced by water injection dredging in the Port of Rotterdam. It was concluded that the new rheology-based method show a potential for understanding of strength development in fluid mud layers. Finally, some open research questions with respect to the applicability of the navigation through fluid mud are discussed.

## 1. INTRODUCTION

Safe navigation in ports and waterways should be insured by the port authorities and a good safety record is of utmost importance for the competitive position of the harbors. An important factor for safe navigation is the space that is available under a ship's keel, known as the under keel clearance (UKC). Sufficient UKC can be achieved by either setting a restriction on the maximum draft of incoming vessels or by maintaining the desired navigable depth with intensive dredging operations in silted areas. The first option is usually undesirable from an economic point of view and would result in a severe restriction on future development of larger and thus more energy-efficient ocean traversing vessels. The second option is favorable in general, although the cost and environmental impact of the required dredging operations to dispose the fluid mud can become quite substantial.

Fluid mud is typically deposited on the bottom of the shipping route when the net sedimentation rate is larger than the consolidation rate (Winterwerp, J. C. & van Kesteren, W. G. M. (2004)). Settling and consolidating in low-energy areas, fluid mud forms river and sea beds. Fluid mud consists of a highly concentrated suspensions of sediment particles combined with microbial slimes. These slimes can be seen as a network of polyelectrolytes that keep the sediment particles in suspension, and fluid mud can be seen as a visco-elastic fluid. Navigation in ports and waterways with fluid mud seabed can be challenging due to several factors. The fluid mud layer cannot be reliably detected by traditional acoustic methods. The interpretation of the measured acoustic data is ambiguous since the position of the seabed on the acoustic charts is not clear. Another challenge for navigation in muddy areas is the generation of internal waves (undulations). The controllability and maneuverability of a vessel can be hindered by such waves in case of a ship navigating in a close vicinity of a water-mud interface. In particular, the amplitude of the undulations affects the rudder and propeller efficiency as was observed during the both in-situ and laboratory experiments.

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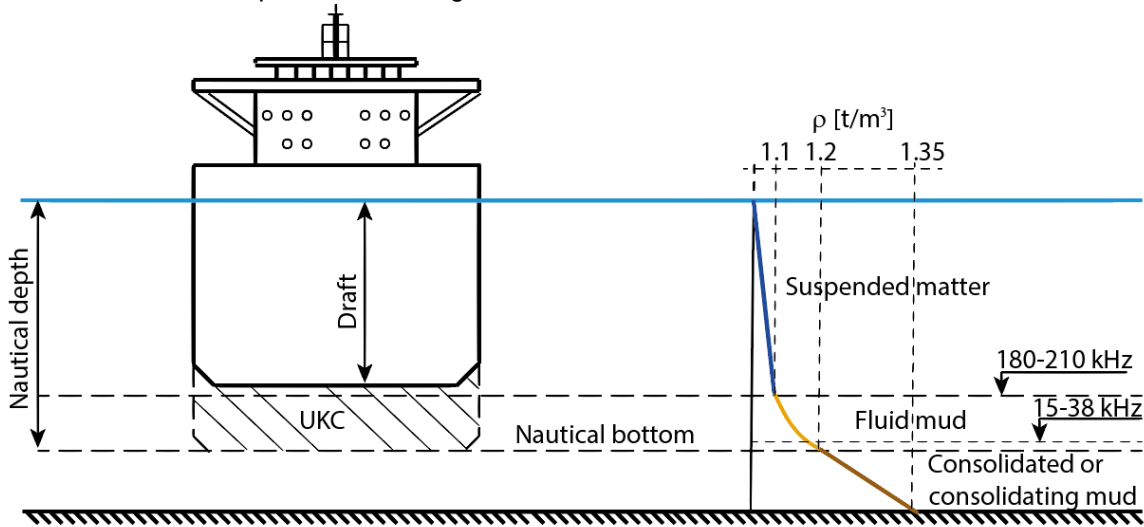
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In 1970th, it was recognized that sonar measurements are not reliable in areas with substantial mud layers and, therefore, are no longer normative. On the basis of full scale experiments in the Port of Rotterdam, in Bangkok and along the coast of Suriname, it was found that densities up to 1200 kg/m<sup>3</sup> had a tolerable influence on maneuverability. The “Nautical Depth” was defined accordingly. The illustration of this concept is shown in Figure 1.



**Figure 1: The nautical bottom concept, which was developed at the density limit of 1.2 t/m<sup>3</sup>. Adapted from from Nederlof, L. (1978).**

In 1980th, a series of full-scale experiments was conducted at the Port of Zeebrugge. The water-mud interface, that could be detected by the high-frequency (180-210 kHz) echo-sounder, was chosen as the reference for the UKC. The experiments were conducted with positive and negative UKC, that correspond to the level above or below the depth that was detected by high-frequency echo-sounder. It was concluded that fluid mud with a low density may lead to a modified sailing behavior, but does not give rise to dangerous situations. Together with outcomes of towing tank studies, the results of the full-scale experiments led to a change of the nautical bottom density criterion from 1150 to 1200 kg/m<sup>3</sup>, see Table 1.

| Port                 | country         | criterion    | value     | dimension         |
|----------------------|-----------------|--------------|-----------|-------------------|
| Rotterdam            | the Netherlands | density      | 1200      | kg/m <sup>3</sup> |
| Zeebrugge            | Belgium         | density      | 1151-1347 | kg/m <sup>3</sup> |
| Bordeaux             | France          | density      | 1200      | kg/m <sup>3</sup> |
| Nantes-Saint Nazaire | France          | density      | 1200      | kg/m <sup>3</sup> |
| Dunkirk              | France          | density      | 1200      | kg/m <sup>3</sup> |
| Avonmouth            | the UK          | density      | 1200      | kg/m <sup>3</sup> |
| Yangtze              | China           | density      | 1250      | kg/m <sup>3</sup> |
| Liang Yungang        | China           | density      | 1250-1300 | kg/m <sup>3</sup> |
| Yianjing Xingang     | China           | density      | 1200-1300 | kg/m <sup>3</sup> |
| Bangkok              | Thailand        | density      | 1200      | kg/m <sup>3</sup> |
| Paramaribo           | Suriname        | density      | 1230      | kg/m <sup>3</sup> |
| Emden                | Germany         | yield stress | 100       | Pa                |

**Table 1: Criteria for nautical bottom from McAnally, W. H. et al. (2007)**

Currently, the following definition for nautical bottom is used for navigation in muddy areas: “The nautical bottom is the level where physical characteristics of the bottom reach a critical limit beyond which contact with a ship’s keel causes either damage or unacceptable effects on controllability and maneuverability” (PIANC (2014)). Unlike other ports, the Port of Emden uses the yield stress as the criteria for the nautical bottom since 2005 (Wurpts, R. (2005)). In Emden, the adopted criteria above

which fluid mud is navigable is a yield point of 100 Pa. It is thought that this parameter is related to the specific dredging method or the slime properties in this port. It remains to be investigated how the dredging properties affect the composition of the mud, and hence its rheological properties

The overviews of full scale and scaled experiments and modelling for ships navigation in the channels with fluid mud layers can be found in Vantorre, M. (1994), Delefortrie, G (2008) and Delefortrie, G. & Vantorre, M. (2015). The present article provides an additional discussion on surveying methods that can be used for monitoring the fluid mud layers.

## 2. FULL SCALE EXPERIMENTS

The first reported full scale experiments were conducted in the Port of Rotterdam in 1975 (Nederlof, L. (1978) and Nederlof, L. (1979)). The 318t deadweight oil tanker SS Lepton (see Figure 2) was sailing within the Europort area at Hoek van Holland in and out the port. During the tests maneuverability data and the density depth profiles were recorded. The average mud layer thickness in the investigated area was about 1.15 m. The maneuvers were done at UKC of 6 % of the draft with respect to the depth indicated by the 210 kHz echo-sounder. Although the pilots experienced the entry as 'difficult', a comparison of the maneuvering behavior of the Lepton with that of other incoming tankers shows that in fact it was not more difficult than other large ships and even easier than other vessels. This conclusion was also supported by the measurement of the speed of the tanker, maximal percentage of available rudder and propulsion which were analyzed during the experiment.



**Figure 2: The 318t deadweight oil tanker SS Lepton was a subject of investigation for the full scale experiment at the Port of Rotterdam in 1974. Here, SS Lepton is filled with water enters the Port of Rotterdam. Observers on board carefully follow the sailing behavior of the ship.**

**The Lepton was 350 m long and 55 m wide, the draft was 20.90 m, the average throat clearance was 1.60 m, the average mud layer was about 1.15 m. The photo is taken from Nederlof, L. (1979).**

Other well-reported full scale experiments were conducted in Zeebrugge in 1986-1988. Seventeen full scale tests of three types were carried out with the trailing suction hopper dredger Vlaanderen XVIII (van Craenenbroeck, K. & Vantorre, M. (1991)). Short engine maneuvers (acceleration/deceleration tests), constant power maneuvers, yawing tests at zero speed by means of bow thrusters were conducted in the outer harbor of Zeebrugge. The maneuvers were performed

with keel clearances from -0.35 to +3.0 m with respect to the depth indicated by the 210 kHz echo-sounder. The rotation tests were conducted at a keel clearance from -0.3 to -0.4 m. During the trials, the presence of internal waves on water-mud interface was confirmed. The solitary stern internal waves were detected by the 210 kHz echo-sounder. An internal wave of about 2 m height was detected by surveyor vessels during the passage of a deep-drafted OBO carrier.

Two full scale trials were conducted in the Port of Delfzijl in 2013-2015. The first trial was conducted with the general cargo vessel CSL Rhine at positive UKC of 14% and larger with respect to mud-water interface that was detected by 210 kHz echo-sounder. The results showed that the maneuvering and propulsion behavior were influenced by the mud layer at UKC smaller than 18%. The second trial was carried out with the hopper dredger Geopotes 15. The tested UKC was between -5% and +17% draft to the depth detected by 210 kHz echo-sounder. During the test it was concluded that during the navigation with the UKC of +14% with respect to the mud-water interface caused less disturbance than to CSL Rhine at the same UKC. It was concluded that the maneuverability was much more favorable with fluid mud layers of 2.5 to 3.5 m thickness in combination with a negative UKC than with a positive UKC from +1% to +13%. At the UKC from +10% to 20% the ship-induced internal waves hindered the propeller and the rudder of the vessel at low viscosity mud layers. It was reported that the vessel's maneuvers were in line with simulation studies (Verwilligen, J. et al (2014) and Barth, R. et al. (2015)).

### 3. SCALED EXPERIMENTS

Scaled modeled tests were performed to get better understanding of ship's maneuvering in muddy environment. These test were coupled to mathematical maneuvering models to quantify the effect of the mud layers on the controllability of the ship. The scaled experiments with real mud can be problematic because of the time effects (e.g. settling, consolidation) of mud. Therefore, a dense viscous fluid is typically used to mimic the fluid mud in a two layer system. The physical properties of an artificial mud (density, viscosity) are chosen to be close to the ones of the fluid mud.

One of the first scaled tests, that were carried out to investigate the effect of fluid mud on maneuvers, were conducted with a 1:82.5 scale model of a tanker that was equipped with rudder and propeller, sailing above or in contact with a dense fluid layer (Sellmeijer, R. & van Oortmerssen, G. (1983)). A mixture of chlorinated paraffin and kerosene was used to simulate the fluid mud layer. Two density values,  $1140 \text{ kg/m}^3$  and  $1240 \text{ kg/m}^3$ , were chosen to mimic the real mud conditions at the Port of Rotterdam during the winter and summer periods, respectively. The tested dense fluid layer thickness, from 1.35 m to 3.85 m, was varied. Both positive and negative UKC with respect to the water-dense fluid interface were tested by changing the water level in the basin. Two types of experiments were carried out: free running tests were conducted to evaluate the total effect of the mud on the maneuvers of the vessel and the captive experiments were carried out to predict standard maneuvers by means of mathematical models, which describe the ship motion in a horizontal plane. The effects of mud on squat and trim of the tanker were analyzed. It was observed that the tanker becomes slower with the UKC of 3-5 % of the draft above the dense fluid. However, further reduction to negative values of UKC makes the tanker less slow in its maneuvers. Furthermore, the presence of dense fluid on the bottom tends to reduce the steady motion and to accelerate the dynamic motions. One important observation was the internal waves that occurred in the water-dense fluid interface when a ship is passing. The amplitude of these internal waves (see Figure 3) increases with the thickness of the dense fluid layer and with decreasing fluid density and affect the propeller efficiency as was observed during the free running trials.

A series of model scale tests were carried out in a wave flume with a tanker model of scales 1:100, 1:70 and 1:55 (Brossard, C. et al. (1991)). The model was equipped with sensors for measuring squat, trim and tractive force. The goal of the experiments was investigating the resistance and squat variations above an artificially composed mud layer. The tested mud layer had density gradients over the depth. Three type of mud was tested: with low, intermediate and high gradients. The layers

with different yield stresses were used in the study. The undulations on the water-mud interface had been observed in this study.



**Figure 3: Propagation pattern of internal waves of the water-dense fluid interface for viscosity 0.002 Pa s (left) and 0.03 Pa s (right). The photos are taken from Delefortrie, G. & Vantorre, M. (2015).**

The self-propelled tests were conducted with scale models of an LNG-tanker and a hopper dredger along a guiding rail above water-mud system with a dense fluid mud layer. Unstable rudder behavior and poor propulsive efficiency was observed if due to a combination of initial UKC, squat effects and internal waves, the ship's keel is in contact with both fluids (Vantorre, M. & Coen, I. (1988)). A series of captive test was conducted for different simulated maneuvers (Delefortrie, G. et al. (2005)). During the tests, longitudinal and lateral force components, vertical motion, rudder parameters and propeller parameters were measured. A mixture of chlorinated paraffin and petrol was used to mimic the mud. Mathematical maneuvering models were developed for fluid type of densities 1100-1250 kg/m<sup>3</sup> and of viscosities 0.03-0.46 Pa s, dense fluid layer thickness of 0.75, 1.5 and 3 m, for 1:80 and 1:75 scaled models sailing with UKC of -12 to +21 % relative to water- dense fluid interface and the speeds between 2 knots astern and 10 knots ahead.

#### 4. MONITORING METHODS

Traditionally, the reflections of acoustic signals are used to determine the positioning of water-bed interface. The emitted acoustic pulse propagates through the water column and reflects back from the bottom of the waterways. The distance from the acoustic source to the reflecting surface is proportional to the travel time of acoustic waves in the water column. In muddy navigational areas, different frequencies of the emitted signal are employed. Standard low frequencies (15-38 kHz) and high frequencies (180-210 kHz) signals are used to provide information about water-fluid mud interface (lutocline) and bed-fluid mud interfaces, respectively. The former typically exhibits a strong contrast. The latter is often inconsistent due to a weak density gradient within a fluid mud layer that plays an important role in the reflection of emitted acoustic signals (Kirby, R. et al. (1980)). Therefore, other measuring techniques have been proposed for the monitoring of the water-bed interface in muddy navigational areas. These techniques are typically based on the physics of the scattered and transmitted gamma-radiation, acoustic and optical backscatter, or through mechanical devices. One of the most accurate methods so far is based on scattered and transmitted gamma-radiation. This nuclear method is typically used to determine the density of the water column, including fluid mud layers. The instruments that are based on acoustic and optical backscatter typically measure the concentration of suspended particles in the water column. All the non-acoustical methods have several common drawbacks. Due to the nature of the profilers, the spatial resolution of these tools is limited to 1D vertical profiles (see Figure 4). Thus, the interpolation between the measurements to obtain a spatial map is generally done by combining these methods with acoustic sounding. Another important disadvantage of these methods is their intrusive nature of surveying. The measuring tools have to be in a direct contact with fluid mud layers in order to provide quantitative characterization.

Even though it has been recognized that the surveying methods that are based on rheological parameters are the most suited for nautical purposes, the in-situ measurement of these parameters is a challenging task. Two strategies can be found to determine these parameters. The first one is that samples are taken in-situ and analyzed in the laboratory. The second one is to use in-situ instrumentation. Both strategies are discussed below.

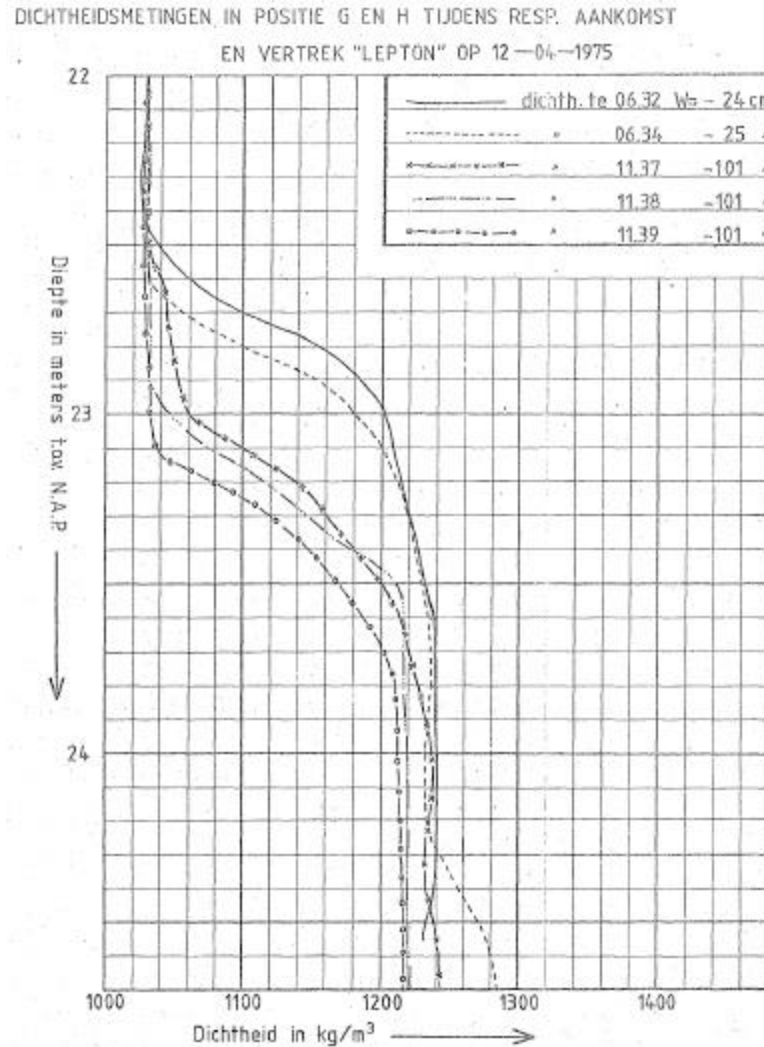
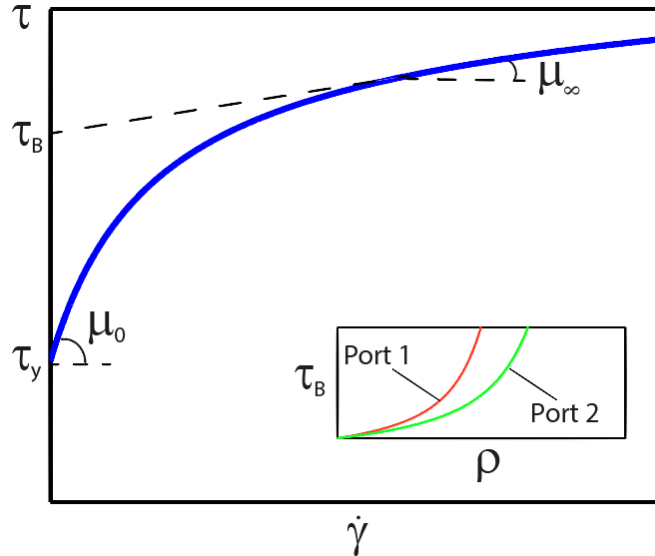


Figure 4: The temporal changes in density profiles during SS Lepton full scale experiment in 1975. The diagram is taken from Rijkswaterstaat (1977).

#### 4.1 Laboratory

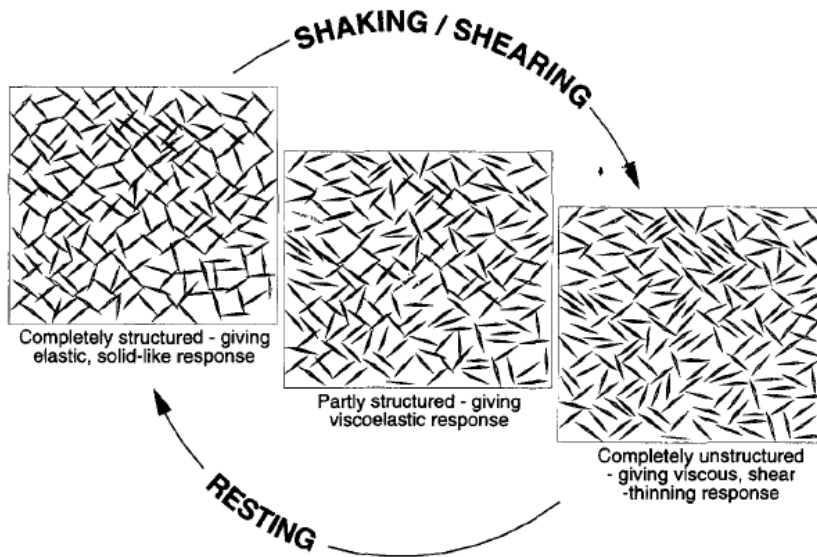
Rheological properties can be routinely determined in the laboratory, for instance by the vane-type tests or rotational rheometers. These laboratory methods measure the resistance of fluid mud samples to flow in response to applied shear forces. This can be done by controlling the shear rate,  $\dot{\gamma}$ , or shear stress,  $\tau$ , that gives the flow curves (see Figure 5) for different mud samples. Two mechanical behaviors of mud can be deduced from a traditional flow curve: elastic and viscous. The elastic behavior is conventionally observed at very low shear strains rates. As soon as the strength of the soil matrix weakens, mud starts to flow exhibiting viscous behavior. In this mechanical state, deformations correspond to the rate of deformation. The shear stress, at which this soil matrix start to deform (or to flow) is conventionally called the yield stress. Typically, the yield stress,  $\tau_y$ , and dynamic viscosity,  $\mu_\infty$ , can be obtained for different mud samples from measured flow curves. Two

additional parameters are required for reconstructing the complete flow curve: the Bingham stress,  $\tau_B$ , and the initial differential viscosity,  $\mu_0$ . As can be seen on Figure 5, a given density does not necessarily correspond to a unique yield stress. This implies that the relation between density and rheological parameters should be carefully studied in order to assess the best set of parameters required to characterize the nautical bottom.



**Figure 5: The sketch of the flow curve with rheological parameters.**

Due to the complexity of fluid mud, the shear stresses exhibit a non-linear relationship with the density,  $\rho$ . This can be explained by the thixotropic behavior (deformation, history and time dependence) that is illustrated in Figure 6. Therefore, sampling and measuring procedures, followed by data processing and interpretation of the measurements, have to be standardized by means of recognized practical protocols (Claeys, S. et al. (2005)).



**Figure 6: Breakdown of the thixotropic structure. Taken from Barnes, H. A. (1997).**



The three next sections concern in-situ instrumentation.

#### 4.2 Free falling cone penetrometers

The physics of a free falling cone penetrometer is based on recording the penetrometer's acceleration/deceleration for getting the information about the cone penetration resistance. Using a calibration procedure, the rheological properties of the site-specific mud can be related to this cone-end resistance. In this way, the water-mud column profiles can be mapped by using this type of instrument.

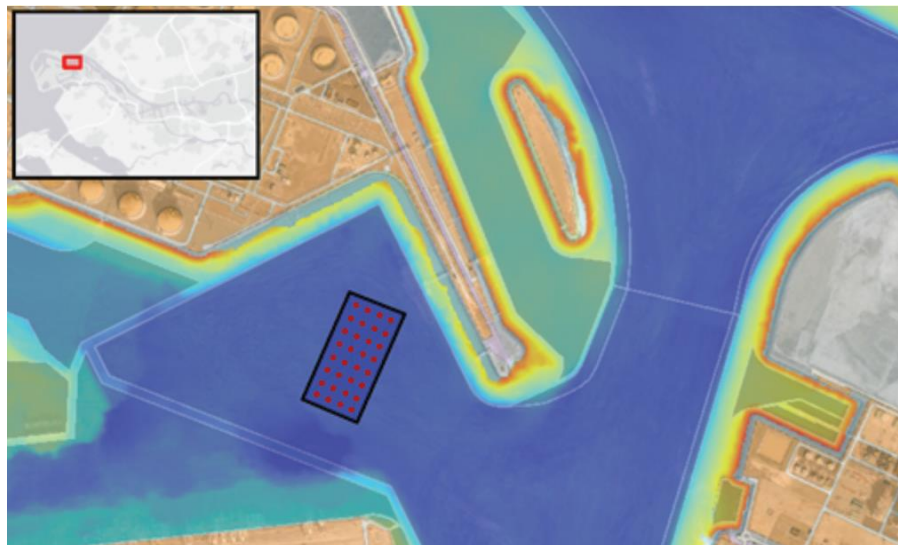


**Figure 7: Examples of rheology-based methods. From left to right: lab rheometer (Anton Paar), free falling cone (Graviprobe), tuning fork (Rheotune), towing object (Rheocable)**

One of the advantages of this type of equipment is that the vertical positioning of the penetrometer can be derived from the recordings of accelerometer. In general, an accelerometer is more accurate in indicating the depth than standard pressure sensors.

#### 4.3 Tuning fork profilers

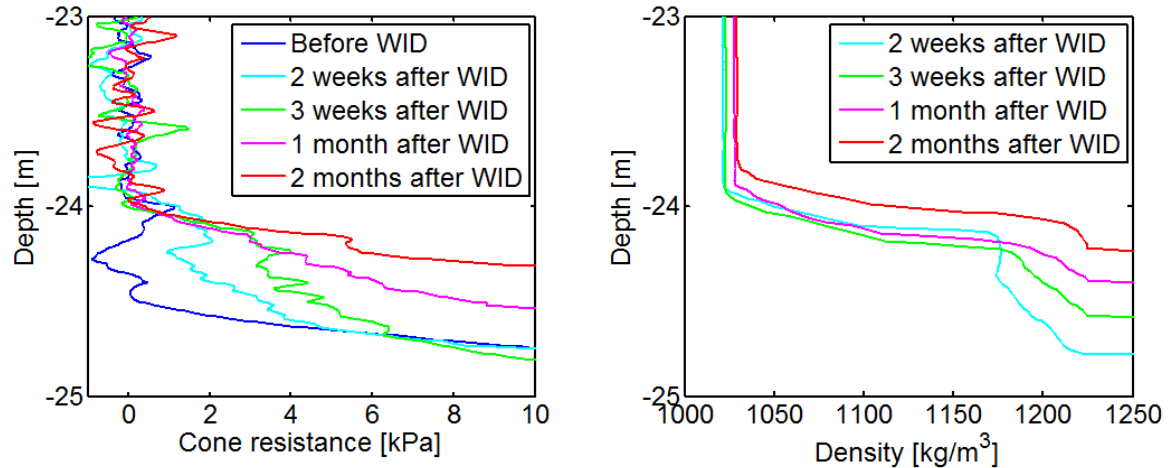
The tuning fork profilers are based on the recording of the amplitudes that are triggered by mechanical vibrations at different frequencies. These recordings can be used to get the information about the yield stress and viscosity of mud. For this purpose, an accurate calibration procedure, that requires laboratory rheological measurements, is necessary. The tuning fork profilers can provide sufficiently accurate rheological properties in the areas of low sediment concentrations.



**Figure 8: Location of the experiment in the 8th Petroleumhaven. The man-made pit has dimensions of 500 m × 200 m.**

#### 4.4 Towing objects

The depth level of the towed object is defined by the viscosity discontinuity between consolidated and fluid mud. The high viscous forces in the consolidated mud and heavy cable weights attached to the towed object assure the cable to position itself on the interface between fluid and consolidated mud unless a critical towing velocity is exceeded and the towed object starts floating in the water above the fluid mud layer. In the case of the Rheocable, the continuous measurements of the electrical resistivity value is used to verify whether the cable is on the seabed or floating above it. The depth level of the towed object is defined by a pressure sensor on the seabed measuring the hydrostatic pressure (Druyts, M. & Brabers, P. 2012).



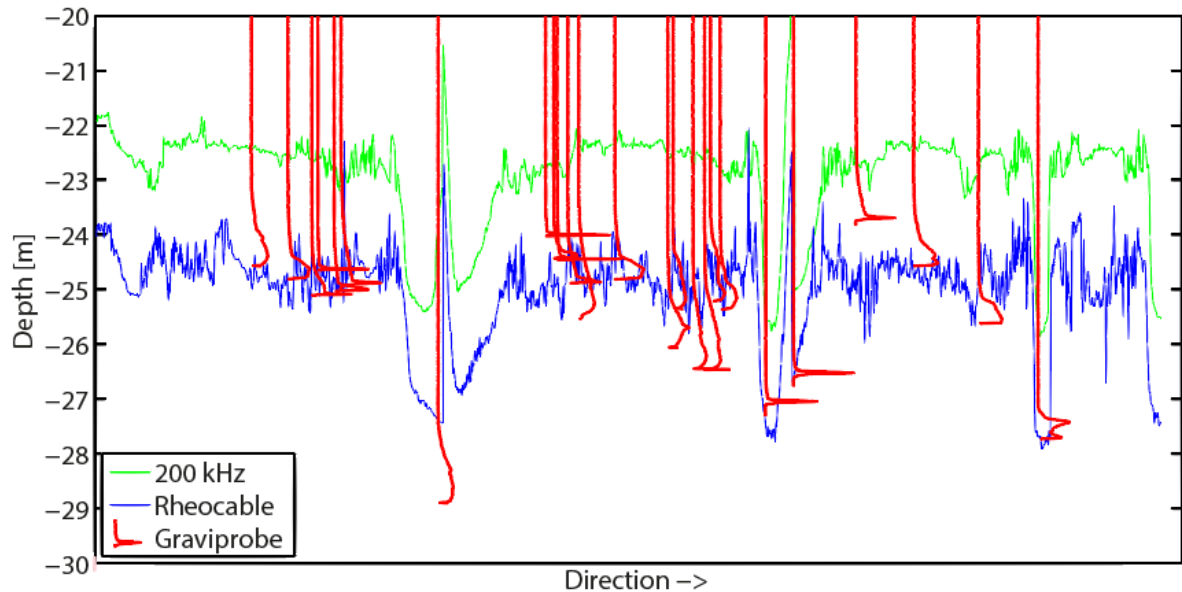
**Figure 9: Fluid mud development in time, that is measured by Graviprobe (left) and DensX (right).**

#### 4.5 Comparison of density- and rheology-based monitoring

In order to compare the density and rheology based monitoring, the water injection dredging method was employed in the 8th Petroleumhaven at the Port of Rotterdam (see Figure 8). The water injection dredging (WID) was used for liquefying the top layers of the sediment around a man-made pit in the river bed so that the mud would flow into the pit (500 m × 200 m). The pit collected the fluid mud layer up to 1.5 m thickness from the surrounded area. The Graviprobe and DensX was used to capture the development of the fluid mud layer in the pit over a period of 2 months. The results of the monitoring are presented in Figure 9.

The recordings of the Graviprobe are shown as the cone resistance measurements as function of depth. The dark blue profile represents the measurements in the pit conducted before mobilizing of fluid mud into the pit by water injection. The cyan, green, magenta and red profiles show the fluid mud strength development in the deepening after 2 weeks, 3 weeks, 1 month and 2 month after the water injection, respectively. The same colors are used to show the density profiles that were measured with DensX. From the measurements, it can be concluded that the density of fluid mud develops faster than its strength.

Figure 10 shows the comparison of the Rheocable and Graviprobe surveys which were conducted after the WID in the 8th Petroleumhaven. The results provide a good agreement regarding navigable depth that is given by the methods. The high frequency echo-sounding measurements (200kHz) are included for comparison.



**Figure 10: Correlation of the high frequency echo-sounding (200 kHz), Rheocable and Graviprobe measurements in the 8th Petroleumhaven.**

## 5. The way forward

The safe navigation requires a new reliable and universally accepted criteria for the definition of the nautical bottom. Until now, this criteria was related to the density of fluid mud layers. Some steps have already been taken toward the new definition, for example in the Port of Emden that considers the yield stress as the parameter for the nautical bottom.

Already several decades ago it was recognized the importance of improving the parameters used in the definition of the nautical bottom. At that time, in-situ rheological experiments were practically impossible. This forced the community to adopt an alternative parametrization, based on density. Over the years, there has been a whole new set of equipment put on the market meant to study the rheological properties of the fluid mud layer (e.g. Graviprobe, Rheotune, Rheocable). These instruments are currently tested in different ports, and it remains to be investigated if the parameters derived from the experimental results are compatible with one another. More advanced 3D acoustic methods are needed for mapping the fluid mud layers. Open questions are:

- 1) How to relate acoustic measurements to the rheological properties of fluid mud?
- 2) Can rheological point-measurements be used to calibrate acoustic mapping?

Measuring rheological parameters, and in particular yield stresses, require a well-thought and universally accepted protocol, as these parameters are strongly history-dependent and lead to thixotropic effects.

- 3) What would be an accepted protocol for measuring rheological parameters?

The measured in-situ rheological parameters have, for calibration purposes, to be compared to samples analyzed in the laboratory. Care should be taken during the sampling, storage and analysis of these samples. The composition of the mud samples (in terms of mineralogy, biological and

organic matter content) should be related to the rheological properties and the thixotropic behavior of mud.

4) How can mud composition be incorporated in the rheological parameters?

The mud properties (density, viscosity, yield stress, mud layer thickness) are time dependent because of consolidation processes in the fluid mud layer. Moreover, mud layers can be mobile. More knowledge is needed to understand the time dependence of the fluid mud layers.

5) What is the development of the mud layers over time and what is the link between density and rheological parameters?

The rheological parameters are to be incorporated in CFD models, to predict the forces acting on the ships, in accordance with the suggestions made by Delefortrie, G. & Vantorre, M. (2015).

6) How to successfully implement the complex rheological behavior of fluid mud in CFD models?

After answering the questions given above, it is necessary to engage all the key stakeholders into the discussions on a global acceptance of new criteria for the nautical bottom.

7) How to obtain and promote an international implementation of the new criteria related to the nautical bottom definition?

All these points are currently under investigation in different research groups world-wide.

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