Safe Navigation in Fluid Mud - Surveying Criteria to Assess Nautical Depth

Norbert Greiser

Key words: Nautical Depth, Nautical Bottom, Fluid Mud, Bathymetric Survey, Density, Shear Thinning

SUMMARY

The concept of nautical depth means to let vessels sail through fluid mud that obeys accepted criteria for a safe maneuvering regardless higher density and viscosity values compared to water. Whereas density will be unaffected by a ship's movement, the viscosity of fluid mud does not stay at the same level when exposed to shear stress or pressure so that even (fluid) mud layers represented by density interfaces of ≥ 1.20 g/cm^3 may become navigable by shear thinning. The presence of fluid mud may cause complex sediment density and viscosity stratifications getting unclear transition interfaces to the consolidated nautical bottom and by fathometer surveys alone it is difficult to decide which frequency will give the best estimation of the nautical depth. Rheological investigations on fluid mud samples from a broad range of European harbors and the U.S. Atchafalaya, Calcasieu, and Gulfport navigation channels have shown that in general fluid mud will become navigable if it is exposed to shear stress. Field tests in Husum (Germany) and other European dredging locations have proven that conditioning of fluid mud to safe density and viscosity levels can be successfully done also in-situ and accompanied by a surveying strategy to generate reliable nautical depth navigation charts. Examples are gives in this presentation.

1. INTRODUCTION

The concept of nautical depth means to let vessels sail through mixtures of water and suspended matter that obey accepted criteria for a safe maneuvering regardless higher density and viscosity values compared to water. Whereas density may be unaffected by a ship's movement, the viscosity of fluid mud does not stay at the same level when exposed to shear stress or pressure. For all muds the measured yield stress increases with higher densities (Figure 1). This is because moving higher mass volumes the same stretch forward within the same time (measured as shear rate), requires stronger thrust forces (measured as shear stress).

But for nautical applications the most important issue is that all types of fluid mud can be fluidized to the same minimum viscosity level, and with lower density and pre-treatment by stirring, less shear stress is needed to achieve this (Figure 2). The most important message from such shear thinning results is that even (fluid) mud layers represented by density interfaces of ≥ 1.20 g/cm^3 will become navigable by active nautical depth (AND) dredging measures.

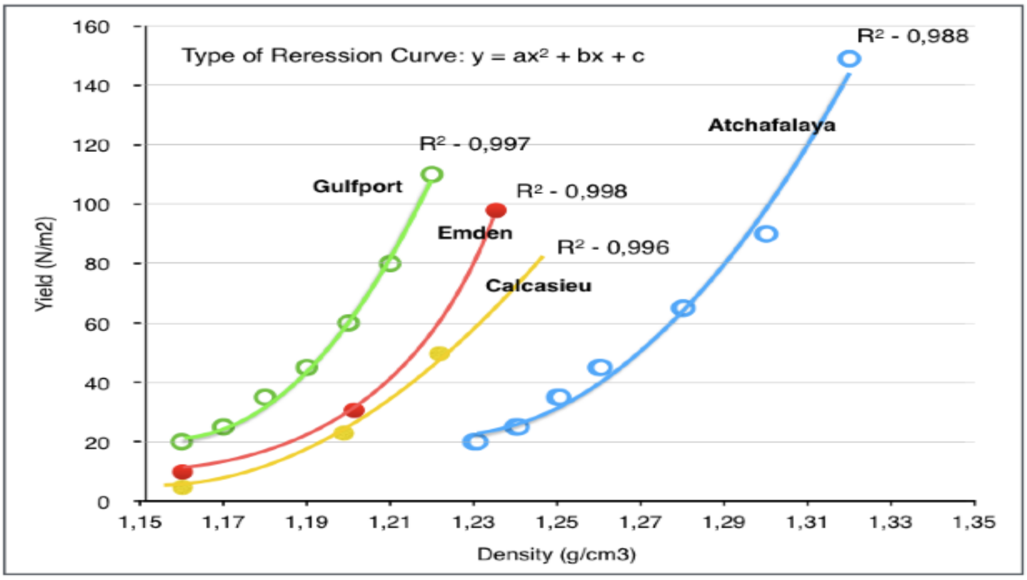

Figure 1: Increasing yield stress with higher density for different kinds of (fluid) mud

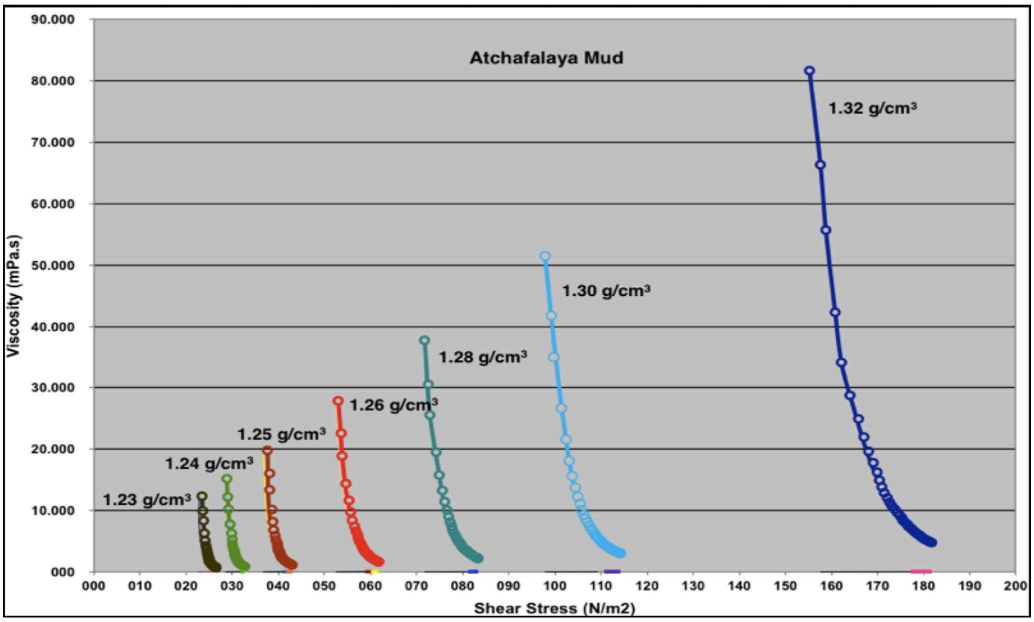

Figure 2: Decrease in viscosity with increasing shear stress (Atchafalaya Mud, different densities)

Yield stress values and and corresponding information from shear thinning curves (Figure 3) can be used to select, adopt and improve the dredging (mud fluidization/conditioning) methods to the individual rheological properties of (fluid) mud at dredging sites. In case of AND the target will be mud shear thinning to a navigable level. Which part of the sediment layer(s) are obeying the physical criteria of navigability, laterally and vertically, and at which depth the nautical bottom will be reached must finally be assessed by surveys in the field. Unfortunately by echosounding only clear shifts in sediment consistency can be detected as significant boundary layers whereas smooth gradients in sediment density and consistency does not give a clear response to the sound waves and in such cases no reliable correlation can be made between the intensity of the ultrasound echoes that are received and the density or viscosity of the sediments.

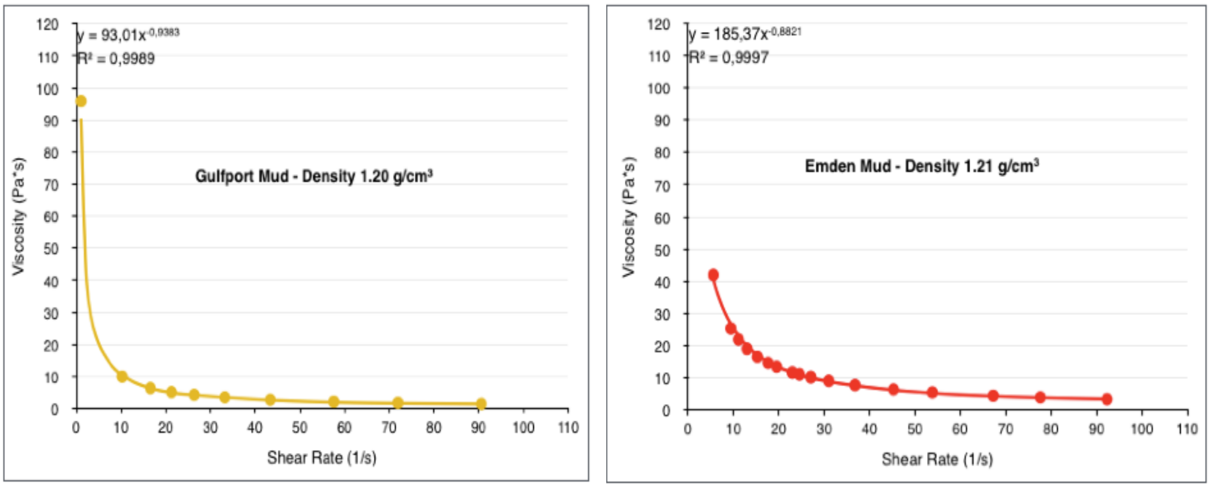

Figure 3: Decrease in mud viscosity with increasing shear rate by stirring (Gulfport and Emden mud samples)

At locations where the nautical bottom is only covered by fluid mud with densities from 1.12 g/cm^3 - 1.18 g/cm^3, common dual frequency echosounding is suitable to determine the lateral distribution and thickness of fluid mud, whereas high frequencies (> 100 kc) respond to the water/fluid mud density interface and low frequencies (eg. 10 kc, 15 kc or 33 kc) to the density shift of the consolidated bottom sediment layer which may represent the limit of nautical depth if the fluid mud on top is accepted to be navigable.

In Emden for instance the thickness of navigable fluid mud is about 2 m – 4 m and its volume remained constant since 1990 due to the beginning of regular AND dredging of the consolidated bottom sediment layer (Figure 4) although the harbor basin is open to the extremely turbid tidal River Ems.

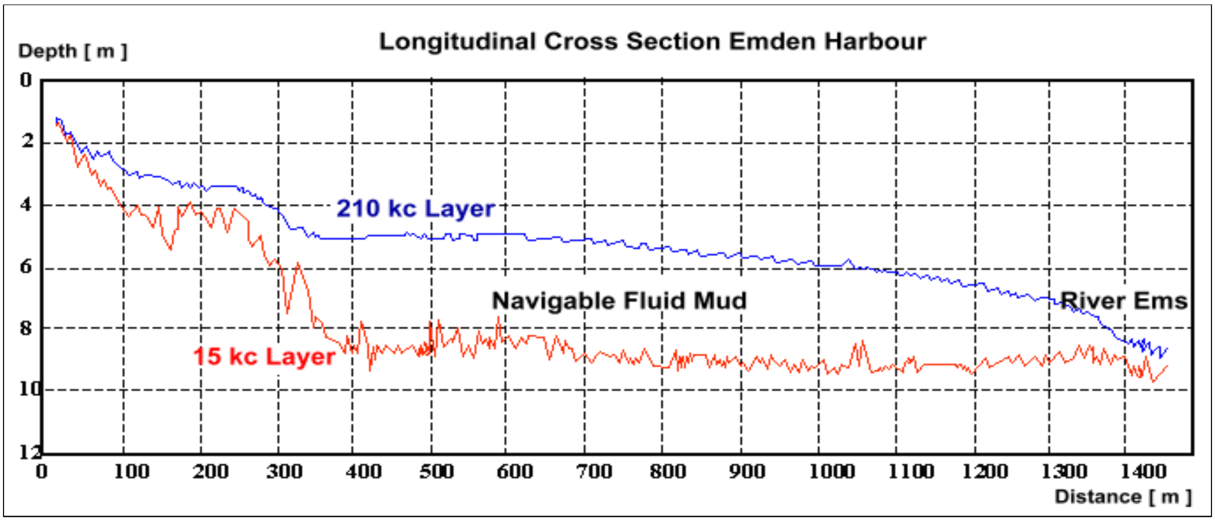

Figure 4: Dual frequency longitudinal fathometer profile from the Aussenhafen basin, Port of Emden

If the particle content and vertical extension of the fluid mud layer exceeds a certain degree, even low echosounding frequencies may not reach the bottom layer due to strong scattering and absorption of the ultrasound waves. In such cases “jumping” echoes can be seen or even none from the bottom sediment layer (Figure 5). In such cases vertical density profiling probes or parametric (high energy emitting) echosounders are recommended to detect the (not navigable) bottom layer. Which measuring strategy and tools will provide satisfactory results at nautical depth surveys and which parameters will be inevitable as navigabiliy assessment criteria are presented in the next chapters.

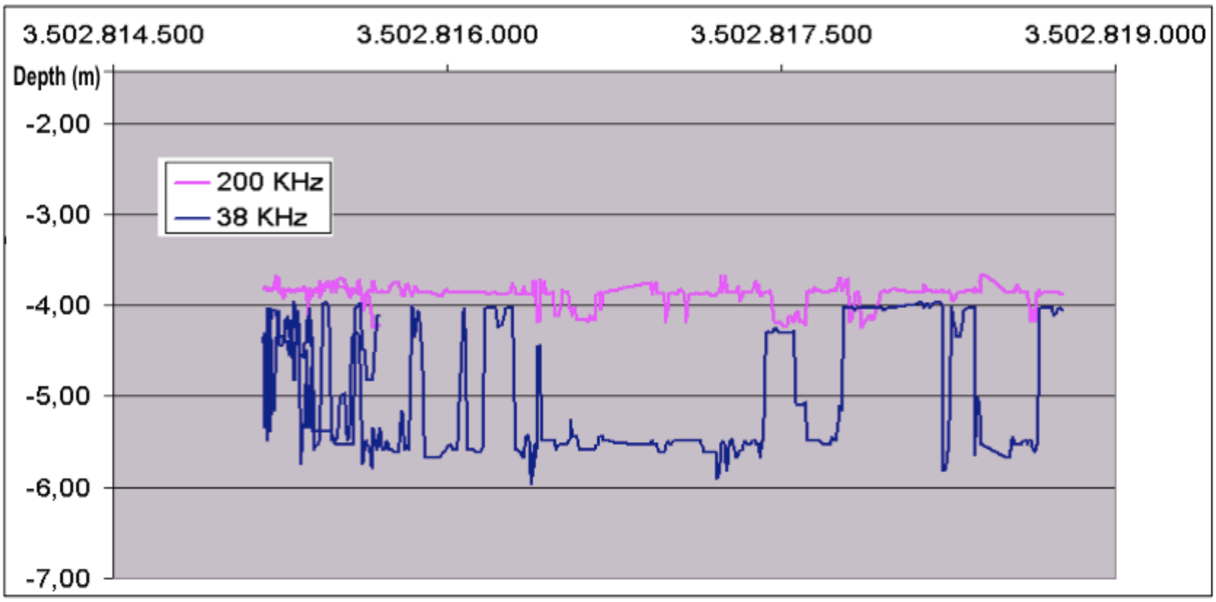

Figure 5: Low-frequency jumps on a longitudinal fathometer profile in the Port of Husum.. Some of them were reduced after the passage of vessel ILKA indicating the “shoal” to be navigable fluid

2. IMPORTANCE OF DENSITY AND VISCOSITY FOR MANEUVERING

Acceptable physical criteria for safe navigation depend on the kind of maneuvering. Sailing straight through fluid mud will in general cause less resistance compared to berthing, cast off and turning maneuvers. At a linear passage in the first degree the bow of a ship has to set the fluid mud into motion, wheres the following parts of the ship’s hull have (only) to deal with the resistance from decreased mud viscosity. In the contrary at cast off, mooring and turning maneuvers much bigger fluid mud volumes have to be pushed aside and accelerated by the broad side of the vessel’s hull so that in this case the density impact on the ship’s movement will raise in proportion to the frictional resistance by viscosity.

Proven by more than 20 years of practical experience in the Port of Emden all maneuvers will be safe until the yield stress of the fluidized mud does not exceed 100 Pa. The additional propulsion power needed to accelerate a vessel and keep the speed while sailing through fluid mud, depends on the submerged portion (and shape) of the vessel’s hull, the type of propeller and the shear thinning behavior of the fluid mud. In case of keeping a straight course through fluid mud, its higher density does not increase the braking force on the vessel's movement very much. For that part of the hull (the bow) which interacts with positive pressure on fluid mud at densities from 1.16 g/cm^3 to 1.20 g/cm^3 it is only a plus 13% to 17% factor. Taking into account that this amount of dynamic pressure only contributes to about 10% of the total resistance (about 90% is related to friction), moving straight through fluid mud gives only an additional 1% - 2% impediment by density.

Exemplary calculations on the dynamic shape resistance F_w can be made with the following formula, assumptions and data about the type and shape of a vessel:

$F_w = c_w \, ½ \times \boldsymbol{p} \times V^2 \text{ x } A_s$

with e.g.

- A_s is adopted to be elliptical (s.picture on the right)
- Ship speed V shall be 15 kt (7.72 m/s)
- The streamline shape coefficient c_w is assumed to be 0.06
- Density p salt water 1025 kg/m^3
- Vessel dimensions: Length 90 m, Cross section 12 m, Draft 4 m

In this case the results for salt water and fluid mud with densities of e.g. 1160 kg/m^3 and 1200 kg/m^3 will be 1,832.7 N/m^2, 2,074.0 N/m^2, 2,145.5 N/m^2 respectively. At a sailing speed of 15 kt this causes - as already mentioned - an additional increase of shape resistance by density of 13.2% and 17.1 %.

But the shape resistance formula also shows that this increase can easily be compensated by a minimal reduction of sailing speed: A deceleration by 1 kt nearly equals the additional resistance of even 1.20 g/cm^3 fluid mud. Also corresponding differences in density will not have a measurable impact on the thrust of the ship's propeller. The dominating negative forces on the vessel's speed, generated by a propeller, are (I) undertow at the stern and (II) turbulent detachment of currents at the propeller's blade tips and hub.

Additionally the fluid mud viscosity will not have measurable effects on the thrust efficiency of the propulsion system because the shear forces caused by the high angular velocity of the propeller blades are strong enough to cause fluid mud shear thinning so that fluid mud will be moved by the propeller at a very low viscosity level.

On the whole, shear thinning is the most important rheological property to assess the maneuvering impediment by fluid mud viscosity. Shear thinning occurs with any type of (fluid) mud as already indicated by Figure 3 and therefor the frictional resistance of a moving vessel varies with the dynamic viscosity of the fluid mud.

Mathematically exact the viscous pressure resistance at the vessel's hull will be the integral of the velocity gradients at the fluid mud-hull-interface:

$T = n\ {}^{dv}/_{dy\ (y=0)}$ which in total for the submerged area is the frictional resistance:

$T = \int n\ {}^{dv}/_{dy\ (y=0)}$

Because a calculation in this way is very complex, alternatively the following equation is used to determine the frictional resistance R_F:

$R_F = c_F\ \frac{1}{2} \times p \times V^2 \text{ x } A_s$

whereas c_F is the drag coefficient according to ITTC (International Towing Tank Conference) which refers to the viscosity of the medium, the submersed part of the vessel's hull, and the flow rate at the hull-medium interface.

So regarding fluid mud viscosity at least two aspects have to be taken into account: (I) The shear thinning force needed to achieve a navigable viscosity level, and (II) the frictional resistance that occurs at this particular level. From more than 20 years of experience in the Port of Emden even fluid mud at a viscosity of 2 Pa*s is clearly navigable. At this level fluid mud has the same consistency as for instance ketchup, mayonnaise or salad dressing (Figure 6).

Figure 6: Consistency of fluid mud, ketchup/mayonnaise, and salad dressings at the 2 Pa*s level

The additional shear force to reach this level by shear thinning will be 120 - 338 N/m^2 for e.g. Atchafalaya, Calcasieu, Gulfport, and Emden fluid mud. Referring to the calculation for the dynamic hull shape resistance above, shear thinning may cause an increase of 6.6 % - 18 %, but because the dynamic shape resistance only accounts for 10% of the total resistance, this will only be an additional 0.7 - 2 % impediment factor at a sailing speed of 15 kt .

The contribution of viscosity to the calculation of the total frictional resistance according to ITTC is represented by the drag coefficient c_F which is related to the viscosity dependent Reynolds Number R_n:

$R_n = V \text{ x } L_{WL} \text{ x } 1/\nu$

whereas ν is the kinematic viscosity, V the sailing speed and L_{WL} the length of the vessel.

The kinematic viscosity is the quotient of the dynamic viscosity by density. For sea water at 68° F the corresponding value is 0.984 x 10^{-6} m^2 /s. Taking the exemplary vessel dimensions (L_{WL} = 90 m) and sailing speed (15 kt/7.72 m/s) from above the value of the Reynolds Number for sailing in sea water will be 7.06 x 10^8 and the corresponding drag coefficient 1.6 x 10^3 . Sailing with the same vessel and speed through e.g. Atchafalaya fluid mud with a density of 1.30 g/cm^3 and 2 Pa*s viscosity, the Reynolds Number will be 4.52 x 10^5 and the related drag coefficient 5.6 x 10^3. With this drag coefficient the frictional resistance R_F for sailing through Atchafalaya fluid mud instead of sea water will be 4.4 times higher.

This higher resistance can for instance be compensated by halving the sailing speed from 15 kt to 7 kt. If for instance the vessel plunges in the fluid mud with only 50% of its draft the compensatory speed reduction will be 6 kt, for 25% draft 5 kt, and with just bottom (keel) contact 3 kt respectively.

Common passive nautical depth concepts often take the 1200 kg/m^3 density criterion for assessing the nautical bottom. To our rheological investigations on fluid mud samples this density value coincides very well with a (fluid) mud consistency shown in Figure 7. So the above calculations on the density and viscosity related resistance forces - dynamic shape resistance $F_{W,}$ and frictional resistance R_F - confirm that this type of bottom material usually represents a safe limit of navigable/nautical depth.

Fluid mud layers on top, delineated by high frequency fathometers, almost have much lower densities in the range of 1120 kg/m^3 to 1160 kg/m^3 and once moved, a tenfold lower viscosity with a significant reduction of the frictional resistance compared to the 1200 kg/m^3 nautical bottom. With 100% draft the frictional resistance will be 2.5 fold higher compared to sea water. At 50 % draft the factor is 1.9, at 25% draft 1.6 and with bottom (keel) contact to the fluid mud layer just 1.3.

A tugboat with about 50 t (495,000 N) bollard pull will be able to move even much bigger vessels as that one taken for the calculations above easily through such layers. The frictional resistance R_F for the reference vessel at 100% draft in 1140 kg/m^3 fluid mud will be 120,000 N. So if the above mentioned density and viscosity related parameters and values calculated thereof are accepted to determine the navigability of fluid mud, the task of nautical depth surveying is to assess this in the field.

3. ASSESSMENT OF NAUTICAL DEPTH IN THE FIELD

At most fluid mud dredging sites the extension of those layer can be reliably determined with common dual frequency fathometers like it is shown in Figure 4. The slopes of the digitzed water/fluid mud boundary layers indicate the viscous cohesion of the fluid mud material: The steeper the slope, the higher the yield strength - but navigable fluid mud will never show steep trenches and humps like consolidated mud.

As far as the dual frequency chart pattern does not change significantly it can be assumed, that the fluid mud layer´s density and viscosity stays in the same range. So only a few vertical density profiles must be taken for a reliable proof. In Emden such profiles look like the examples shown in Figure 7.

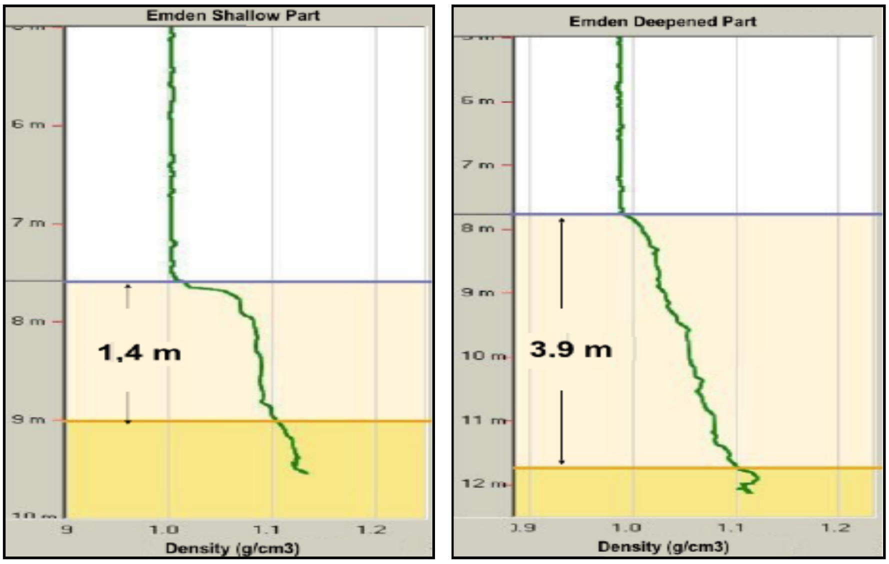

Figure 7: Fluid mud density profiles from the Emden Aussenhafen (shallow and deepened part s. Fig. 4)

Because of the regular AND dredging method (mud conditioning) in Emden the transition in density towards the bottom mud is smooth and the top layer of this mud is also navigable. As shown by our investigations, at any other fluid mud sites such pattern of density profiles is typical. Figure 8 gives corresponding examples from the U.S. Gulfport navigation channel and the Atchafalaya Bar Channel. For both the Mississippi is supposed as the source of the fluid mud generating suspended particles.

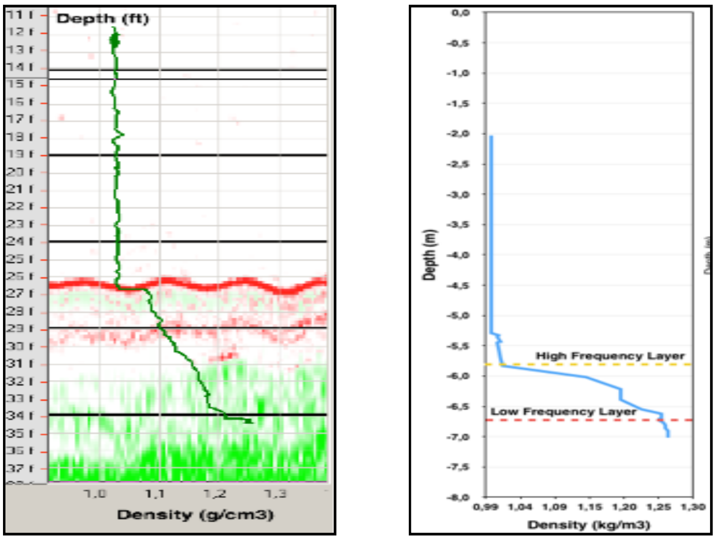

Figure 8: Density profiles from the U.S. Gulfport Navigation Channel and Atchafalaya Bar Channel

Navigability of such low density fluid mud layers is widely accepted but the rheological properties should be investigated on some samples anyway. If parts of the consolidated bottom mud or mud in general is intended to become navigable by AND dredging measures, the generated significantly denser fluid mud layers may not be detectable by common dual frequency echosounding but, in all cases investigated, with the parametric echosounder *SES 2000* (*Innomar GmbH*).

The latest positive example has been the Port of Husum (Germany). It is a non-fluid mud port but in most parts covered with thick layers of mud (Figure 9). As shown by Figure 5 mud fluidization regularly occurs by passing vessels so that this should be also possible with in situ conditioning dredging methods. The picture on the right (Figure 9) shows the bed leveller frame that has been used for a corresponding dredging test.

Figure 9: View at the mud shoals in the Port of Husum at low tide / Bed leveller used for mud conditioning

Figure 10 shows the longitudinal parametric fathometer profile through the test area after the bed leveller operation. The conditioned area can clearly be distinguished from the unaffected parts of the harbor bottom mud east and west of it where the sediment surface is uneven, bumpy and much stronger stratified. The shearing of these layers by the bed leveler has created a viscous (pasty) fluid with a smoothed surface which can be seen in the centre of the fathometer chart below.

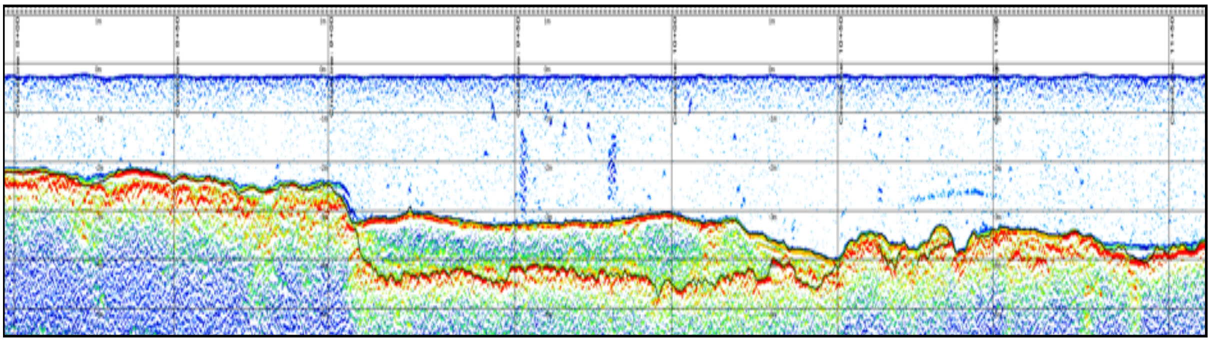

Figure 10: Longitudinal *SES 2000* fathometer profile that covers the bed leveller operation area (central part of the profile) and the untreated bottom sediments west and east of it

With the proof of acceptable density values in the range of 1.20 g/cm^3, marked with a red line in Figure 11, the fluidized mud is stated to be navigable. Corresponding post surveys showed that this situation will last over some months and can be maintained with comparatively simple dredging methods.

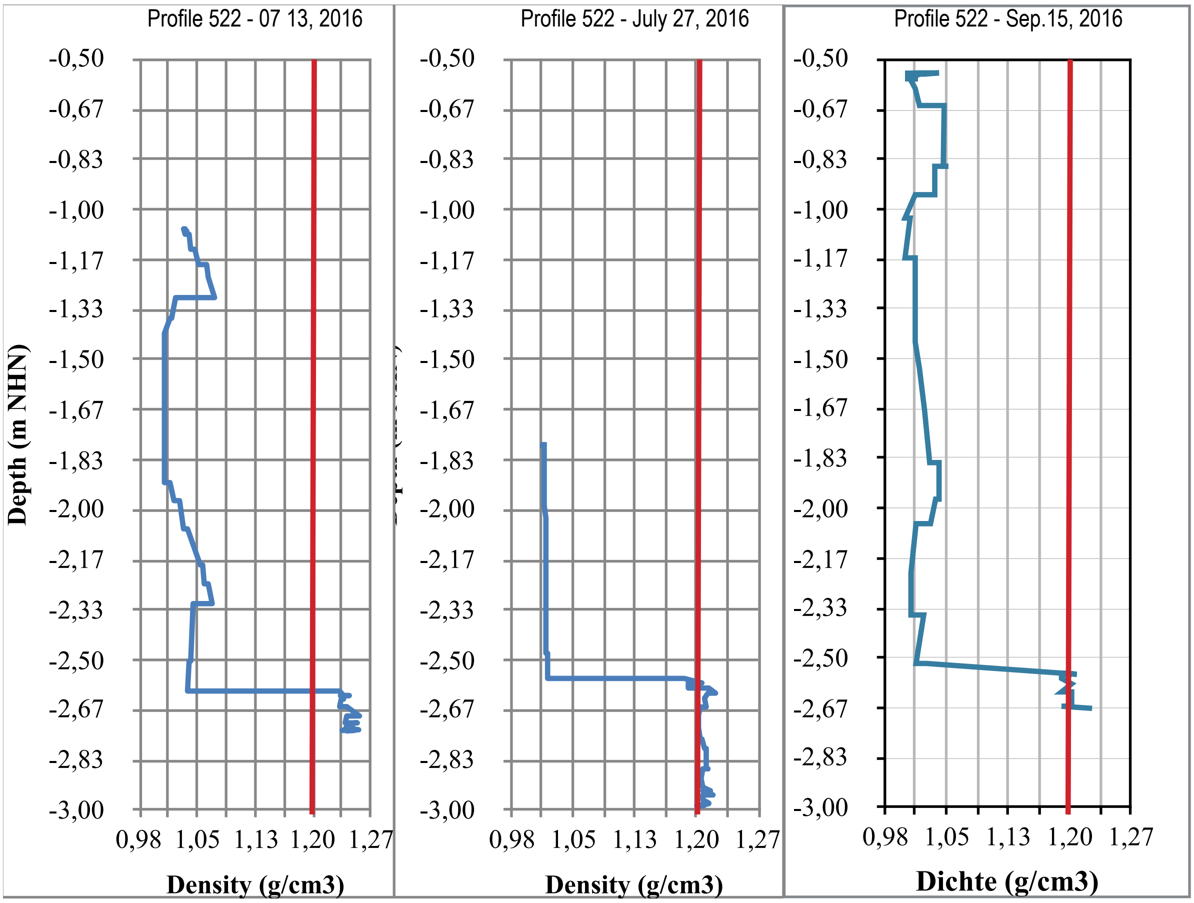

Figure 11: Density profiles before (July, 13.) and after mud conditioning with the bed leveller

Furthermore operation control can be improved markedly by a density monitoring at the bed leveller frame or in the suction tube if a hopper or cutter dredger is used to perform the AND job. In Husum both options were tested. Figure 12 shows how the special designed density probes were mounted and Figure 13 exemplary measuring results from the bed leveller operation.

Figure 12: Density probes mounted on the bed leveller frame and at the suction pipe of the cutter dregder

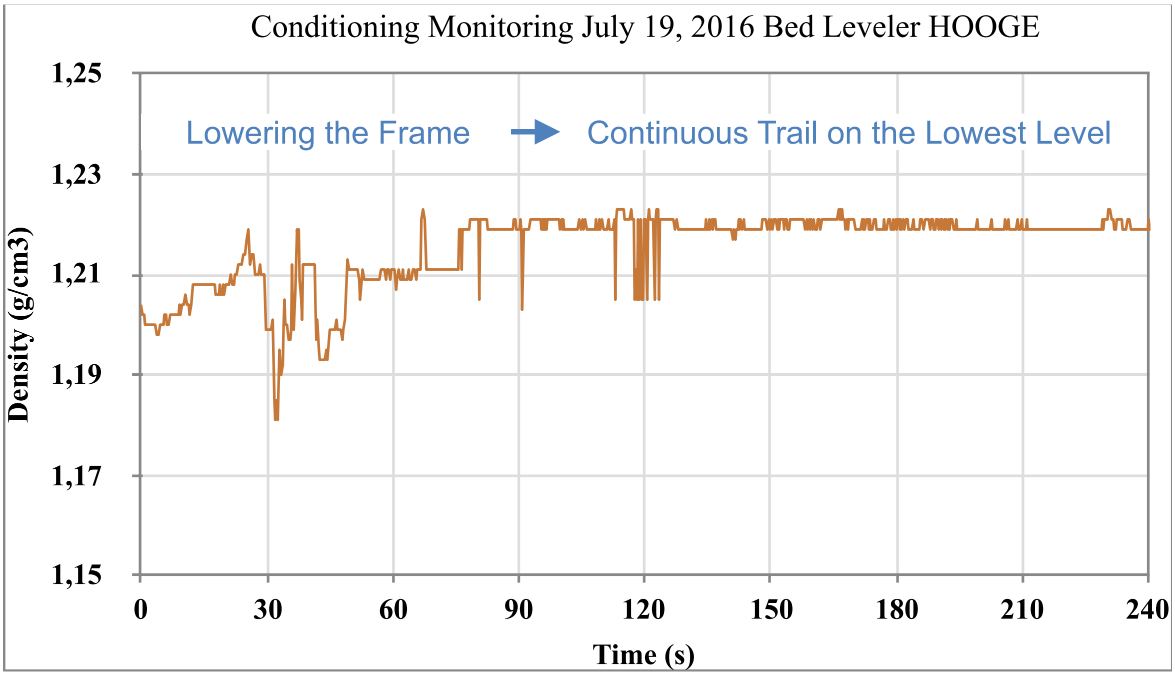

Figure 13: Measured density at the bed leveller frame

The density values during the bed leveller operation indicate a mud homogenization to an average density of 1.21 - 1.22 g/cm^3. The high weight, the inclined cutting edges and the slow trailing speed kept the frame continuously deep inside the mud layer. A comparative trailing test in fluidized and unprocessed mud showed that in the latter case much higher engine power and sailing speed is needed to pull the frame: With the first contact the frame behaved like an anchor whereas after its transition into the already fluidized layer it moved smoothly through the mud, thus hanging almost vertically on the steel cable. Operating straight inside the layer the mud is diluted only slightly with water. If the frame is pulled up, a much stronger dilution with water is clearly visible by the lower and more variable density values (see data record above).

This also means that even with a bed leveler fluid mud with different target densities below or higher than 1,20 g/cm^3 can be produced - if the dredging process is continuously monitored in-situ with a density probe and operated in relation to the recorded results. Suitable surveying tools to assess the navigability of fluid mud and the nautical depth in space and time are available on the market, but they should be tested for their effectiveness and reliability at any particular dredging site. A comprehensive information about the basic nautical depth related issues is given in the paper cited below.

4. REFERENCES

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CONTACTS

Dr. Norbert Greiser
Consultants Sell-Greiser GmbH & Co. KG
Zum Nordkai 16 -EGZ
26725 Emden
Germany
Tel. +49 4921 4509 543
Fax +49 4921 8737 249
Email: norbert.greiser@sell-greiser-consultants.de
Web site: www.sell-greiser-consultants.de