Project Nautical Depth
New Approaches in safe berthing and sailing through fluid mud at Hamburg-Port

Ohle, N.; Schmekel, U.; Bottner, C.; Shevchuk, I.; Abdel-Maksoud, M.; Kirichek, A.

Publication date
2024

Document Version
Final published version

Published in
Proceedings of the 35th PIANC World Congress 2024

Citation (APA)
Ohle, N., Schmekel, U., Bottner, C., Shevchuk, I., Abdel-Maksoud, M., & Kirichek, A. (2024). Project Nautical Depth: New Approaches in safe berthing and sailing through fluid mud at Hamburg-Port. In J. S. Schoonees (Ed.), *Proceedings of the 35th PIANC World Congress 2024* (pp. 258-264). PIANC.

35th PIANC World Congress, 29 April – 03 May 2024, Cape Town, South Africa
Paper Title: Project Nautical Depth: New Approaches in safe berthing and sailing through fluid mud at Hamburg-Port
Authors Names: Ohle N., Schmekel U., Böttner C., Shevchuk I., Abdel-Maksoud M., Kirichek A.

Project Nautical Depth: New Approaches in safe berthing and sailing through fluid mud at Hamburg-Port

Ohle N.[1], Schmekel U.[1], Böttner C.[2], Shevchuk I.[3], Abdel-Maksoud M.[3], Kirichek A.[4]
1 Hamburg Port Authority, Hydro Services, Hamburg, Germany
2 Federal Waterways Engineering and Research Institute, Hamburg, Germany
3 TU Hamburg, Institute for Fluid Dynamics and Ship Theory, Hamburg, Germany
4 TU Delft, Civil Engineering & Geosciences, Delft, The Netherlands

Abstract: For future strategies in water depth maintenance in the Port of Hamburg, determining the navigability limit (i.e., the safe nautical depth) is of major importance. For this purpose, the project Nautical Depth was set up at the Hamburg Port Authority. The aim of the project is to measure a safe nautical depth under various boundary conditions and to identify limits for a safe passage in port areas with fluid mud. Among other things, the project is conducted in close collaboration with the Port of Antwerp Bruges, the Port of Rotterdam, and TU Delft within the research platform MUDNET (www.tudelft.nl/mudnet).

To gain the necessary acceptance for a reassessment of the nautical depth, it is important to determine the rheological properties of the sediment in-situ. Several existing survey devices for monitoring nautical relevant rheological sediment properties have been tested. However, these devices cannot be used for spatial determination of rheological properties as they only provide cross-sectional measurements and depth profiles. Therefore, new evaluation algorithms were developed to correlate echo sounding data with in-situ rheological properties to ensure spatial coverage of a safe nautical depth.

As a first step, hydrographic surveys and sampling campaigns were carried out to provide system knowledge of the water column and the riverbed. Basic scientific research on the rheological behaviour of the fluid mud was also carried out. In a second step, the safe conditions for adapting the fluid mud layers at the berths for the nautical bottom concept were investigated and new nautical depth approaches were introduced at different locations in the Port of Hamburg. The next step was to analyse the effect of the fluid mud on the manoeuvrability of the ships. To this end, existing Computational Fluid Dynamics (CFD) models were extended to determine the non-linear effects and forces of non-Newton fluids on ship hull, rudder, and propeller efficiency. The results of the CFD model have been and are being validated with hydraulic model tests (scale 1:60) and in-situ measurements in the Port of Hamburg. In a final step, the results of the CFD model will be used to adapt the software of existing ship handling simulators. These simulations will be used to define the safe boundary conditions and limits for a new nautical depth for vessels to navigate through the fluid mud.

Keywords: nautical bottom, port maintenance, sediment, rheology, CFD

Introduction

The main aim of the project Nautical Depth of the Hamburg Port Authority (HPA) is to define and use a safe nautical depth under various boundary conditions. The criteria of the new nautical bottom shall insure a safe passage of vessels and the approach shall (re-)define the under-keel clearance (UCK) on a basis where the yield stress of fine-grained sediments (mud) and the density of it plays a major rule [1]. The application of this navigable bottom approach may reduce operational and maintenance costs, particularly in areas with significant layers of fluid mud. Optimised management of fine-grained sediments in this approach therefore requires knowledge of the sediments' rheological and bio-geo-chemical properties [2].

Organic matter interacts with the charged sediment mineral surfaces and thereby influences the sediment properties relevant for port navigability, i.e., rheological characteristics and settling and consolidation behaviour. Beyond the rheological characteristics it is therefore important to analyse the bio-geo-chemical parameters and to understand the organic matter dynamics, including organic matter stability and degradability.

The HPA project Nautical Depth therefore also aims to gather understanding of fundamental processes of sediment dynamics regarding, amongst others, rheology, hindered settling, consolidation, gravity currents, and organic matter stability, to explore the feasibility of the navigable bottom approach and develop sustainable sediment management strategies for port accessibility.

The main purpose of the paper is to introduce in the main objectives of project, to summarise key background information and to give and short overview of results of several research projects financed and/or accompanied by HPA.

35th PIANC World Congress, 29 April – 03 May 2024, Cape Town, South Africa
Paper Title: Project Nautical Depth: New Approaches in safe berthing and sailing through fluid mud at Hamburg-Port
Authors Names: Ohle N., Schmekel U., Böttner C., Shevchuk I., Abdel-Maksoud M., Kirichek A.

Layout of Project Nautical Depth
The HPA project Nautical Depth is split up in 5 sub-projects which are briefly described below [3].

SUBPROJECT SEDIMENT PROPERTIES (SP1)
SP1 forms the basis for all investigations. Here, the properties of the sediments in the Hamburg port are analysed. Sampling is used to describe the spatial and temporal variability of the sediments regarding parameters as density, yield stress, organic content, etc. The dependencies of the substances on the sediment properties and regarding the project objectives are analysed and the results are also used for the numerical simulations (SP3)

SUBPROJECT MONITORING TECHNICS (SP2)
In SP2, monitoring methods should be developed, including the implementation of technics which detects the variable material properties in different depth zones. Since, the nautical depth is dependent on the yield stress and the density of the bottom sediments essential research works are carried in this context. The aim is to develop an area-based relative measurement method which is calibrated to a discrete absolute measurement method. For this purpose, it is necessary to know the relevant material properties from SP1.

SUBPROJECT SHIP TECHNOLOGY AND NUMERICAL CFD-SIMULATIONS (SP 3)
In SP3, framework conditions from ship technology must be considered when working on the topic. Conceivable influences here are the type of propulsion, the shape of the ship or the flow and effectiveness of the rudder as well as possible impairments to the cooling water systems of ships. The transmission of force between the silt and the ship's hull must also be described and implemented in numerical models. The results of the CFD-simulations will be incorporated into SP 4 and SP 5.

SUBPROJECT NAUTICAL ASPECTS AND HYDRAULIC MODEL TESTS (SP 4)
To carry out investigations in ship handling simulators, an upgrade for these simulators is planned in SP 4. An update is necessary as parameters such as the above-mentioned yield stress and density are not considered in the existing simulators. Based on the theoretical principles and the results from SP 1 and SP 3, limits of the bottom sediments must be defined, which exclude the intolerable effects on controllability and manoeuvrability of vessels. Those analyses should be done with hydraulic model tests of free sailing model ships and in the updated ship handling simulators. If successful, these limits are then also to be tested in field trials. Internationally, new framework conditions with the new limiting values should be incorporated into regulations and should be implemented in co-operation with all partners and stakeholders.

SUBPROJECT SHORT-TERM MEASURES FOR MOORED VESELS (SP 5)
In SP5, measures are being developed which may be trialled on a short-term basis in the port, especially in berths. As a first step, it is planned to carry out measurements in various berths and to determine additional or different criteria in those areas which are independent of the sailing of ship criterions. Those definition shall insure the safety of vessels which may penetrates or use fluid mud layers during low tide phases.

Investigation Approach regarding the Monitoring of Sediment Properties

In the period 2018-2022, sediment samples were collected every four to six weeks in a total of 35 campaigns at fixed locations P1 to P9 in the Hamburg Port (see Figure 1) along a transect from Elbe river-km 616 to 643. One upstream (P0) and one downstream (P10) location were added later and were not included in the regular sampling scheme. The locations mostly reflect hotspots of sedimentation and therefore high efforts to maintain the nautical depth.

Figure 1: Investigation area around the Port of Hamburg (adapted from Hamburg Port Authority) with sampling locations between river km 598 (P0, upstream) and 646 (P10, downstream).

Sediment samples were collected with a 1.2m long Frahmlot corer. On board, the core was divided into three layers based on differences in visual consistency and strength: fluid mud (FM), pre-consolidated sediment (PS), and consolidated sediment (CS), from top to bottom (see Figure 2).

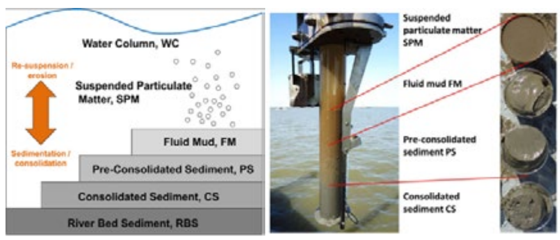

Figure 2: Schematic of sediment layers from top to bottom: suspended particulate matter (SPM), fluid mud (FM), pre-consolidated sediment (PS) consolidated sediment (CS) and riverbed sediment (RBS).

35th PIANC World Congress, 29 April – 03 May 2024, Cape Town, South Africa
Paper Title: Project Nautical Depth: New Approaches in safe berthing and sailing through fluid mud at Hamburg-Port
Authors Names: Ohle N., Schmekel U., Böttner C., Shevchuk I., Abdel-Maksoud M., Kirichek A.

Moreover, at some location, samples of suspended particulate matter (SPM) were collected. SPM refers to a fine suspension in the water layer; FM is a very fine-grained colloidal sediment suspension showing fluidic properties; PS is a non-fluidic sediment layer in the initial stages of consolidation, representing the topmost, freshly settled material. This layer is most pronounced in areas of high sedimentation rates; CS is a dense, compact, relatively water-depleted layer [4].

Influence of Organic Matter

Organic matter plays a major role in global ecosystems and has several functions in terrestrial and marine environments. As organic matter impacts, among others, the rheological behaviour and settling rates of mineral sediment particles, it is of great relevance to the definition and maintenance of the nautical depth in ports and waterways. The microbial decay of organic matter leads to the emission of climate forcing gases like CO_2 and CH_4. Analyses of field and laboratory experiments using sediment samples delivered new details of the sediment organic matter (SOM) behaviour [5]. The focus lay on sampling locations with high sedimentation rates and targeted the chemical, physical and biological parameters, and their variability in space and over time (see Figure 3).

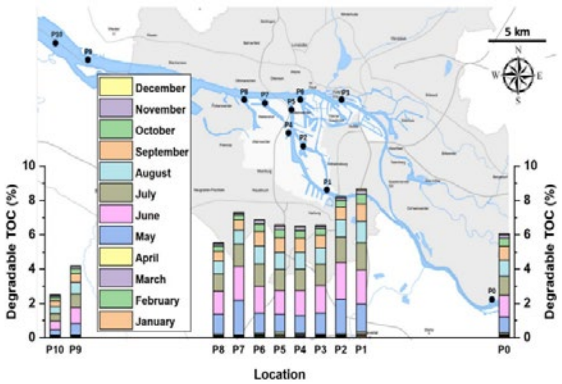

Figure 3: Sum of cumulative anaerobically degradable carbon (% TOC) for one year per month for PS layers from data between 2018 and 2020 with consideration of the monthly temperature, assuming all sediment to be deposited in the month of May.

The analyses and experiments allowed to quantify the share of anaerobically and aerobically degradable sediment organic matter in a depth profile and along a transect of about 30 km within the tidal Elbe River. Sediment organic matter in the port originates from the catchment (upstream) or the North Sea (downstream). Young organic matter, entering the system from upstream, has predominantly biogenic sources. Upstream organic matter originates from the catchment, containing plankton-derived and more easily degradable components.

It was analysed that the most upstream location was nourished primarily by upstream fluviatile sediments. These locations were characterised by the highest concentrations of chlorophyll a, microbial biomass, silicic acid, EPS, humic acids, and hydrophilic organic matter, the most negative δ13C signature and by the highest oxygen consumption rate, with decreasing trends towards downstream locations. At downstream locations, organic matter is mainly of allochthonous origin, entering the harbour mainly with the tidal flood current from the direction of the North Sea.

The organic matter degradability was the lowest at downstream locations and organic matter was stabilised in organo-mineral associations. Spatial patterns of organic matter degradability can be explained by a source gradient. Sediment organic matter lability is inversely linked to its stabilisation in organo-mineral complexes.

The degradability gradient could be explained by different organic matter quality in relation to its origin. A fast, medium, slowly, and non-degradable pool (pool 1 to pool 4) were identified based on the measured organic matter lability. Temporal and spatial variabilities (gradient and depth) were observed as well as seasonal changes of degradable organic matter pools. An age gradient was found with easily degradable material in top layers and increasing stabilization of organic matter in organo-mineral compounds with depth. Degradability was larger under aerobic conditions but the differences between aerobic and anaerobic decay decreased from upstream to downstream.

Implication for nautical depth and dredging: the investigation area mostly comprised stabilised organic matter. Thermometric pyrolysis was shown to serve as a useful proxy to predict organic matter degradability in river sediments, with the Hydrogen-Index (HI) correlating well with degradability. Further, it was analysed that the sediment organic matter decay has a biological, chemical, and physical effect on the shear strength. Degradation of organic matter significantly affects sediment strength, especially under the anaerobic conditions.

The formation of gas bubbles under anaerobic conditions added an additional physical component to the effect of biological organic matter decay. The susceptibility of the sediment to yield stress changes might depend on the availability of easily degradable organic matter. Pronounced spatial trends were found with higher changes in yield stress at upstream locations and lower yield stress changes at downstream locations. Temporal and spatial gradients were found for aerobic and anaerobic carbon fluxes as well as for potentially degradable organic carbon.

35th PIANC World Congress, 29 April – 03 May 2024, Cape Town, South Africa
Paper Title: Project Nautical Depth: New Approaches in safe berthing and sailing through fluid mud at Hamburg-Port
Authors Names: Ohle N., Schmekel U., Böttner C., Shevchuk I., Abdel-Maksoud M., Kirichek A.

Physical Characterisation of Port Sediments
The nautical bottom (the level at which contact with a ship's keel causes either damage or unacceptable effects on controllability and manoeuvrability of a ship) should be associated to a measurable physical characteristic. Today the density is typically used as a criterion for nautical bottom by many ports worldwide. However, the rheological properties particularly the yield stress of mud would be better parameters for defining a criterion for nautical bottom due to their strong correlation with the flow properties of mud and navigability. The density-yield stress correlation depends significantly on different parameters of mud such - as shown – on organic matter type and content, but also on clay type and content, particle size distribution and salinity. Therefore, a single critical value of density cannot be chosen for the nautical bottom criterion in a port like Port of Hamburg, where the above-mentioned parameters are varying from one harbour location to another (see Figure 3).

In the begin of the investigation the chose and implementation of a suitable rheological geometry and the definition of a measuring protocol are important to ensure a comparative analysis of yield stresses. In a first step the Couette geometry was found to be the most suited for analysing the rheological properties of soft mud layers (defined as fluid mud and pre-consolidated mud). Vane geometry was found more appropriate to study the rheology of consolidated mud, to avoid the wall-slip phenomenon occurring with the Couette geometry for consolidated layers. Regarding rheological protocols, stress ramp-up test proves to be the fastest, reliable, and repeatable test for measuring the two yield stresses (defined as "static" and "fluidic") associated to the structural breakdowns in the undisturbed (unremoulded) mud samples.

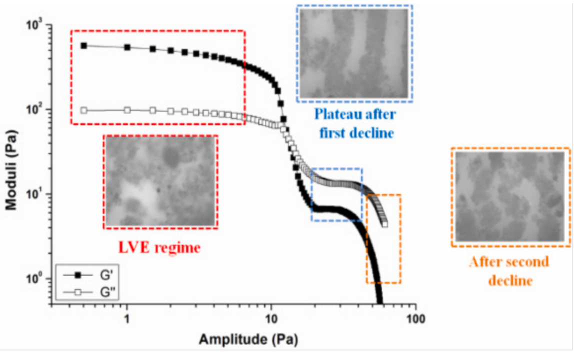

Figure 4: Schematic of the two-step yielding observed by amplitude sweep tests for mud samples The image proves that the double yield is associated with a change of structure as the images show. The two-step yielding is caused by the occurrence of a narrow gap between the instrument and the cup, thus allowing the floc to re-organize. The fluidic yield stress allows in-situ condition to define a constraint for the nautical bottom in ports and waterways.

These static and fluidic yield stresses were found to be correlated with conventional yield stresses (defined as "static" and "dynamic/Bingham" yield stresses in the literature). No extensive pre-shearing before or during the rheological protocol was used as done in other protocols, to obtain the yield stresses of undisturbed mud samples, which is a state typically found under in-situ conditions. The two-step yielding nature of the investigated sediment is attributed to two structural breakdown moments and reorganization during shearing and is visually confirmed by rheo-optical analysis [6] (see Figure 4).

In a second step, the depth and spatial variability in the rheological properties of mud from Port of Hamburg were investigated. The rheological properties were observed to increase as a function of density (i.e., buried depth) of mud. Mud samples having higher organic matter content (represented by Total Organic Carbon, TOC) showed higher elasticity than the samples having lower organic matter content, for a given density.

This variation in organic matter content along the port (i.e., higher TOC at upstream while lower TOC at downstream) defines the spatial variability in the rheological properties particularly for the density-yield stress correlation. The organic matter content was further observed to influence the flocs characteristics (size and density), which is eventually reflected by the bulk rheological properties. For samples with a same TOC content, it was found that the increase in rheological properties as a function of density is strongly dependent on the sample origin.

Two types of samples were investigated:

(i) samples collected in-situ as a function of depth (naturally deposited sediment),

(ii) samples prepared by diluting / conditioning the consolidated mud sample of the same location (diluted samples).

It was found that the yield stress of naturally deposited sediment is higher than for diluted samples, for a same density. This difference is attributed to the breakage of organic matter bonds with clay particles during the preparation of diluted samples. The two-step yielding nature of mud, for the entire investigated shear rate range, was modelled using the sum of two empirical expressions (one for each yield step). The switching from one expression to another is ensured using a step function. The proposed model effectively captures the two-step yielding behaviour of mud within the density range of 1050 to 1200kg/m³.

The proposed two-step yielding model has been implemented in the software of the rheological in-situ equipment of Port of Hamburg, where the fluidic yield stress will be measured in-situ for nautical bottom application. Structural recovery tests of mud samples were also performed as these tests enable to estimate both recovery time and recovery extent after shear. The structural recovery after extensive shearing of mud was observed to be larger for samples having low density and/or organic matter content as compared to the samples having high density and/or organic matter content. This result enables to predict that there should be a strong spatial and depth variability in structural recovery behaviour in the port as well, in addition to a spatial and depth variation in yield stresses and moduli. The characteristic time for recovery was found to be significantly affected by the pre-shear rate and organic matter content [7].

CFD-model Adaption and first sensitive Studies
In a first step different CFD-models as Open Foam or Star CFD were adapted to take the above-described two-step flow model into account. Then the influence of different rheological parameters on the following quantities were analysed:

- total resistance
- coefficient (C_T),
- pressure resistance coefficient (C_P),
- viscous resistance coefficient (C_V) and
- total yaw moment coefficient (m_zT).

In Figure 5 the dependence of the total resistance on the organic content resp. the total organic carbon (TOC) is depicted. Obviously, this parameter has a significant influence on the resistance.

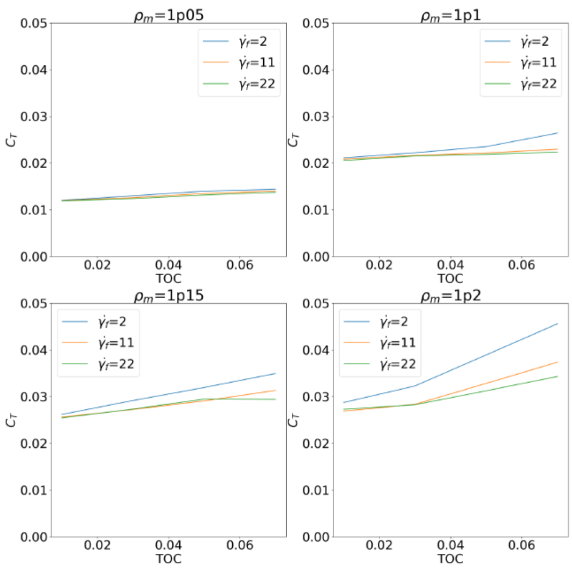

Figure 5: Dependence of the total resistance coefficient on the TOC

The increase of TOC in all cases leads to the growth of the ship's resistance. This effect is dependent on the density and the yield shear rate. For small densities the increase of C_T is approximately 20%, for the highest density and small yield shear rate it can rise by up to 60%.

Analyzing the different resistance components one can notice only slight influence of TOC on the pressure component. Moreover, at higher densities, this dependency vanishes completely. On the contrary, the viscous resistance coefficient is barely changed as the TOC is increased for density of 1050kg/m³, but for 1200 kg/m³ this causes a rapid increase in resistance. Therefore, for the high densities the total resistance increase due to TOC comes from the viscous component. This can be easily explained: TOC and the yield shear rate influence the kinematic viscosity of the fluid, but in the Navier-Stokes equations the dynamic viscosity is used, where the density is a multiplier. So as the density is increased, the same TOC and the $\dot\gamma_f$ result in a higher apparent dynamic viscosity.

Furthermore, the fluid-mud density seems to be the most relevant parameter for the resistance of the ship. In Figure 6 one can see a dramatic increase in resistance as the density becomes higher. For the TOC of 1% the change of density by just 150kg/m³ leads to a 140% jump in resistance. Also, a significant influence of TOC on the curves C_T (ρ) can be seen at high TOC, the C_T rises already by 220% as compared to a density of 1050 kg/m³. This enormous influence of density is due to the fact, that is affects both the wavemaking of the ship at the water/fluid-mud influence and at the same time the apparent dynamic viscosity.

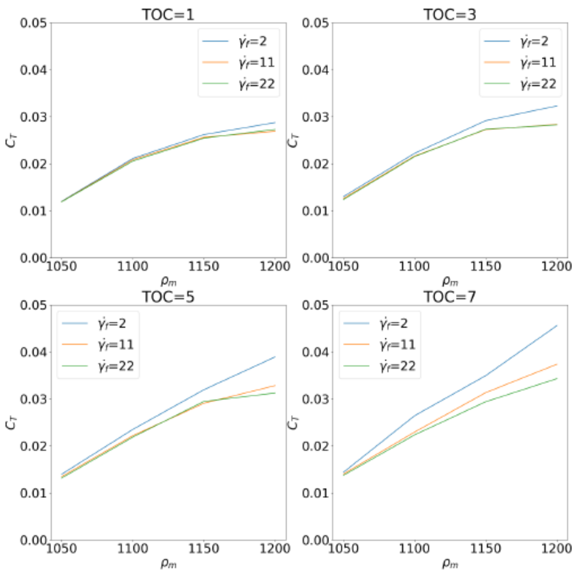

Figure 6: Dependence of the total resistance coefficient on the fluid-mud density

35th PIANC World Congress, 29 April – 03 May 2024, Cape Town, South Africa
Paper Title: Project Nautical Depth: New Approaches in safe berthing and sailing through fluid mud at Hamburg-Port
Authors Names: Ohle N., Schmekel U., Böttner C., Shevchuk I., Abdel-Maksoud M., Kirichek A.

Generally, one can see, that as the yield shear rate increases, the resistance decreases by up to 50%. Clearly, the lower is the yield shear rate for the same yield stress, the higher apparent viscosity is obtained. And of course, higher viscosity means higher resistance. Again, this effect becomes significant only for higher densities. It can also be analysed, that the pressure resistance exhibits almost no changes, as $\dot{\gamma}_f$ is varied. On the contrary, the $C_V(\dot{\gamma}_f)$ seems to be responsible for the entire variation of C_T.

In further analysis (not shown in Figures) the influence of TOC on the yaw moment is rather moderate. A clear trend can be seen only for low densities, where the increase of TOC leads to a app. 13% rise of m_zT. For higher densities a nonmonotonic behaviour is observed. On the other hand, at high apparent viscosities and densities one can expect a larger scatter in the simulation data. Just like for the resistance coefficient, the most significant influence on the yaw moment is that of the density. The increase of density almost in all cases regardless of TOC leads to a monotonic increase of the yaw moment coefficient. The relative growth in different in each case, but it normally lies in the range between 70 and 80%. Therefore, the density plays a much more important role as compared to the TOC. As for the $\dot{\gamma}_f$ its influence is quite small. Even though in some cases it can reach 12%, but in most cases does not exceed 5%.

Nautical Depth Analysis and Field Test at Berths
Due to the tidal changes of water level in harbours, the vertical position of mooring ships varies in the day resp. tide. Usually, the vertical shift matches the change of water level. However, in the case when the ship encounters the fluid mud layer, which has a higher density than water, particular differences between the expected and the actual ship position can be seen because of the changes in the Archimedes force, exerted on the ship.

In order to quantify this effect and to show that the change of the free board of moored vessels during this process is just dependent on the density change, measurements of the ship position was conducted for a trailing suction hopper dredger (TSHD) which was moored at a jetty in the Köhlfleet harbour and penetrates a fluid mud layer in a field test.

The ship position was tracked using GPS and total-station measurements and the change of their vertical positions was compared to the that of the water level in the harbour. The result of this comparison can be seen in Figure 7. The hypothesis is that these changes are due to the variation of the density in the vertical direction, when the ship encounters fluid mud, which also leads to the differences in the Archimedes force.

To reproduce this effect a computation was carried out to check the hypothesis and to estimate the effect of the density distribution on the Archimedes force and therefore on the vertical direction. The result of these computation is also plotted as dots resp. solid line in Figure 7.

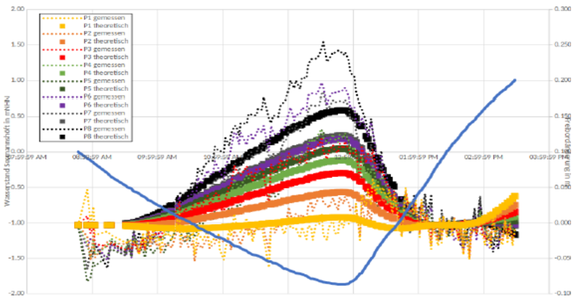

Figure 7: Comparison between the measured and the predicted vertical coordinates of P1-P8

It is shown that the changes of the free board of the vessel is just induced to the density changes while penetration the fluid mud layer.

Discussion and Conclusion
In summary, the analysis of the sediments of the Hamburg show that even small amounts of organic matter can significantly change the rheological behaviour of mud. This also leads to a two-step yielding behaviour for mud, which also can be explained by the analysis of flocs and their behaviour. It could be also shown that the organic matter (represented by TOC) and the density have the highest influence on the resistance force of the ship hull during the interaction of a sailing through mud processes.

Furthermore, laboratory and field test helped in defining a fluid mud criterion based on yield stress (50Pa) and density (1150kg/m³), which is currently being adopted in key locations in Hamburg Port for pilot experiments. At these locations berthed vessels can penetrate the fluid mud during low water conditions. Yield stress limits of fluid mud for navigation purposes are still under investigation and will be lower than the 50 Pa fluidic yield stress [8].

For the sailing through mud aspects further investigations in hydraulic model tests and ship handling simulators must be carried out. However, the same understanding and knowledge (rheological properties and yield stress limit for navigability) could be applied to various ports by doing similar analysis. The correlation between static and fluidic yield stresses is an open field of study. Experiments with different clay type, ionic strength, pH, particle size and particle size distribution may help to study better the influence of each parameter on the rheological fingerprint of bottom sediment in ports [9].

References

[1] PIANC. (2014), Harbour Approach Channels - Design Guidelines, Report 121, PIANC, Brussels.

[2] Kirichek, A., Chassagne, C., Winterwerp, H., Noordijk, A., Rutgers, R., Schot, C., Nipius, K. and Vellinga, T. (2018), How navigable are fluid mud layers? Terra Aqua, 151, pp.6-18.

[3] Ohle, N. and Schmekel, U. (2019) Das Projekt „Nautische Tiefe“ im Hamburger Hafen, Proceedings of the HTG-Kongress 2019.

[4] Shakeel, A., Zander, F., de Klerk, J., Kirichek, A., Gebert, J. and Chassagne C. (2022), Effect of organic matter degradation in cohesive sediment: A detailed rheological analysis, J. of Soils and Sed., 22, 2883–2892.

[5] Zander, F., Shakeel, A., Kirichek, A., Chassagne, C., and Gebert, J. (2022), Effect of organic matter degradation in cohesive sediment: A spatiotemporal analysis of yield stresses. J. of Soils Sed., 22, pp. 2873 – 2882.

[6] Shakeel, A., Kirichek, A. and Chassagne, C. (2020), Rheological analysis of mud from Port of Hamburg, Germany. J. of Soils Sed., 20, pp. 2553-2562

[7] Shakeel, A. (2022), Rheological analysis of mud: towards an implementation of the nautical bottom concept in the Port of Hamburg, Gildeprint, Enschede, pp. 1-164.

[8] Shakeel, A., Chassagne, C., Bornholdt, J., Ohle, N. and Kirichek, A. (2022), From fundamentals to implementation of yield stress for nautical bottom: case study of the Port of Hamburg, Ocean Eng., 266, 112772.

[9] Kirichek, A., Shakeel, A. and Chassagne, C. (2020), Using in situ density and strength measurements for sediment maintenance in ports and waterways. J. of Soils and Sed., 20, pp. 2546-2552.