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Sailing through fluid mud: current advances and challenges

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Abstract: Instead of maintenance dredging, an alternative option for port authorities is to adapt the PIANC's nautical bottom approach. For practical purposes, the nautical bottom is defined as the level at which the fluid mud reaches either a critical density or a critical yield stress (the shear strength). These values generally correspond to a level at which the mud undergoes a so-called "rheological transition", where the density and strength of the mud increase rapidly over a short distance. Below this level, the mud becomes more and more like solid ground and is therefore no longer navigable.

Recently, new scientific and practical research has been conducted in order to gain additional knowledge on navigability in ports with fluid mud layers. In particular, a systematic rheological analysis was conducted to determine the critical limits of the yield stresses and density of fluid mud. Furthermore, a Computational Fluid Dynamics (CFD) model was developed to numerically investigate the ship-mud interaction. The model was applied to study the effects of muddy bottoms on the full-scale resistance of a modern oil tanker at speeds between 3 and 9 knots. It was confirmed that not only the density but also the yield stress of the fluid mud should be considered in the practical application of the nautical bottom. Finally, the paper discussed how the standard maintenance dredging methods can be used for producing navigable fluid mud layers.

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

Introduction

Nautical accessibility is essential for sustainable operations in any port. Accessibility is primarily determined by the available water depth, which is conventionally defined as the distance between the water level and the maintained bed level. Typically, there are three approached that are employed by port authorities for maximizing nautical accessibility: the establishment of tidal windows, the maintenance of the bed levels by dredging operations and the adaption of the nautical bottom concept. The latter is defined by PIANC as: "a level at which 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" [1]. The increasing size of ships combined with the presence of fluid mud layers on in ports and waterways has led to ships often navigating close to or even through mud layers by adapting the nautical bottom concept (see Figure 1).

The definition of nautical bottom, however, still leaves room for interpretations. Over the past decade, a number of scientific and practical studies have been conducted in order to clarify the questions related to the physical characteristics and to the unacceptable effects on controllability and manoeuvrability, as these are not clearly defined [2]. Particularly, research initiated by the Port of Rotterdam, Hamburg Port Authority and Rijkswaterstaat focussed on studying the physical characteristics for the nautical depth and the effect of fluid mud on the ship's resistance [3], [4]. In this paper, the main results of this research are discussed. Furthermore, the dredging methods used for sediment conditioning (creating navigable fluid mud layers) for the nautical bottom approach are presented.

Physical characteristics and critical limits

For practical reasons, port authorities define the nautical bottom as the level where the mud reaches either a critical density or a critical yield stress, i.e. the shear stress below which the fluid behaves as a solid-like material [1], [5]. The reason for selecting density as a physical characteristic for the nautical bottom concept is linked to the limitations of in-situ measurements of yield stress (or shear strength). Typically, the density's critical limit is ranging from 1150 to 1250 kg. m^{-3} with the corresponding yield stress values from 50 to 100 Pa [2], [5], [6]. These values usually correspond approximately to a depth where the mud undergoes a 'rheological transition', in which the density and shear strength of the mud increase rapidly over a short distance. Below such depth, the mud resembles more and more a 'solid' bottom.

In order to define a critical limit of the yield stress for the adaptation of the nautical bottom concept in the Port of Hamburg, Germany, the fluidic yield stress and the density of sediment samples were measured at key locations in the Port of Hamburg (see Figure 2). The fluidic yield stress is measured using the rheological stress sweep protocol presented in [5] and further adapted in [7]. It was found that 50 Pa can be used as a limit to determine a fluid mud for all these locations, with a corresponding critical limit of the density of 1150 kg. m^{-3}. However, it is important to highlight that the corresponding density for the Rethe (RT) location at 50 Pa is about 1120 kg. m^{-3}, which is slightly lower than for the other locations. This lower value of the critical density is mainly due to the higher organic matter content of mud samples [8]. Moreover, the critical densities corresponding to 50 Pa for the far upstream (RV: Reiherstieg Vorhafen) and far downstream (SW: sediment trap Wedel) locations are 1085 and 1215 kg. m^{-3}, respectively (Figure 2b).

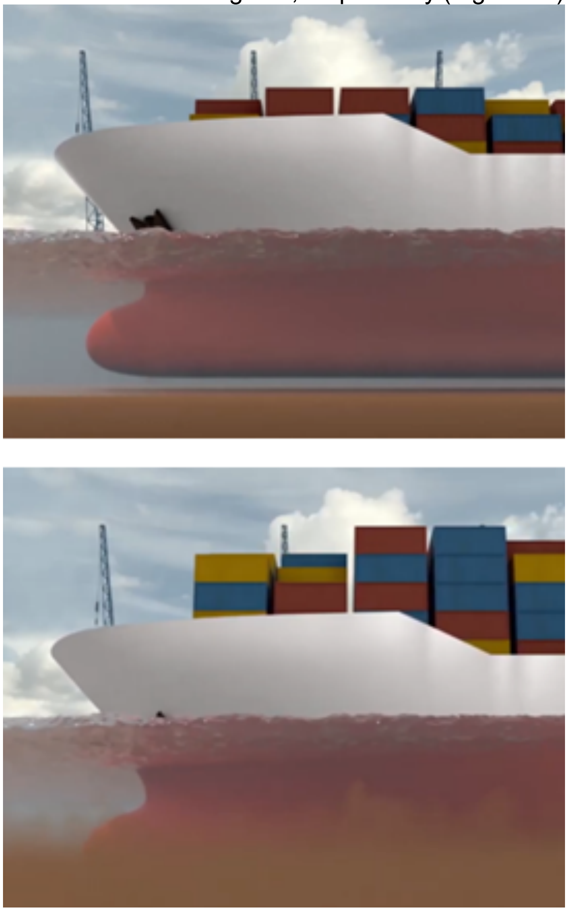

Figure 1 A container ship moving above (top) and through (bottom) a fluid mud layer (snapshots taken from www.youtube.com/watch?v=LSbQhUJMBJw).

The lower critical density for RV location is mainly linked to the higher organic matter content while the higher critical density for SW location is associated to the lower organic matter content and the higher sand content, which eventually lead towards an increase in bulk density and a decrease in yield stresses due to the presence of non-cohesive sand particles [7]. This behaviour proves that the density is not a suitable parameter for defining the fluid mud areas in Port of Hamburg, as it varies from 1085 to 1215 kg. m^{-3} for a certain yield stress value. This also justifies the selection of yield stress for defining navigable mud layer. In literature, yield stress has been used to define the nautical bottom, for instance, Port of Emden uses a yield stress of 100 Pa as a criterion to define navigable mud layer [5]. However, this value is twice higher than the value suggested in this study (i.e., 50 Pa) as an upper limit for the navigability criterion of mud from the Port of Hamburg. This difference in values can be associated to the difference in composition of mud (clay content and organic matter content), state of organic matter (fresh or degraded) and criterion of estimating the yield stresses [10, 11]. It is important to note that 50 Pa limit as navigability criterion of mud in Hamburg is only valid for ships at berths, which will not sail through the mud. The controllability and manoeuvrability of sailing ships are still an open question to investigate and will be analysed with adapted ship handling simulators.

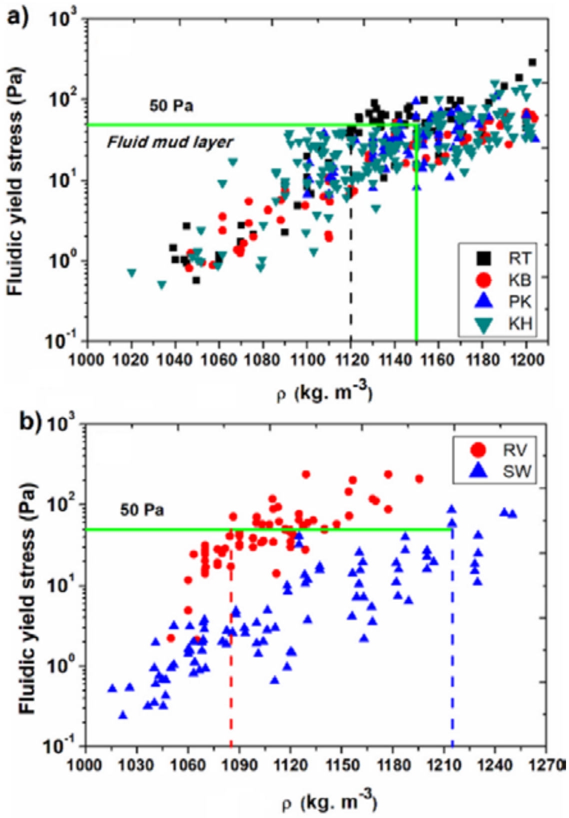

Figure 2 Fluidic yield stress (equivalent to shear strength) as a function of density of mud for (a) different locations in the Port of Hamburg (see [3] for the details), (b) far upstream (RV) and far downstream (SW) locations in the Port of Hamburg, Germany. Green solid line represents the critical value of yield stress (50 Pa) and density (1150 kg. m^{-3}) for the physical characteristics of mud. Dashed lines represent the critical density value for RT, RV and SW locations corresponding to 50 Pa. Adapted from [9].

In addition to yield stress, thixotropy or structural recovery is one of the very frequently observed complex rheological behaviours of the mud [12]. This particular property can significantly influence the yield stress values (lower yield stress values for disturbed sample and higher yield stress values for undisturbed sample) and, hence, its correlation with the yield stress values is critical. The correlation between fluidic yield stress and the hysteresis area (obtained from the thixotropy loop test) for mud from different locations in the Port of Hamburg is presented in Figure 3a. It can be clearly seen that there is a strong correlation between both parameters, even for the locations which represent boundary conditions (i.e., RV and SW). Moreover, the critical value of hysteresis area corresponding to the suggested yield stress value of 50 Pa is around 1400 Pa. s^{-1}. This confirms that the mud samples having fluidic yield stress below 50 Pa exhibits weak thixotropic behaviour (i.e., a small hysteresis area), which verifies that the selected yield stress value (50 Pa) is not significantly influenced by the thixotropic character of mud.

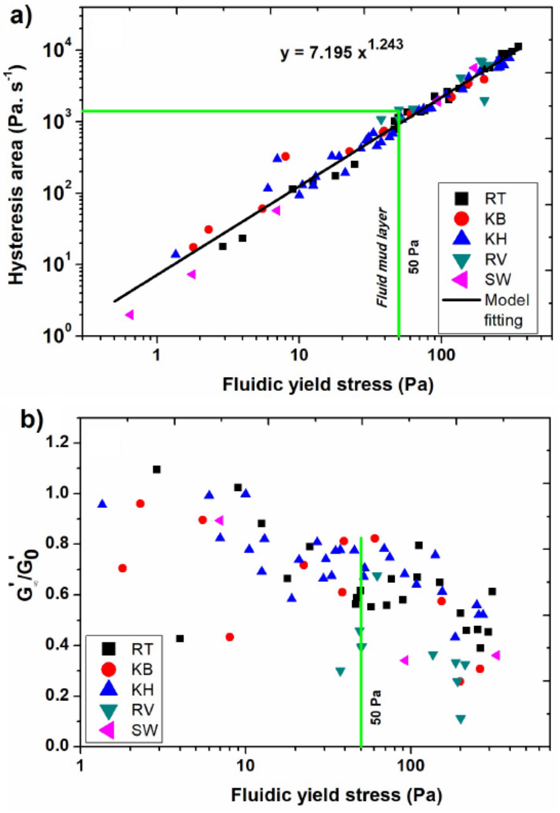

Figure 3 Hysteresis area (obtained from the thixotropy loop test) as a function of fluidic yield stress for different locations in the Port of Hamburg, (b) equilibrium structural parameter (G'_∞/G'_0) as a function of fluidic yield stress for different locations in the Port of Hamburg. Green solid line represents the critical value of fluidic yield stress (50 Pa) and hysteresis area (1400 Pa. s^{-1}). Adapted from [9].

The correlation between the structural recovery (i.e., in terms of G'_∞/G'_0) and fluidic yield stress of mud from different locations is shown in Figure 3b. The samples having fluidic yield stress lower than 50 Pa show structural recovery up to 70 - 100% indicating that the structure fully recovers itself (within about 500 ‐ 700 s) and verifies the lower thixotropic character of mud. For mud samples with fluidic yield stress higher than 50 Pa, the structural recovery is around 30 - 70%, i.e., pronounced thixotropic behaviour. However, this correlation is not very strong as compared to the correlation between fluidic yield stress and hysteresis area, which shows that the thixotropic loop test is a fast and reliable method to determine the thixotropic character of mud.

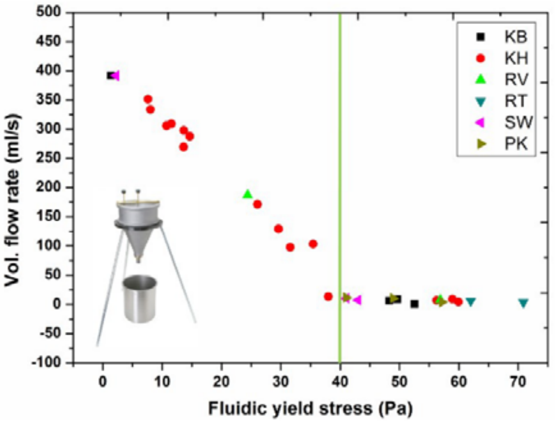

Figure 4 Volumetric flowrate (obtained from funnel test) as a function of fluidic yield stress for mud samples from different locations. Green solid line represents the critical value of fluidic yield stress (40 Pa) where the volumetric flow rate is almost zero. Adapted from [9].

Apart of laboratory measurements of yield stress and density on collected sediment samples, in-situ surveying tools are also available for measuring density and yield stress (or shear strength) vertical profiles [10]. Even a simple funnel test can be performed to understand the flow behaviour of fluid mud by measuring the volumetric flow rate of the sample coming out of the funnel. The correlation between fluidic yield stress and the volumetric flow rate obtained from the funnel test is shown in Figure 4. It is found that for low fluidic yield stresses, the volumetric flow rate is high. At a certain critical value of fluidic yield stress (40 Pa), the volumetric flow rate is almost zero and remains constant for higher fluidic yield stress values. This critical value of fluidic yield stress shows the transition between fully flowing material (fluid mud) and pre-consolidated material. It is also found that this critical fluidic yield stress value is lower than the suggested yield stress value (50 Pa), which is mainly due to the fact that a funnel test is based on the bulk flow of material, which requires lower yield stress values, as gravity is the main driver for flow. Furthermore, the presence of larger fibres and sand particles in mud can significantly affect its flowing behaviour.

Ship-mud interaction

The most substantial research effort to better understand ship-mud interaction was done on scaled models [14], [15], [16], [17]. The problem has also been investigated using potential flow theory (e.g. [18],[19]). With the increasing power of today's computers, viscous-flow calculations using Computational Fluid Dynamics (CFD) have become a viable tool investigate the ship-mud interaction [20], [21], [22]. CFD allows to account for the viscous effects that are neglected by the less computationally expensive potential-flow solvers.

In our recent CFD study [23], the effect of muddy beds on the full-scale resistance of an oil tanker (KVLCC2) sailing straight ahead has been investigated using a finite-volume Reynolds-Averaged Navier-Stokes (RANS) flow solver combined with the Volume-Of-Fluid (VOF) method to capture the mud-water interface. The objective was to determine the influence of factors such as the densimetric Froude number[1], UKC and mud rheology at speeds between 3 and 9 knots. The rheological behavior of mud was modelled with the Bingham model. The depth-to-draught ratio was fixed at 1.5.

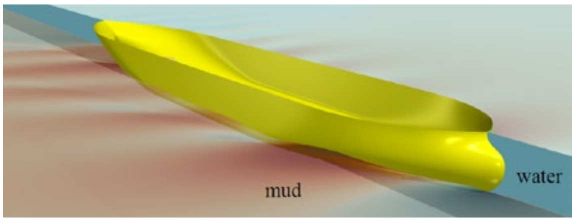

Figure 5 Mud undulation generated by passing ship (souce: [4]).

The CFD investigation confirmed some findings from previous research, i.e. that the presence of mud alters the hull forces because of two main effects. The first stems from the high viscosity of mud, which tends to increase the viscous forces in case of contact with the hull. The second effect can occur even without contact and is due to the generation of internal waves on the mud-water interface (see Figure 5). When sailing close to critical speeds (i.e., when the densimetric Froude number, Fr_i, is close to 1) these waves can significantly alter the pressure distribution on the hull and therefore the resistance and the manoeuvring behaviour.

In terms of pressure resistance, a peak is observed close to $Fr_i=1$ (Figure 6). Remarkably, compared to the case without mud, C_P can become more than twenty-fold larger. However, note that with a depth-to-draught ratio fixed at 1.5, the resulting mud layer thicker than for typical harbour navigation. In reality the effect is expected to be lower with thinner mud layers. Furthermore, with thinner layers, the critical speeds for the internal wave are also lower, hence the peak in C_P is expected at lower speed (although still for Fr_i close to 1).

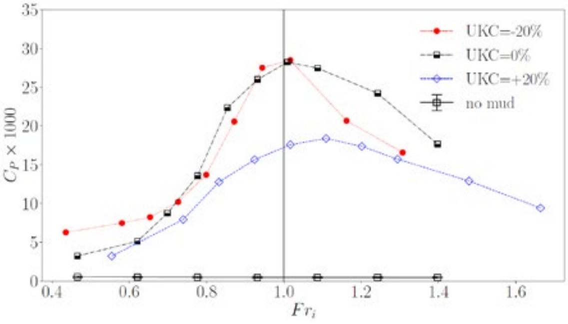

Figure 6 Pressure resistance coefficient versus densimetric Froude number for different UKCs.

The densimetric Froude number in **Error! Reference source not found.** 6 was varied by varying the speed. The CFD study also showed that the influence of the internal wave on C_P is not solely controlled by Fr_i but also by other parameters including speed, under-keel clearance, mud layer thickness and density. This also means that the resistance curves against Fr_i are not unique but they rather depend on how Fr_i is varied (e.g. if it is varied by changing speed, mud layer thickness or its density). The relationship between C_P and these other parameters is rather complex and not straightforward to illustrate, as changing one parameter can affect the others.

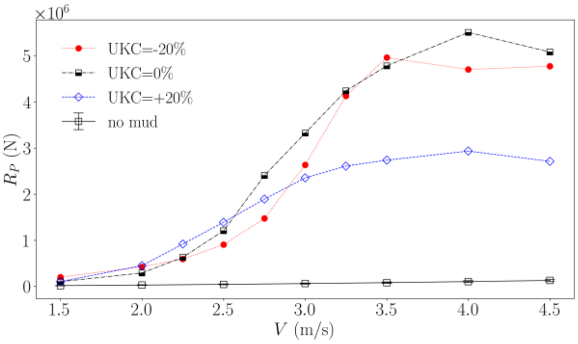

Figure 7 Pressure resistance versus speed for different UKCs.

When looking at the dimensional pressure resistance (Figure 7), it becomes clear that a peak in C_P does not directly correspond to a peak in R_P, but rather to a range of speeds in which R_P increases sharply. Note that, for a given speed in Figure 7, the densimetric Froude number is different for each UKC. At 2.5 m/s, the highest R_P is for UKC=+20% because at that speed the ship is already in the trans-critical range (effect of Fr_i), whereas the other two cases are still sub-critical.

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[1] The densimetric Froude number is defined as the ratio between the ship's speed and the critical speed of the internal waves (see also [23] for its mathematical definition).

For speeds above 3.0 m/s, the cases with zero and positive UKC enter the trans-critical range, where the resistance undergoes a steep increase. At the higher speeds, the cases with zero UKC exhibit the largest R_P due to the stronger proximity effects (the ship's keel is closer to the mud-water interface).

To investigate the effect of the mud rheology, the three mud conditions that were used in our previous work [24] were selected. These three mud conditions were respectively labelled as Mud_10, 17, and 23, where the number represents the Bingham yield stress. The larger the yield stress the larger also the Bingham viscosity and the density.

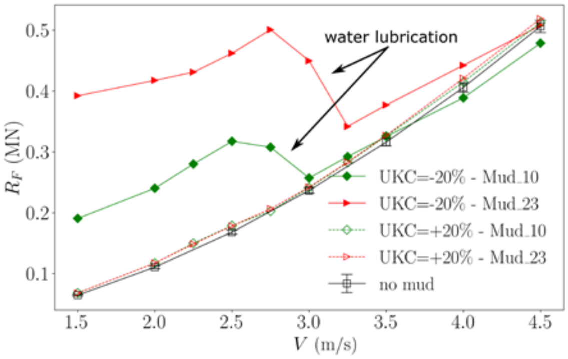

Figure 8 Frictional resistance versus speed for different UKCs and mud conditions

For positive UKC, the mud rheology has little influence on friction for the whole investigated speed range (Figure 8). In general, the mud rheology is expected to influence the frictional resistance mostly when sailing with negative UKC. While this is confirmed in Figure 8, a significant influence of the mud rheology is observed only at low speeds. The weak influence of the mud rheology at high speed is in part attributable "water lubrication", which reduces the contact area between the hull and the mud layer. In fact, as the speed increases, the high pressure at the bow tends to push the mud layer down, allowing water to get in between the hull and the mud layer (see Figure 9). While this phenomenon can be physically explained, it may have been exaggerated by the CFD model, which tends to preserve a sharp interface between mud and water. Further experimental investigation are needed to confirm the extent of this phenomenon.

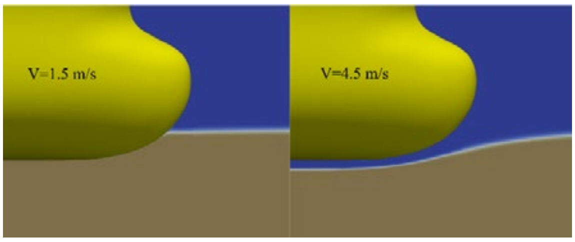

Figure 9 Effect of speed on the mud layer at the bow.

The total resistance, which combines pressure and frictional resistance, is shown in Figure 10. Compared to the situation without mud, the total resistance with muddy bottoms can become between 2 and 15 times larger. However, as already mentioned, these figures are probably lower in real life, where the mud layer are typically thinner than the mud layer considered.

At higher speeds, the total resistance is completely dominated by the pressure component and therefore by the internal wave. At low speed, the frictional resistance becomes significant, especially when sailing with negative UKC. When sailing through mud, the effect of the mud yield stress is also evident: as V→0, the total resistance does not tend to zero. This means that, when starting to move from zero speed, the ship must be able to overcome an initial resistance due to the mud yield stress. This is initial resistance can be estimated as the yields stress times the surface area of the hull in contact with mud.

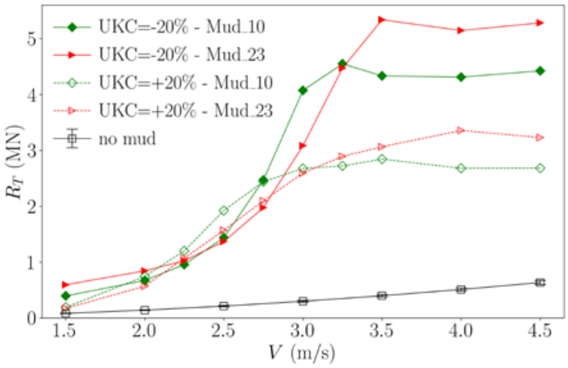

Figure 10 Total resistance versus speed for different UKCs and mud conditions.

To summarize, a strong link between the mud rheology and the resistance is observed at low speed and with negative UKC, where the increase in resistance due to contact with the mud layer is proportional to the mud yield stress. At the higher speeds, this is no longer true as the influence of the internal wave becomes dominant. Hence, at higher speeds (above 2-2.5 m/s), the resistance depends mostly upon the UK and the fluid mud layer thickness and density, as these are linked to Fr_i and to the amplitude of the internal wave [23].

Maintenance dredging methods for sediment conditioning

The concept of nautical bottom concept is often applied together with the methods of conditioning maintenance dredging, which are used to produce navigable fluid mud layers. For example, sediment re-circulation is used in the Port of Emden, Germany, for reducing the strength of the sediment [5], [25]. Another example of sediment conditioning is applying Water Injection Dredging (WID) in port areas with low energy regions. The Port of Rotterdam, the Netherlands, tested WID for conditioning the sediment in the Calandkanaal (the Port of Rotterdam) [26]. The WID-induced fluid mud layer can be then used for estimating the nautical depth by adapting the density limit of 1200 kg. m^{-3} for the nautical bottom concept. Finally, sediment conditioning can be done by a bed leveller or underwater plough.

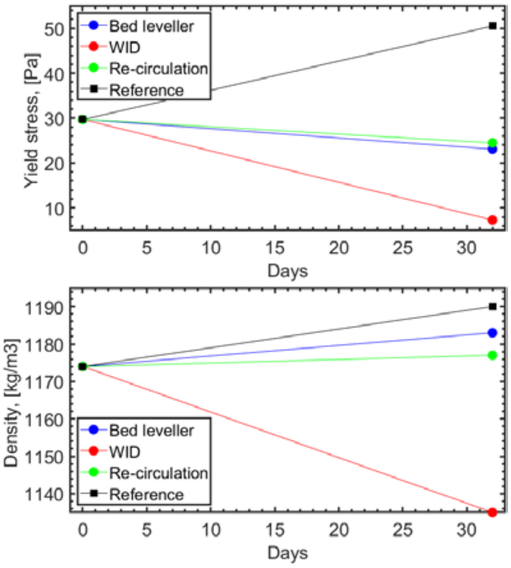

Figure 11 Effect of conditioning methods (WID, re-circulation and bed leveller) on the yield stress and density of mud

Scaled experiments were conducted to replicate the effects of bed leveller, WID and re-circulation on the yield stress and density of sediment from the Port of Hamburg. Sediment conditioning was carried out once a week over a period of 32 days. All three methods were efficient as they kept the yield stress below the reference value (30 Pa). The WID loosened the yield stress of the sediment the most through fluidization processes (see Figure 8a). WID was also efficient in reducing the initial density of the sediment. Conditioning with the other two methods (bed leveller and re-circulation) kept the density of the sediment close to the original density of the sediment and mainly affected the yield stress (see Figure 8b). All three methods reduced the yield stress of the sediment during conditioning and thus produced fluid mud layers that can be used for the application of the nautical bottom concept.

Discussion and conclusions

This study helped to define a fluid mud layer based on the yield stress of mud (50 Pa), which is currently being used for pilot testing at key locations in the Port of Hamburg. At these locations, berthed ships can be submerged in the fluid mud layer at low tide. The limit values for the yield stress of fluid mud for navigation purposes are currently still being investigated and will be below the 50 Pa yield stress limit.

Regardless of how advanced a CFD model may be, obtaining reliable experimental data to validate such a model is one of the biggest challenges for navigation with muddy bottoms. Experiments with scaled models seem out of reach as ship model basins are reluctant to work with fluids other than water, although this may change in the future. For now, this leaves no other option but to consider simplified problems, such as a plate [21] or a cylinder [22] moving through mud. Nevertheless, studies on simplified problems can also provide useful insights for CFD developers.

Full-scale experiments are even more challenging to perform, and it is very difficult to obtain accurate measurements that can be used to validate CFD simulations. Nevertheless, full-scale tests could provide insight into what to expect from CFD simulations. For example, the RPM-speed curves could be measured when navigating above or through different types of mud layers. This could not only provide pilots with useful insights into the behavior of ships, but also confirm or dismiss expected phenomena such as the sharp increase in resistance associated with internal waves.

WID, bed leveller and re-circulation methods were used to condition the sediment in order to create navigable fluid mud layers. The application of all three methods reduced the yield stress of the conditioned sediment. The application of WID resulted in a fluid mud layer (density current), which had a lower density and lower yield stress compared to the original bed. Conducting in-situ conditioning of sediment and using the available survey tools can provide further insight into the coupling of the conditioning methods with the application of the nautical bottom concept.

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