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From fundamentals to implementation of yield stress for nautical bottom: Case study of the Port of Hamburg

Ahmad Shakeel [a,b,c,*], Claire Chassagne [a], Jasper Bornholdt [d], Nino Ohle [d], Alex Kirichek [e]

[a] Section of Environmental Fluid Mechanics, Department of Hydraulic Engineering, Faculty of Civil Engineering & Geosciences, Delft University of Technology, Stevinweg 1, 2628 CN, Delft, the Netherlands
[b] Laboratory of Process Engineering, NeptunLab, Department of Microsystems Engineering (IMTEK), Albert Ludwig University of Freiburg, Freiburg, 79110, Germany
[c] Freiburg Materials Research Center (FMF), Albert Ludwig University of Freiburg, Freiburg, 79104, Germany
[d] Hamburg Port Authority, Neuer Wandrahm 4, 20457, Hamburg, Germany
[e] Section of Rivers, Ports, Waterways and Dredging Engineering, Department of Hydraulic Engineering, Faculty of Civil Engineering & Geosciences, Delft University of Technology, Stevinweg 1, 2628 CN, Delft, the Netherlands

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ABSTRACT

The nautical bottom (i.e., 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. Bulk density is typically used as a criterion for nautical bottom by many ports worldwide. However, the rheological properties particularly the yield stress of mud are eventually more suitable 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 organic matter type and content, clay type and content, particle size distribution and salinity. Therefore, a single critical value of density cannot be chosen for the nautical bottom criterion, where the above-mentioned parameters are varying from one location to another in the port. This justifies the need for a study of the rheological properties (yield stress) of mud. The main objective of this review article is to provide (i) an extensive overview of the rheological properties (particularly yield stress) of mud from different sources, (ii) factors affecting the rheology of mud, and (iii) defining a nautical bottom for berthing areas in the port of Hamburg using a combination of yield stress and density.

1. Introduction

Suspended matter is distributed in the water of rivers, lakes and coastal waters. It consists of organic and inorganic components. Due to their small particle size, the inorganic components remain in suspension despite their significantly higher density compared to water. These clay minerals have a layer charge and therefore have electrostatic forces of attraction on positively charged particles. Organic components have densities like water and are therefore in suspension. Organic components always have functional groups which are not electrically neutral. Depending on the type of functional groups, there are positive and negative charges. When differently charged particles come very close to each other, they attract and combine to form larger structures called flocs. The bonds are of different types such as dipoles and hydrogen bonds. The flocs then consist of organic matter with embedded mineral particles.

Mechanical forces can break down larger flocs into smaller flocs. Flow turbulence thus controls the size of the flocs. In zones with calmer currents, the growth of larger flocs is particularly favored. With increasing floc size, the settling velocity increases, so that the sedimentation of the suspended matter flocs occurs in those areas. During sedimentation process, these suspended matter flocs accumulate near the bottom, where turbulence decreases. This process promotes the formation of even larger flocs. However, higher floc concentrations can impede sedimentation process. Sometimes a transition area forms in which flocs can no longer move independently of each other. This transition layer is structurally a fluid, but distinct from rheological perspective, from the water above, along with higher densities. These transition layers are typically referred to as "fluid mud" (Kineke et al., 1996; Mehta, 1991). With increasing depth, further consolidation

* Corresponding author. Department of Hydraulic Engineering, Delft University of Technology, Stevinweg 1, 2628 CN, Delft, the Netherlands.
E-mail addresses: A.Shakeel@tudelft.nl (A. Shakeel), C.Chassagne@tudelft.nl (C. Chassagne), Jasper.Bornholdt@hpa.hamburg.de (J. Bornholdt), Nino.Ohle@hpa.hamburg.de (N. Ohle), O.Kirichek@tudelft.nl (A. Kirichek).

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occurs. They no longer consist of individual flocs, but form a large network of water, clay minerals, sand, silt and organic substances (such as living microorganisms and in particular their excreted biopolymers) (Mehta, 2013). The presence of these larger network structures of mud can be observed particularly well in erosion tests (Zhang et al., 2018). In the field of marine geology, fluid mud layer is typically referred to as a fluffy layer (Zhang et al. 2021, 2022), puff layer (Brun-Cottan et al., 2000) or wave-supported mud layer (Hooshmand et al., 2015; Wen et al., 2020).

In fluid mud, solid particles are no longer suspended in the mud layers. The water is then stored between greater network structures. These mud layers are typically subject to continuous wave motion and disturbances caused by ship motion (Mehta, 2013; Ross and Mehta, 1989), human intervention such as dredging (Gordon, 1974), natural climate events, and bioturbation (Harrison and Wass, 1965). Water body of a river, coastal water or lake in calmed areas can be divided into different layers from top to bottom:

- Water body contains suspended matter (SPM), (No impairment of shipping)
- Solid suspension close to the ground with predominantly fluid properties (fluid mud (FM)) but it differs significantly from the SPM areas in terms of density and rheology, (this layer can be made accessible to shipping)
- Pre-consolidated sediment (PS), (Not navigable! possibly tolerable at moorings)
- Consolidated sediment (CS), (Not navigable! If CS is above the target depth, it must be dredged) (Shakeel et al., 2020d)

The near-bottom fluid mud layer is exposed to strong local fluctuations. In some places it can be several meters thick, in other places it is completely absent. Fluid mud, the most important mud layer from a navigational perspective, is typically identified as a layer with a density of 1030–1300 kg. m^{-3} whereby hindered settling of particles plays a role due to the presence of the described flocs (Inglis and Allen, 1957; McAnally et al., 2007; Whitehouse et al., 2000). All mud layers, but particularly the fluid mud layer, display complex rheological behavior, i.e., combination of thixotropy, shear-thinning, two-step yielding and viscoelasticity (Coussot, 1997; Van Kessel and Blom, 1998). The rheological/cohesive properties of mud are observed to vary as a function of solid fraction (or bulk density), type and concentration of organic matter, type of clay minerals and ionic concentration (Malarkey et al., 2015; Parsons et al., 2016; Paterson et al., 1990; Paterson and Hagerthey, 2001; Schindler et al., 2015; Shakeel et al., 2019a, 2020d; Wurpts and Torn, 2005). The thorough understanding of the rheological characteristics of mud, as a function of above-mentioned parameters, needs to be performed to estimate the strength, the flow and thickness of (fluid) mud in ports and waterways. The quantification of the rheological properties for fluid mud also facilitates the definition of boundary conditions for sediment transport modelling, which in turn helps optimizing the dredging operations and defining the proper maintenance strategy for navigational channels (Kirichek et al., 2018, May, 1973, Parker and Kirby, 1982, Richard Whitehouse et al., 2000). However, in order to calibrate and improve the *in-situ* measurement techniques, it is essential that the key rheological parameters are extensively estimated beforehand in the laboratory using suitable protocols.

First of all, in this review paper, nautical bottom concept is explained from rheological point of view in section 2. In the next section, different rheological protocols used to measure the yield stresses of mud are detailed and compared. Furthermore, the two-step yielding behavior of mud is described from microstructural point of view followed by the presentation of semi-empirical model used to capture that two-step yielding behavior. The influence of different factors such as density, organic matter content, dilution, organic matter degradation, salinity and temperature on the rheological behavior of mud is discussed in Section 3. In the end, the nautical bottom is defined on the basis of rheological properties of mud for Port of Hamburg as a case study.

2. Defining nautical bottom based on rheology

Safe navigation and excellent accessibility within ports and waterways is vital for port authorities. Safe navigation is primarily controlled by the space available under the ship's keel, referred to as under keel clearance (UKC). There are two approaches for maintaining a sufficient UKC: (i) by restricting the maximum draft of vessels, and (ii) by controlling the desired nautical bottom with dredging operations (Kirichek et al., 2018). The nautical bottom is typically defined 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*" (PIANC, 1997).

The first approach is uneconomical because it would restrict the accessibility of the port for larger and energy efficient vessels. The second option is more favourable for port authorities, however, the environmental impact and cost of the dredging operations can limit its applicability. The nautical bottom definition provides a general viewpoint without giving a practical solution. Moreover, this definition raises a number of questions including:

1. How to define and quantify "unacceptable effects"?
2. Which physical parameter(s) are associated to the "characteristics of the bottom"?
3. How to define and estimate critical value(s) of this/these parameter (s)?

The answer to the first question depends on several parameters such as training and expertise level of pilots, local environmental conditions, size and speed of the vessel, quality of navigational assistances (availability of tug assistance) and influence of the fluid mud on the manoeuvrability of the vessels. For the other two questions, the selected physical characteristics should directly relate to the forces exerted by the mud layer on the ship's hull upon its contact.

Two different approaches are typically used to maintain the desired nautical bottom: (i) passive approach (McAnally et al., 2016) and (ii) active approach (Wurpts and Torn, 2005). Passive approach relies on a bathymetric survey method which ultimately leads to the recommendation of a mud property beyond which it is safe/unsafe for a ship to sail. This mud property is typically the bulk density for most cases. For example, the ports of Rotterdam, Suriname, Bangkok, Bordeaux, and Nantes adopted a density criterion of 1200 kg. m^{-3} (McAnally et al., 2016). Bottom surveying techniques such as echo-sounding are generally used to detect the mud-water level. However, the frequency dependence of echo-sounding results is the most common problem with this technique, and a proper calibration is difficult owing to the variability in mud composition (Vantorre et al., 2006). On the other hand, active approach relies on the maintenance of navigational channels whereby the physical, biological and chemical properties of fluid mud are tuned in order to significantly influence its rheological and settling behaviour. This methodology has been adopted in the Port of Emden. The mechanical destruction of the mud's floc structure restricts the rapid consolidation of mud (McAnally et al., 2016).

As navigability is strongly linked to the flow properties of the water-mud medium, rheological properties like viscosity and yield stress (i.e., stress required to initiate the flow of mud) are better candidates to define suitable physical characteristics and can be utilized to define a suitable criterion. The reason for selecting bulk density as a criterion for nautical bottom is linked to the limitations of *in-situ* measurements of rheological properties and the lack of systematic investigation of rheological characteristics of mud. However, recent developments made it possible to effectively analyse the *in-situ* rheological properties of mud (Kirichek and Rutgers, 2020). On the other hand, German ports like the Port of Emden defined the nautical bottom on the basis of yield stress of mud (50–100 Pa) (Wurpts and Torn, 2005) with the corresponding density values ranging from 1100 to 1250 kg. m^{-3} (Uliczka, 2005). This variation in density values is linked to the fact that the relation between density and yield stress can be significantly influenced by several parameters including type and content of organic matter, clay type, particle size distribution and salinity. Hence, it is difficult and impractical to choose a critical value of the density for a port with varying above-mentioned parameters along the port. In short, for defining nautical bottom based on rheological properties of mud, the following points need to be considered: (i) systematic analysis of the influence of different parameters (TOC content, type and state of organic matter, bulk density and salinity) on the rheology of mud, (ii) appropriate tools for *in-situ* measurement of rheological properties, and (iii) proper correlation between lab and *in-situ* measurements.

3. Yield stress

Bingham and co-workers introduced the term yield stress for plastic yielding in metals (Barnes, 1999; Bingham, 1922). The estimation of yield stress is vital for various industrial processes particularly for defining nautical bottom for ports and waterways (Kirichek et al., 2018; Møller et al., 2006; Nguyen and Boger, 1992). In addition to the yield stress, other rheological properties of mud are also important particularly the viscosity, moduli and shear rate. High shear rate viscosity (i.e., infinite viscosity) is typically used in sediment transport modelling along with the yield stress of sediments. However, in this review paper, only yield stress is considered and explained because this rheological property is used in literature for defining nautical bottom (Wurpts and Torn, 2005).

3.1. Rheological protocol

Several experimental techniques and protocols have been developed, in the past two decades, to estimate the yield stress of soft materials. However, the yield stress values obtained from these protocols/techniques may vary depending upon the handling procedure of sample and selected method (James et al., 1987; Nguyen et al., 2006; Steffe, 1996; Uhlherr et al., 2005; Zhu et al., 2001), which is attributed to the differences in criterion of yield stress definition, principle and time scale associated with the chosen methodology (Cheng, 1986).

There are several conventional methods to measure yield stresses such as steady ramp-up (based on stress or shear rate), oscillatory sweep (based on stress or strain), stress growth (at constant shear rate) and creep (at constant shear stress) (Coussot, 2014; Dinkgreve et al., 2016; Nguyen and Boger, 1992). In addition to these methods, some protocols are specially designed for estimating the yield stresses of mud samples. For example, Claeys et al., (2015) developed a protocol to measure the yield stresses (in terms of undrained shear strength and dynamic yield stress) of mud by obtaining an equilibrium flow curve using vane geometry. This protocol starts with the application of a lower shear rate (1 s^{-1}), which gives the undrained shear strength of mud, followed by the application of nine or more shearing cycles (15–20 min) at required shear rates with intermittent shearing at 1000 s^{-1}, to completely destroy the structure and to obtain the reproducible state. The resultant equilibrium flow curve gives the dynamic yield stress at lower shear rates. This protocol is not very suitable to estimate the yield stresses of a large number of samples. Moreover, the use of vane geometries in fluid sediment samples should be assessed critically, because of the secondary flows particularly at higher shear rates.

Different rheological geometries are available to perform rheological experiments including concentric cylinder, cone and plate, parallel plate and vane. However, each geometry has its own benefits and limitations and is typically selected on the basis of nature/composition of sample. In literature, the rheological properties of mud samples from different sources have been extensively investigated by using different geometries and rheological methods (Babatope et al., 2008; Bai et al., 2002; Coussot, 1997, 2007; Fass and Wartel, 2006; Huang and Aode, 2009; Jiang and Mehta, 1995; Van Kessel and Blom, 1998). For instance, Van Kessel and Blom (1998) presented a comparative analysis of rheological properties of natural and artificial mud samples using three different geometries: (i) Couette, (ii) double concentric and (iii) cone and plate. The results showed that the yield stress values were dependent on the geometries.

Moreover, the comparison of different protocols in terms of apparent viscosity as a function of shear stress for mud samples from Port of Hamburg is shown in Fig. 1. Two yield stresses (static and fluidic) extracted from the two viscosity declines are presented in Table 1. The higher yield stresses are obtained by using shear rate ramp-up step of CSRT test, increasing equilibrium flow curve (EFC) test and stress ramp-up test, which is associated to the fact these protocols destroy the mud samples from an undisturbed state. Therefore, these protocols are suitable to estimate the yield stresses of mud samples which are present in undisturbed or unremoulded state (or fast recovery after disturbance) under *in-situ* conditions. Moreover, the stress ramp-up test is fastest and more reliable to measure yield stresses of large number of mud samples. The remaining protocols (decreasing equilibrium flow curve, ramp-down step of CSRT, pre-shear and Claeys et al.) give lower yield stress values, which verifies the extensive structural breakdown of samples during measurement. These protocols are, however, useful to measure the yield stresses of mud samples which exist in disturbed state (remoulded state) under *in-situ* conditions. This analysis also highlights that the yield stresses of both remoulded and unremoulded sample can be obtained by performing a shear rate ramp-up and ramp-down test (CSRT) along with some information about the thixotropic or time-dependent behaviour of mud.

3.2. Two-step yielding

In addition to the single-step yielding, a prominent two-step yielding behaviour was found for different soft materials such as carbopol microgel (Shao et al., 2013), colloidal glasses (Pham et al., 2008), colloidal gel (Chan and Mohraz, 2012), muscovite dispersions (Nosrati et al., 2011) and magneto-rheological systems (Segovia-Gutiérrez et al., 2012). This two-step yielding behaviour is either linked to the wall slip artefact (Barnes, 1995), which can be easily checked by performing experiments with different gaps or with roughened geometries (Shakeel et al., 2020b), or attributed to the material's response due to the existence of different structural levels/structural (re)organizations (Ahuja

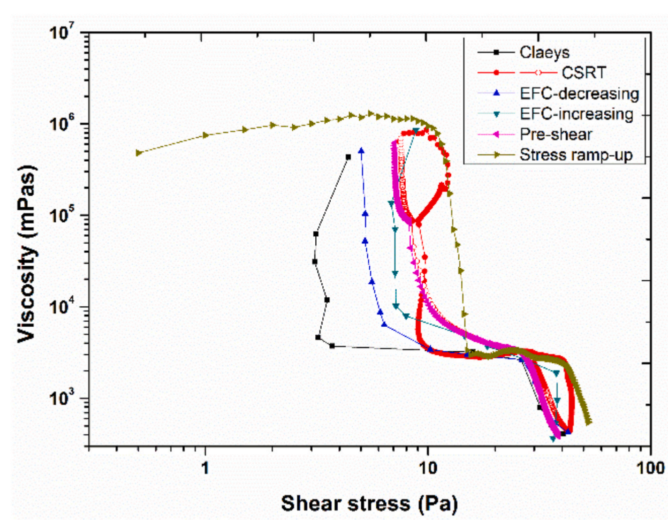

Fig. 1. (a) Apparent viscosity as a function of shear stress for mud sample collected from port of Hamburg using Couette geometry; solid symbols in CSRT protocol represent the ramp-up and the empty symbols represent the ramp-down; solid lines are just the guide for the eye. More detailed information about the protocols can be found elsewhere (Shakeel et al., 2021b).

Table 1
Static and fluidic yield stress values of mud sample from port of Hamburg obtained from viscosity declines with Couette geometry for different protocols (Shakeel et al., 2021b).

Method	Static Yield Stress (Pa)	Fluidic Yield Stress (Pa)
Claeys et al.	3.1–4.4	26
CSRT-ramp up	9.0–12.3	40
CSRT-ramp down	7.6	29
EFC-decreasing	5.2	26
EFC-increasing	7.1	38
Pre-shear	7.1	27
Stress ramp-up	11	40

et al., 2020). Oscillatory amplitude sweep test is typically performed to analyse the two-step yielding behaviour of a sample by recording the moduli (G' and G'') as a function of applied oscillatory stress or strain. The storage (G') and loss (G'') moduli are the in-phase and out-of-phase responses of the material, respectively, to the applied sinusoidal stress/strain. The two-step yielding response is identified by the two declines in the moduli, which are typically associated to the bond and cage breaking process (Dagois-Bohy et al., 2017). Moreover, it is important to note that at higher amplitudes it is difficult to define G' and G'' in a conventional way due to the presence of higher harmonics and, therefore, it is useful to analyse the data in terms of Lissajous plots.

Nie et al., (2020) reported the two-step yielding behaviour of mud by using both steady and oscillatory tests. The authors attributed the first yield point to the breakup of particle network structure while the second yield stress was linked to the complete breakup of aggregates. After the second yield point, the aggregates/flocs became individual particles and the mud sample behave like a viscous fluid. A similar two-step yielding behaviour was observed for mud samples by plotting the data in terms of viscosity as a function of shear stress obtained from different creep tests (Mehta et al., 2014). The origin of this two-step yielding behaviour in mud was also investigated by using a parallel plate shearing device with an upright microscope (RheOptiCAD® (Shakeel et al., 2019b),). The results showed that the first yield point was linked to the breakage of interconnected network of flocs, followed by the formation of hollow cylinder-like structures which provided the second plateau in moduli or viscosity. The second yield stress was associated to the collapse of these reorganized cylinder-like structures into smaller flocs or aggregates, see Fig. 2 (Shakeel et al., 2021c).

3.3. Two-step yielding model

In literature, several rheological models have been used to fit the flow curve of mud samples particularly for estimating the yield stresses such as Bingham model, Herschel-Bulkley model, Worrall-Tuliani model, Toorman model and Casson model (Babatope et al., 2008; Bai et al., 2002; Coussot, 1997; Huang and Aode, 2009; Messaoudi et al., 2018; Van Kessel and Blom, 1998; Xu and Huhe, 2016). For instance, the rheological properties of mud samples from Port of Rio Grande, Port of Santos and Port of Itajaí were investigated by fitting the flow curve data with the Bingham model (Fonseca et al., 2019). Likewise, Worrall-Tuliani model was used to fit the rheological experimental data of mud samples from two different locations of Hangzhou Bay, China (Huang and Aode, 2009). All these models are typically used to fit the flow curve of the sample with single step yielding. However, these models particularly Bingham and Herschel-Bulkley models can be used to capture the two-step yielding behaviour by applying these models in two different shear rate regimes defined by a critical shear rate (Huang and Aode, 2009; Xu and Huhe, 2016). For practical purposes, it is still useful to develop a model that can capture both yielding regions with a single equation.

Shakeel et al., (2021b) proposed an empirical model to capture the two-step yielding nature of mud, for the entire investigated shear rate range, by using the sum of two empirical expressions (one for each yield step). At lower shear rates ($\dot{\gamma}$), the shear stress is depending on τ_s and can be fitted by the function τ_{stat} while at higher shear rates, the resultant stress is dependent on τ_f and fitted by the function τ_{fluid}, where the transition between the two functions occurs at a shear rate defined as $\dot{\gamma}_0$. The model gives important rheological parameters of mud such as static yield stress (τ_s), fluidic yield stress (τ_f) and infinite viscosity (μ_∞) and is formulated as follows:

$$\tau = \alpha\tau_{stat} + (1-\alpha)\tau_{fluid} \quad (1)$$

where the step function α is given by:

$$\alpha = 1 - \frac{1}{1+\exp(-k(\dot{\gamma}-\dot{\gamma}_0))} \quad (2)$$

This function gives $\alpha(\dot{\gamma} < \dot{\gamma}_0) = 1$ and $\alpha(\dot{\gamma} > \dot{\gamma}_0) = 0$ with a transition at $\dot{\gamma} = \dot{\gamma}_0$, with a sharpness that depends on the value of k. The function τ_{stat} is given by:

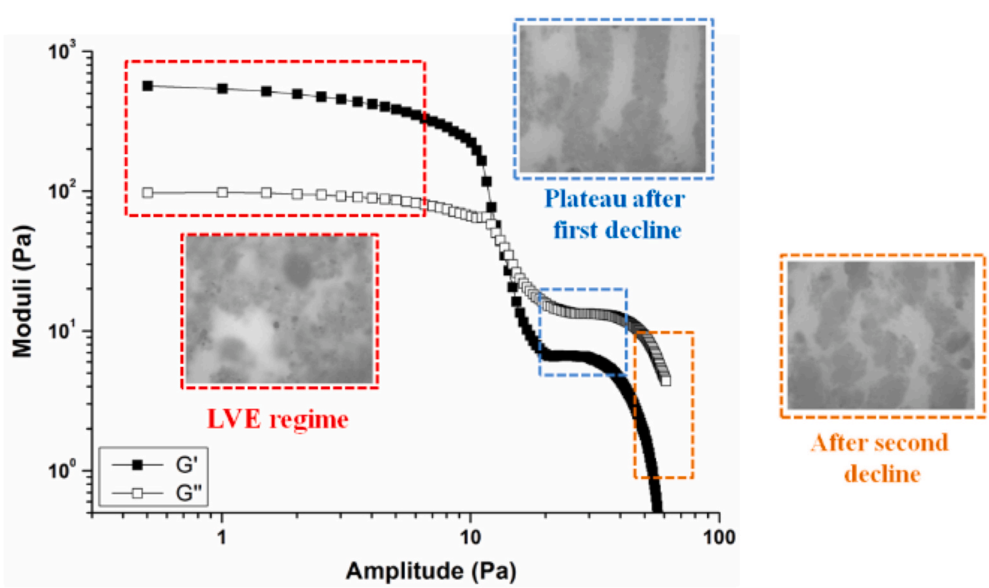

Fig. 2. Schematics of the two-step yielding observed by amplitude sweep tests and RheOptiCAD® images for mud samples (Shakeel et al., 2021c).

$$\tau_{stat} = \frac{\tau_s}{1 + \dot{\gamma}_s/\dot{\gamma}} \tag{3}$$

From the analysis of this function, we find that:

$$\tau_{stat}(\dot{\gamma}_s \ll \dot{\gamma}_0) = \tau_s \tag{3.1}$$

$$\tau_{stat}(\dot{\gamma} = \dot{\gamma}_s) = \frac{\tau_s}{2} \tag{3.2}$$

$\dot{\gamma}_s$ represents the shear rate at which τ_s is half of its value. The curvature of the first function can be tuned by varying $\dot{\gamma}_s$. The second yielding step is captured by the function τ_{fluid} given by:

$$\tau_{fluid} = \tau_s + \frac{\tau_f}{1 + \left((\dot{\gamma}_f - \dot{\gamma}_0)/(\dot{\gamma} - \dot{\gamma}_0)\right)^d} + \mu_\infty(\dot{\gamma} - \dot{\gamma}_0) \tag{4}$$

The coefficient d enables to tune the "sharpness" of the curvature. The experimental data of stress ramp-up test is fitted with the proposed model (Eq. (1)) by using a Matlab script with the least square method, for mud samples from port of Hamburg. The model shows a good agreement with the experimental data (see Fig. 3).

3.4. Effect of density

Density (i.e., solid content and/or water content) is an important characteristic of mud which can significantly influence their rheological properties such as yield stress, thixotropy and moduli. For instance, Xu and Huhe (2016) observed an exponential increase in yield stress values of mud, collected from Lianyungang, China, as a function of volume concentration of particles. A similar increase in yield stresses as a function of solid content/density of mud is presented by other researchers as well (Carneiro et al., 2017; Fonseca et al., 2019; Soltanpour and Samsami, 2011). However, this density-yield stress correlation is observed to be significantly dependent on the organic matter content, sample collection and preparation (natural or diluted) and state of organic matter (fresh or degraded), which is explained in the next sections.

3.5. Effect of organic matter content

Organic matter in fine-grained sediments comes from (i) natural sources including eroded topsoils, plant litter, pelagic and planktonic biomass, or (ii) anthropogenic sources such as urban sewage and surface runoff, as listed in Zander et al., (2020). In suspended form, organic matter can interact with clay particles either by charge neutralization or by creating hydrogen bonds between the particles (Lagaly et al., 2013), forming a flocculated/aggregated system. In mud layers close to the ground, the floc concentration can become so large that the individual flocs encounter each other, and cross-floc bonds are formed. A large network is thus created and a transition from the fluid to mud establish. This is accompanied by a complex rheological behaviour of mud including viscoelasticity, shear thinning, thixotropic behaviour and two-step yielding (Coussot, 1997; Shakeel et al., 2020d; Van Kessel and Blom, 1998). For example, a substantial increase in yield stresses and complex modulus (Fig. 4a) was observed for mud samples having similar densities but with high organic matter content, which was attributed to the formation of a strong network (Shakeel et al., 2019a). The correlation between density and yield stresses was also observed to vary as a function of organic matter content for mud samples from different locations (with varying organic matter content) of port of Hamburg (see Fig. 4b) (Shakeel et al., 2021b).

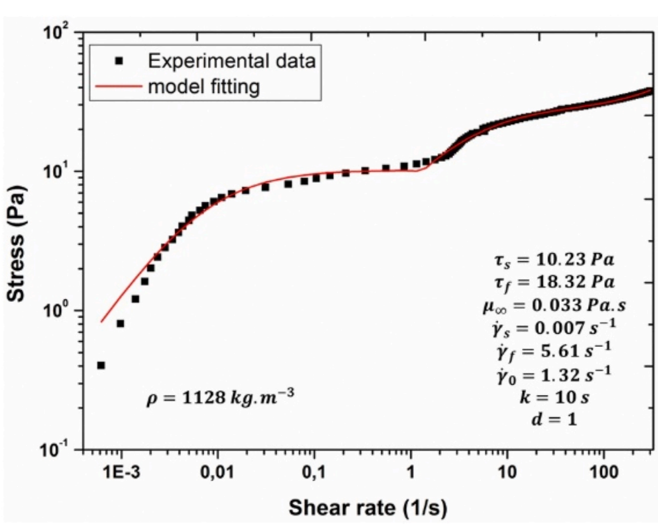

Fig. 3. Stress as a function of shear rate for mud sample from port of Hamburg obtained by performing stress ramp-up test using Couette geometry. The solid line represents the model fitting (Eq. (1)) (Shakeel et al., 2021b).

3.6. Effect of dilution and organic matter degradation

In literature, the rheological properties particularly yield stresses of mud are investigated as a function of density either by diluting dense mud sample (Huang and Aode, 2009; Van Kessel and Blom, 1998) or by collecting natural mud layers with varying density (Shakeel et al., 2020d). Both these approaches can result in significantly different rheological behaviour of mud. Moreover, organic matter degradation under *in-situ* conditions can significantly influence the rheological properties of mud due to the breakage of clay-organic matter bonds or structural breakup of organic matter. The correlation between fluidic yield stress and bulk density for natural mud samples, artificially made mud samples (diluted) and anaerobically degraded mud samples is presented in Fig. 5. It is found that the degraded mud samples show intermediate behaviour of fluidic yield stress as compared to the other two types of samples. This result shows that the dilution of mud samples causes a significant decrease in yield stresses, which is attributed to the mixing effect imposed during the dilution along with the differences in the composition. Moreover, the dilution series of mud and the measurement of changes in rheological properties due to dilution are to be viewed critically because this process does not occur in nature. On the other hand, the reduction in yield stresses due to the degradation of organic matter is lower than the one observed for diluted samples. This information is very important for both laboratory studies where mud dilution is typically performed to investigate the density-yield stress correlation and also for *in-situ* studies where microbial degradation occurs as a function of time.

3.7. Effect of salinity and temperature

In literature, the rheological properties of cohesive sediments are found to be strongly dependent on the physic-chemical factors such as salinity (Whitehouse et al., 2000), which can significantly affect the natural settling and consolidation process of mud. Hence, the rheological properties of mud having different salinities would be quite different after settling and consolidation phenomenon. Torrance (1999) reported an increase in the yield stress of remoulded marine clay by increasing the salt content. Moreover, the structural recovery in marine sediments was found to be faster above a certain salt concentration (50 g/l) (Knappe et al., 2020). On the other hand, Yang et al., (2014a) reported no influence of salinity on the rheological properties of cohesive sediments within the range of fresh water to 50 g/l. Hence, the influence of salinity on the rheological properties of cohesive sediments is quite dependent on the nature of the sediments along with their composition.

In the end, temperature is another parameter which can significantly influence the rheological fingerprint of mud. For instance, Chandrasekharan Nair et al., (2019) reported a decrease in viscosity of cohesive sediments by increasing the temperature from 5 °C to 15 °C.

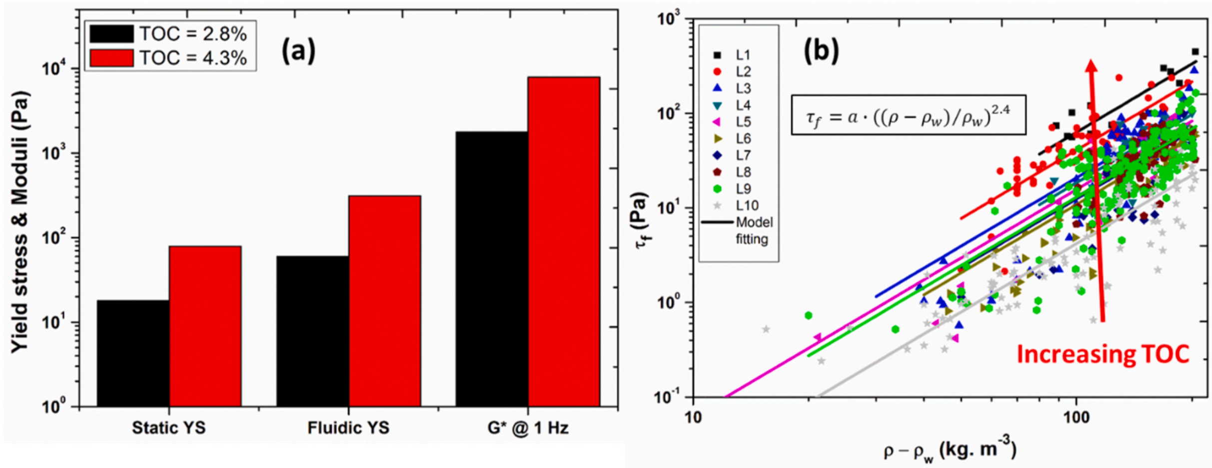

Fig. 4. (a) Yield stress values and complex modulus (G^*) at 1 Hz for mud samples having similar density (1210 kg. m^{-3}) and different organic matter content (2.8% and 4.3%) obtained from Port of Hamburg (Shakeel et al., 2019a, 2021a), (b) fluidic yield stress as a function of excess density for different locations from port of Hamburg. L1 to L10 represent the locations from river side towards seaside in the Port of Hamburg. The solid lines represent the power law fitting with one fitting parameter 'a' and the fixed value of parameter 'b' (Shakeel et al., 2021b).

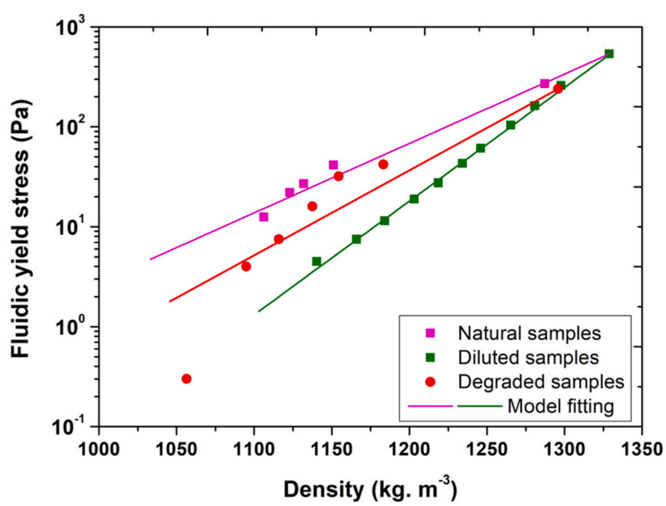

Fig. 5. Fluidic yield stress as a function of bulk density of natural mud samples, artificially made samples (diluted) and anaerobically degraded mud samples collected from port of Hamburg. The solid lines represent the simple exponential model fitting (Shakeel et al., 2020c).

Similarly, Guo et al., 2020 showed an increase in yield stress and viscosity values (about 36.3%) by decreasing the temperature from 22 °C to 0.5 °C. Likewise, a slight decrease in static yield stress and an increase in dynamic yield stress was found as a function of increasing temperature from 5 °C to 50 °C (Xu and Huhe, 2016). Moreover, the structural recovery in mud was found to be higher at 25 °C as compared to the structural recovery at 5 °C (Shakeel et al., 2020a).

In summary, stress ramp-up tests with couette geometry were proven to be practical and time efficient tests for measuring all structural breakdowns within the mud samples associated to static and fluidic yield stresses (two-step yielding). This two-step yielding behaviour was further correlated to the microstructural changes in the mud sample during shearing. The first yield point was linked to the existence of interconnected network of flocs and the second yield point was attributed to the breakage of cylinder-like structures. A semi-empirical model was used to describe and capture this two-step yielding behaviour of mud, which provides useful parameters including yield stresses, infinite viscosity and critical shear rates. Rheological properties of mud were found to be significantly influenced by bulk density and organic matter content, in addition to the mud dilution, organic matter degradation, salinity and temperature. Table 2 presents a detailed overview of the rheological properties of mud samples obtained from different sources.

4. Port of Hamburg: a case study

It was found that the mud samples from port of Hamburg exhibited two yield stresses (static and fluidic), which were attributed to the structural reorganization due to shearing action (Shakeel et al., 2021c). It was, therefore, important to first identify which yield stress (static or fluidic) is more appropriate to use in the definition of the nautical bottom. The first yield point (static) represents the breakage of interconnected network of flocs while the plateau behaviour of viscosity/moduli after the first decline shows the formation of cylinder-like structures. Hence, it is important to note that the existence of two-step yielding is mainly due the narrow gap between bob and cup, which allows the re-organization of flocs. In *in-situ* conditions, the static yield point may not be observed as it corresponds to an undisturbed state of the mud and, therefore, the fluidic yield stress would be the important parameter to define a limit for the nautical bottom in ports and waterways. Fluidic yield stress was linked to the complete structural breakdown in mud, which is needed for controllability and manoeuvrability of vessels.

To define a critical value of yield stress for the characterisation of fluid mud and, therefore, to get an "upper" boundary for the nautical bottom approach, the fluidic yield stress values are plotted as a function of excess density for key locations in Port of Hamburg, Germany (Fig. 6a). It was found that 50 Pa can be used as a criterion for the definition of a fluid mud characterisation for all these locations, with a corresponding critical bulk density of 1150 kg. m^{-3}. However, it is important to highlight that for Rethe (RT) location the corresponding density is about 1120 kg. m^{-3} for 50 Pa, slightly lower than the other locations. This lower value of critical density is mainly related to the higher organic matter content of mud samples. 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 (Fig. 6b). 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. This behaviour proves that bulk density is not a suitable parameter for

Table 2
Detailed overview of the rheological properties of mud from different sources.

Study area(s)	Rheometer and geometry	Density range (kg. m^{-3})	Rheological method for yield stress	Yield stress range (Pa)	Modulus range (Pa)	Viscosity range (Pa.s)	Main outcome(s)	Ref.
Debris flow (Manival, Possuet, Mount St. Helens)	Rheometer: 1. Rheometrics RMS-800 2. CarriMed Geometry: 1. Parallel plate 2. Cone and plate	1512–1792[a]	Herschel–Bulkley model fitting on flow curve obtained from controlled shear rate test	29–470	–	–	• The rheological properties (i.e., yield stress) of mud suspensions were observed to vary significantly as a function of clay type, solid content, electrolyte concentration and pH.	Coussot & Piau (1994)
Southwest Coast, IndiaOkeechobee Lake, FloridaMobile Bay, Alabama	CarriMed	1046–1118[a]	–	–	0.10–119	224–27600	• A small-strain rheological model was developed to analyse the viscoelastic properties of mud. • The viscoelastic properties were observed to significantly depend on the applied frequency, for a particular solid content. • The proposed model was semi-empirical and only applicable for stresses below the yield stress.	Jiang & Mehta (1995)
Port of Rotterdam, the Netherlands	Rheometer: 1. Rheometrics RMS-800 2. CarriMed Geometry: 1. Couette 2. Double concentric 3. Cone and plate	1064[a]	Toorman model fitting on steady and transient tests	1	45	0.0136	• The transient experiments for mud showed the time-scale of few seconds for short term structural changes while for long-term structural recovery a time-scale of the order of 10^4–10^5 s was observed. • The Toorman thixotropic model (Toorman, 1997) successfully captured the flow curve of mud by using both short-term and long-term structural changes. • The mud sample displayed higher yield stress values than the china clay due to its cohesive nature. • Below 0.01 strain level, the mud samples exhibited a solid-like behaviour in oscillatory experiments. • A large variability in structure and composition of mud (both in space and time) makes it difficult from practical point of view.	Van Kessel & Blom (1998)
La Penzé Estuary, Morlaix, France	Rheometer: CarriMed Geometry: Parallel plate	1380–1630	Decline in viscosity in flow curve	291–43164	970–143880	775564 – 11.5 $\times 10^7$	• The flow curves of mud samples showed four different transition regimes.	Aubry et al. (2003)
Emden Port	Rheometer:	1013–1142	Stress ramp-up test	0.07–90	–	0.1–2	• A good correlation between the solid content and yield stress of mud was observed for samples from different locations.	(Oberrecht and Wurpts, 2014; Wurpts and Torn, 2005)

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Table 2 (*continued*)

Study area(s)	Rheometer and geometry	Density range (kg. m^{-3})	Rheological method for yield stress	Yield stress range (Pa)	Modulus range (Pa)	Viscosity range (Pa.s)	Main outcome(s)	Ref.
	Rheologica Stresstech HTHP Geometry: Couette						• A decline in viscosity or change in slope of shear rate as a function of stress was found to be a reliable method for yield stress determination, verified by creep and recovery method. • The Toorman model was modified by using the empirical correlations between the rheological properties and solid content.	
Eckernförde Bay, GermanyKieler Förde Bay, Germany	Rheometer: Brookfield RVT 8-speed coaxial rotational viscometer Geometry: Couette	1038–1280	Bingham model fitting on flow curve obtained from controlled shear rate test	1.07–20.50	–	0.111–0.673	• Higher yield stress values along with shear thickening behaviour was observed for mud samples having higher concentrations of silt-sized particles (silt/clay >1). • Lower yield stresses and shear thinning behaviour was found for mud samples having abundance of clay-sized particles (silt/clay <1). • The removal of organic matter by chemical treatment of mud resulted in lower yield stress values and enhanced shear thinning behaviour. • The influence of type and content of organic matter and type of clay on the rheological properties of mud needs to be investigated in detail.	Fass & Wartel (2006)
Weston Supermare Estuary, UK	Rheometer: CarriMed Geometry: Vane	1032–1239[a]	Stress ramp-up test	1–82	10–22000	–	• The results showed an exponential relation between the yield stress and solid content of mud. • The dynamic bulk density, viscoelastic properties and water turbidity from the mud bed was determined in response to plane shear waves at a fixed frequency in a flume.	Babatope et al. (2006)
Hangzhou Bay, China	Rheometer: Rheometrics RMS-605 Geometry: 1. Couette 2. Cone and plate	1145–1634	Worrall-Tuliani and Dual Bingham model fitting on flow curve obtained from controlled shear rate test	1.06–182.75	0.02–15	0.002–1.225	• The outcome of this study showed that Dual-Bingham model is much easier to implement than Worrall-Tuliani model for the flow curve of mud. • The results showed that both steady and dynamic rheological properties of mud vary exponentially as a function of volume concentration of solids, with fitting parameters dependent on clay content, organic matter content, particle size distribution, mineral composition, etc.	Huang & Aode (2009)
Cassino Beach, Patos Lagoon, Brazil	Rheometer: Brookfield RVT 8-speed coaxial rotational viscometer Geometry: Couette	1050–1300	Bingham model fitting on flow curve obtained from controlled shear rate test	1.05–7.6	–	0.02–4.7	• The shear strength of remoulded samples was observed to be 2-3 orders of magnitude lower than the strength of sediment bed determined by vane or penetrometer.	Reed et al. (2009)

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Table 2 (*continued*)

Study area(s)	Rheometer and geometry	Density range (kg. m^{-3})	Rheological method for yield stress	Yield stress range (Pa)	Modulus range (Pa)	Viscosity range (Pa.s)	Main outcome(s)	Ref.
Cassino Beach, southern BrazilAtchafalaya mud stream, LouisianaNeuse River Estuary, North Carolina	Rheometer: Brookfield RVT 8-speed coaxial rotational viscometer Geometry: Couette	1132–1138	Bingham model fitting on flow curve obtained from controlled shear rate test	1.7–5.4	–	1.9–70	• The flow curves obtained from Brookfield with fixed shear rates (Newtonian fluid) and (Krieger and Maron, 1954) approach with variable shear rates (Non-Newtonian fluid) matched quite well. • The clay content, its surface area and its interactions with organic content can significantly influence the rheological properties of mud, which needs further investigation.	Faas & Reed (2010)
Hendijan Coast, Persian Gulf	Rheometer: Anton Paar Physica MCR 300 Geometry: Parallel plate	1417–1545[a]	Bingham model fitting on flow curve obtained from controlled shear rate test	20–98	3122–24,993	3.1–13.7	• The steady (i.e., Bingham) rheological parameters were significantly affected by the water content. • The dynamic (i.e., viscoelastic) rheological properties were observed to by highly dependent on frequency. • The large differences in the magnitude of both steady and dynamic rheological properties between kaolinite and mud highlighted the necessity of direct measurements on natural mud samples.	Soltanpour & Samsami (2011)
German Ems Weser estuaries	Rheometer: Anton Paar Physica MCR 301 Geometry: Parallel plate	1035–1065[a]	Extrapolation (i.e., Bingham) of flow curve obtained from stress ramp-up test	1–13	–	0.007–0.01	• The dependence of apparent viscosity of mud on the solid fraction and shear rate was investigated. • The flow curve of mud was fitted with a modified Worrall–Tuliani model using parametrization of rheological properties.	Knoch & Malcherek (2011)
Suisun Bay, California	Rheometer: AR2000ex, TA Instruments Geometry: Vane	1641	Cross over between G′ and G″ in amplitude sweep test	55.7	–	–	• The results showed an exponential relation between flow-point stress (i.e., bed yield point) and the solid concentration. • A similar exponential function was used for other locations (i.e., Grizzly Bay) where the potential exists for fluid mud formation.	Samsami et al. (2012)
Yangcheng Lake, ChinaShoal of Hangzhou Bay, ChinaMouth of Yangtze River, China	Rheometer: Rheolab-QC, Anton Paar Geometry: Vane	1650–1761	1 Stress ramp-up test 2 Stress growth test at fixed shear rate using Vane 3 Herschel–Bulkley model fitting on flow curve obtained from controlled shear rate test	772–3960 303–4950 89.64–220.75	–	11.28–119.69	• The outcome of this study showed that all the investigated approaches produced different values of yield stress.	Yang et al. (2014a)
Mouth of Yangtze River, China	Rheometer:	1240[a]	–	–	–	4.1×10^6	• The sandy sediments displayed typical thixotropic behaviour while the cohesive mud and kaolin samples showed anti-thixotropy at lower shear rates.	Yang et al. (2014b)

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Table 2 (*continued*)

Study area(s)	Rheometer and geometry	Density range (kg. m^{-3})	Rheological method for yield stress	Yield stress range (Pa)	Modulus range (Pa)	Viscosity range (Pa.s)	Main outcome(s)	Ref.
	Brookfield viscometer (DV-II) Geometry: T-bar spindles						• The complex viscosity of mud was observed to decrease by applying oscillatory load, which even become stronger at higher oscillatory frequencies. • The recovery time after fluidization was longer for cohesive mud and kaolin as compared to the sandy sediments.	
Suisun Bay, California	–	1641	1 Bingham and Casson model fitting on flow curve 2 Creep test	175–217	–	0.84–11	• The definition and implementation of nautical bottom concept in port channels requires an understanding of the biochemical effects on the rheological properties of mud and resistance against ship movement.	Mehta et al. (2014)
Lianyungang, China	Rheometer: Thermo Scientific HAAKE RheoStress 6000 Geometry: Couette	1098–1305	Dual Herschel–Bulkley model fitting on flow curve obtained from controlled shear rate test	0.358–28.029	2–1050	0.001–1.483	• The outcome of this study showed that the influence of consolidation time and temperature on the rheological properties (i.e., yield stress) of mud became stronger as a function of increasing solid content. • Two regions, i.e., elastic dominant and viscous dominant, were observed in the amplitude sweep tests for mud. • The steady and dynamic rheological properties showed an exponential relation with the sediment volume concentration.	Xu & Huhe (2016)
Adriatic Sea Sediments, Po delta,ItalyMediterranean Sea Sediments, Cap de Creus Canyon, France	Rheometer: Rotovisco RV-12, Thermo Haake Geometry: Couette	1111–1239[a]	Bingham and Herschel–Bulkley model fitting on flow curve obtained from controlled shear rate test	5–4800.35–300	–	–	• A viscous resistance term was obtained by normalizing the flow curve (i.e., by dividing the shear stress and shear rate by a reference value). • A linear correlation between the viscous resistance and strength parameters (viscosity, yield stress, etc.) of sediments was observed, which provided an easy and simple approach for approximating flow properties.	Jeong & Park (2016)
Port of Santos, Brazil	Rheometer: Rheolab-QC, Anton Paar Geometry: Vane	1109–1310	Bingham model fitting on flow curve obtained from adapted Claeys protocol	10.6–567.2	–	–	• The results showed the spatial variability in rheological properties of mud even at a reach of 3 km, which highlighted the necessity of detailed rheological analysis of mud.	Carneiro et al. (2017)
Yueqing Bay, China	Rheometer: AR-G2, TA Instruments Geometry: Parallel plate	1370	Maximum stress point in amplitude sweep test	38	2×10^7	–	• The oscillatory strain amplitude was observed to significantly influence the mud fluidization. • The frequency of oscillation displayed negligible effect on the viscoelastic properties of mud obtained within the linear viscoelastic (LVE) regime.	Yang et al. (2018)
Chorfa dam, Algeria	Rheometer:	1032–1254[a]	Empirical fitting of flow curve obtained from	0.011–29.39	–	0.0002–0.0164	• The results showed a non-Newtonian behaviour along with the increase in	Messaoudi et al. (2018)

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Table 2 (*continued*)

Study area(s)	Rheometer and geometry	Density range (kg. m^{-3})	Rheological method for yield stress	Yield stress range (Pa)	Modulus range (Pa)	Viscosity range (Pa.s)	Main outcome(s)	Ref.
Geometry: Couette	Thermo Scientific HAAKE RheoStress 600 • The data of mud samples was best fitted by using power law model.		controlled shear rate test using: •Power law model • Herschel–Bulkley model • Bingham model • Casson model				viscosity by increasing the solid concentration of mud higher than the critical concentration. • The shear thinning behaviour was evident for the mud samples.	
West Lake Hangzhou, China	Rheometer: Rheolab-QC, Anton Paar Geometry: Vane	1032–1426[a]	Stress ramp-up test	25–2570	–	8.29×10^{-7} – 4.09	• The sediments displayed non-Newtonian and shear thinning behaviour, which was described by Carreau model. • The results showed an exponential increase in zero shear viscosity and critical shear stress as a function of sediment concentration while the corresponding shear rate and critical shear rate were found to be independent of solid content.	Yang et al. (2018)
Port of Santos, BrazilPort of Rio Grande, BrazilPort of Itajaí, BrazilAmazon South Channel	Rheometer: Rheolab-QC, Anton Paar Geometry: Vane	1085–1512	Bingham model fitting on flow curve obtained from adapted Claeys protocol	5–379	–	–	• A correlation between viscous amplitude of tuning fork and the Bingham yield stress of mud was developed by using four mud samples having significantly different physical properties.	Fonseca et al. (2019)
Krishna-Godavari basin, Bay of Bengal	Rheometer: Anton Paar Physica MCR 52 Geometry: Couette	1142–1452[a]	–	–	0.003–76.3		• The results showed a variation in viscosity values from 76.3 to 0.003 Pa s as a function of density (1142–1452 kg. m^{-3}), temperature (5–15 °C) and shear rate (0–1000 s^{-1}).	Chandrasekharan Nair et al. (2019)
Lianyungang Port, China	Rheometer: Anton Paar Physica MCR 302 Geometry: Couette	1107–1546	1 Flow curve from shear rate ramp-up test 2 Decline in G′ from strain amplitude sweep test	0.014–380	300	0.002–0.22	• The static and fluidic yield stress values showed an exponential relation with the bulk density of mud. • The frequency of oscillation showed a negligible effect on the elastic regime while the transition and viscous regimes were significantly influenced by frequency during amplitude sweep tests. • The large amplitude oscillatory tests (i.e., stress waveform and Lissajous pattern by the Fourier transformation method) showed an increase in nonlinearity at the transition regime. •	Nie et al. (2020)
Hemipelagic marine sediment	Rheometer:	1170–1340	Bingham model fitting on the ramp-down curve of controlled shear rate test	18–702	–	8.9–126.4	• The mud sample showed the existence of a yield stress even at 10% of particle concentration.	Knappe et al. (2020)

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Table 2 (*continued*)

Study area(s)	Rheometer and geometry	Density range (kg. m^{-3})	Rheological method for yield stress	Yield stress range (Pa)	Modulus range (Pa)	Viscosity range (Pa.s)	Main outcome(s)	Ref.
Salton Sea mud volcano Cone and plate	Thermo Scientific HAAKE Rheoscope 1 Geometry:	1670–1760		145–769		9.3–125.1	• The yield stress and consistency of sediments was observed to increase by increasing the particle concentration.	
Taiwan shoal slope, South China Sea	Rheometer: RST rheometer Geometry: Vane	1312–1468	Herschel–Bulkley model fitting on flow curve obtained from controlled shear rate test	9.494–264.112	–	0.3–6	• The results showed an increase in yield stress and viscosity values (about 36.3%) by decreasing the temperature from 22 °C to 0.5 °C. • At a particular temperature, the yield stress and viscosity values of the sample having the density of 1468 kg. m^{-3} were about 24 times greater than the values of the sample having density of 1312 kg. m^{-3}.	(Guo et al. 2020, 2021)
Port of Hamburg, Germany	Rheometer: Thermo Scientific HAAKE MARS I Geometry: Couette, Vane, Parallel plate	1020–1500	1. Stress ramp-up test 2. Creep test 3. Decline in moduli from stress amplitude sweep test 4. Stress growth test	0.2–550	$0.2 - 3 \times 10^4$	0.002–0.22	• Stress ramp-up test with Couette geometry was proved to be a fast, reliable and repeatable test for measuring yield stresses of mud. •The yield stresses (static and fluidic) showed a significant dependence on density (depth variation) and organic matter content (spatial variation). • The density-yield stress correlation was observed to be significantly different for natural mud samples, diluted mud samples and degraded mud samples. •An empirical model was proposed to fit the two-step yielding behaviour of mud. • Structural recovery in mud was observed to vary as a function of density, organic matter content, pre-shear rate and shearing geometry. • A critical value of fluidic yield stress (50 pa) was used to define the nautical bottom in the port of Hamburg.	(Kirichek et al., 2020, Shakeel et al., 2019a, 2020a, d, c, b, 2021a, Shakeel et al., 2021b, Shakeel et al. 2021c, Shakeel et al. 2022a, Shakeel et al. 2022b, Zander et al., 2022)

[a] Calculated from weight percentage.

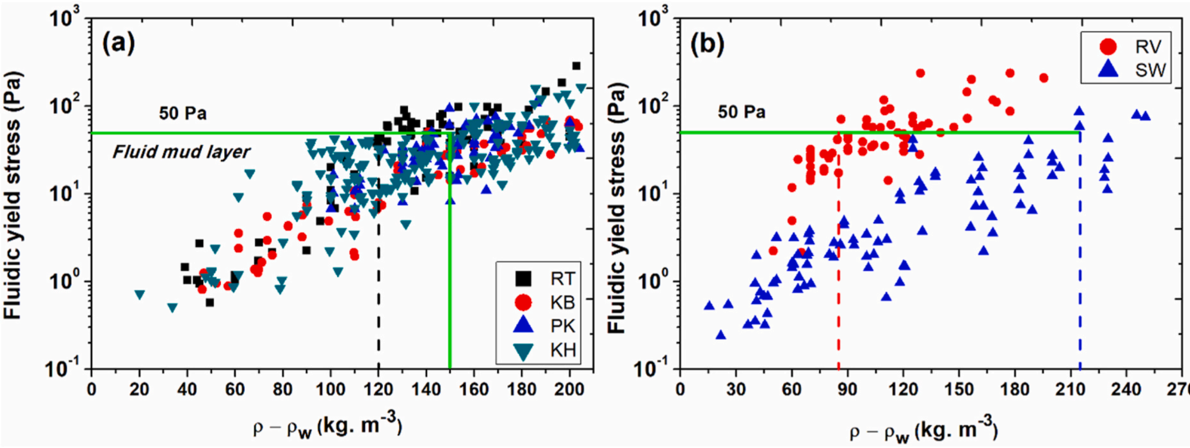

Fig. 6. Fluidic yield stress as a function of excess density ($\rho - \rho_w$) for (a) key locations, (b) far upstream (RV) and far downstream (SW) locations in Port of Hamburg, Germany. Green solid line represents the critical value of yield stress (50 Pa) and density (1150 kg. m^{-3}) for the fluid mud characterisation. Dashed lines represent the critical density value for RT, RV and SW locations corresponding to 50 Pa. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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 (Wurpts and Torn, 2005). 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 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. 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 boundaries for sailing ships are still an open question to investigate and will be analysed with adapted ship handling simulators.

In addition to the yield stress, time-dependent properties or structural recovery is one of the very frequently observed complex rheological behaviours of the mud. This peculiar property can significantly influence the yield stress values (lower yield stress values for disturbed sample/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 hysteresis area (obtained from the time-dependent test) for mud from different locations of Port of Hamburg is presented in Fig. 7a. 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 criterion of the fluid mud layer (50 Pa) is around 1400 Pa. s^{-1}. This confirms that the mud samples having fluidic yield stress below 50 Pa exhibits weak time-dependency (i.e., small hysteresis area), which verifies that the selected yield stress value for the fluid mud characterisation approach will not be significantly influenced by the time-dependent behaviour of mud. Moreover, 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 Fig. 7b. It is clear that the samples having fluidic yield stress lower than 50 Pa shows structural recovery up to 70–100%, which shows that the structure fully recovers itself (within about 500–700 s). For mud samples with fluidic yield stress higher than 50 Pa, the structural recovery is around 30–70%. However, this correlation is not very strong as compared to the correlation between fluidic yield stress and hysteresis area, which shows that the time-dependent test is a fast and reliable method to determine the thixotropic character of mud.

In order to identify the fluid mud layers on the vessel during sampling campaigns, funnel test was performed. This is a simple test to understand the flow behaviour of slurries/suspensions by measuring the

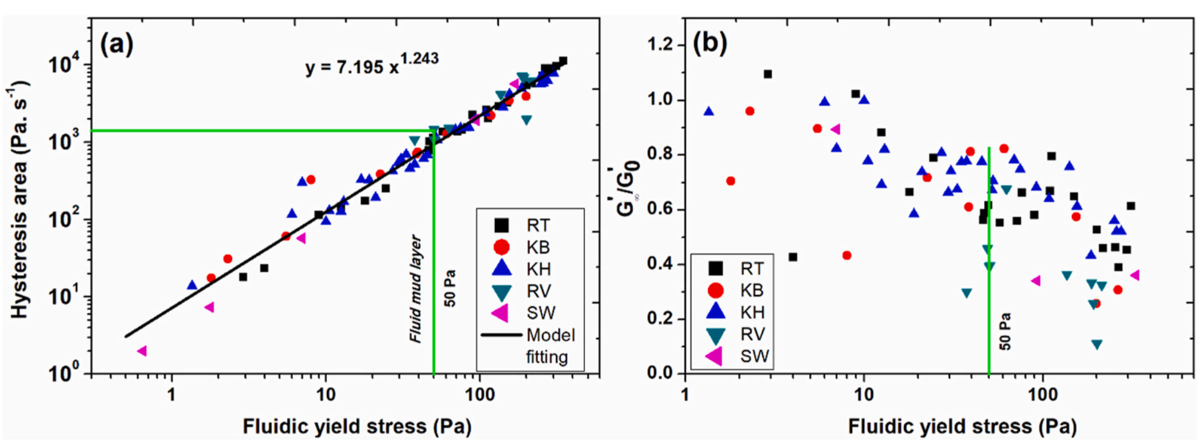

Fig. 7. (a) Hysteresis area (obtained from the time-dependent test) as a function of fluidic yield stress for different locations, (b) equilibrium structural parameter (G'_∞/G'_0) as a function of fluidic yield stress for different locations. Green solid line represents the critical value of fluidic yield stress (50 Pa) and hysteresis area (1400 Pa. s^{-1}) for the fluid mud characterisation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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 Fig. 8. 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 value selected for the fluid mud characterisation approach (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.

In summary, the fluidic yield stress value is an important parameter to define a limit for the nautical bottom in ports and waterways. Fluidic yield stress was linked to the almost complete structural breakdown in fluid mud, which is needed for controllability and manoeuvrability of vessels. It was found that 50 Pa can be used as a criterion for the definition of a fluid mud characterisation for Port of Hamburg, with a corresponding critical bulk density of 1150 kg. m^{-3}. However, for far upstream location RV, this critical bulk density was found to be 1085 kg. m^{-3} and for far downstream location SW, this critical bulk density was observed to be 1215 kg. m^{-3}. This result verifies that bulk density is not a suitable parameter for defining the fluid mud areas in Port of Hamburg and justifies the selection of yield stress for defining navigable mud layer. Moreover, the mud samples having fluidic yield stress below 50 Pa exhibited weak time-dependency (i.e., small hysteresis area), which verifies that the selected yield stress value for the fluid mud characterisation approach will not be significantly influenced by the time-dependent behaviour of mud. In the end, funnel test showed its potential to find the transition between fully flowing material (fluid mud) and pre-consolidated material along with its nice correlation with the yield stress of mud.

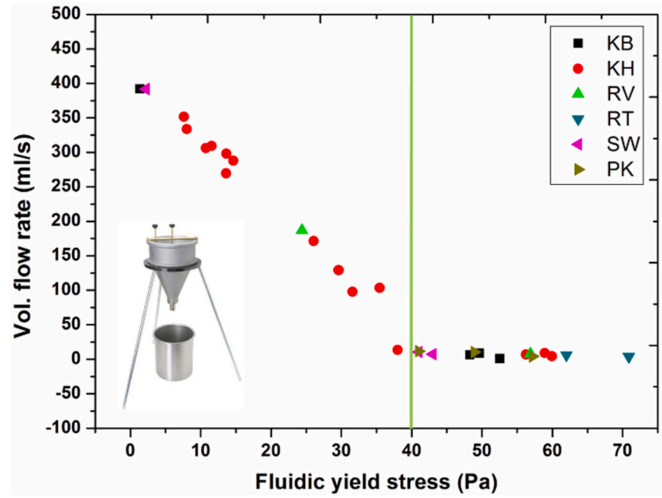

Fig. 8. Volumetric flow rate (obtained from funnel test) as a function of fluidic yield stress for mud samples from different locations. Green solid line represents the critical value of fluidic yield stress (40 Pa) where the volumetric flow rate is almost zero. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

5. Conclusions and future directions

In summary, the approach presented in this review, i.e., the systematic study of most relevant parameters of the system, sample types and locations and degradation has shown that this type of approach is essential for a proper system knowledge. The fluid mud layer, in all the locations it was observed, exhibited relatively small yield stress values and weak thixotropic behaviour. This confirms that despite the fact that rheology of fluid mud is complex, this layer can be navigable due to its liquid-like nature. Furthermore, this study clearly demonstrated that even small amounts of organic matter can significantly change the rheological behaviour of mud. This research further verified the existence of two-step yielding behaviour for mud with the help of rheological and floc analysis. In the end, this study helped in defining a fluid mud layer based on yield stress of mud (50 Pa), which is currently being adopted in key locations of the Port of Hamburg 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 criteria.

The present study is mainly focused on the mud samples collected from Port of Hamburg, Germany. 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. One can wonder whether it is possible to estimate the fluidic yield stress from the static yield stress. The correlation between yield stresses and modulus can in particular be helpful to study the link between the seismic measurements and rheology. Experiments with different clay type, ionic strength, pH, particle size and particle size distribution could be conducted to study the influence of each parameter on the rheological fingerprint (yield stress, moduli and structural recovery) of mud samples. Mineral clay systems with selected biopolymers could be used to mimic in-situ mud samples and investigate the degradation of samples as a function of biopolymer type and content. In future, the correlation between yield stresses and volumetric flow rate from funnel test needs further understanding by performing more funnel tests on-site along with rheological analysis. In the end, the influence of yield stress of mud on the ship navigation needs to be investigated through CFD simulations and *in-situ* pilot experiments.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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