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Effects of recirculation dredging on density, strength, settling and oxygen concentration of fluid mud in the port of Emden

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Abstract

Purpose Recirculation dredging is a port maintenance concept developed in the Port of Emden, Germany to create a navigable fluid mud layer. This study investigates the effects of recirculation on key sediment properties, including density, yield stress, and oxygen concentration.

Methods Six field monitoring surveys were carried out at two locations at different times of the year to assess changes before and after recirculation. Bathymetry, bulk density, yield stress, and oxygen concentration profiles were measured in situ. The settling properties and oxygen concentration levels on collected fluid mud samples were analyzed in the laboratory.

Results The investigation reveals minimal changes in the density of recirculated fluid mud. However, the post-recirculation measurements showed a decrease in yield stress, ranging from 18 to 51% at Große Seeschleuse (GS) and 36% to 52% at Industriehafen (IH). The yield stress and density vary depending on the frequency of dredging. After structural density (1166 kg m^{-3} in GS and 1173 kg m^{-3} in IH), the yield stress of fluid mud increased exponentially. Therefore, monitoring of the yield stress is important for recirculation. A slight increase in oxygen concentration was observed post-recirculation, especially during winter. Yet, the rapid decline in oxygen levels post-mixing in the laboratory showed that sustaining long-term elevated oxygenation levels is not feasible by recirculation dredging alone.

Conclusions The findings highlight the effectiveness of the recirculation on the yield stress, density, and oxygen concentration of fluid mud and illustrate the importance of considering both density and yield stress in sediment management practices. Future research should address the temporal evolution of density, yield stress, and oxygen levels following a dredging intervention and the influence of extracellular polymeric substances (EPS) and organic matter decay on sediment behavior.

Keywords Conditioning · Recirculation dredging · Sediment · Maintenance

1 Introduction

In Europe, around 300 Mt of sediment is dredged every year to maintain the nautical depth of ports and waterways (Snellings et al. 2016). As the removal of sediment disturbs the site-specific hydrodynamic equilibrium, sediment layers rebuild after any intervention, making traditional maintenance dredging a continuous activity. As dredging and reallocation of the dredged material are costly, port and governmental authorities seek new strategies for maintaining the water depth (Salomons and Brils 2004; Erftemeijer and Lewis 2006; Kirichek et al. 2022). One of the alternative maintenance approaches is sediment conditioning. The main goal of all conditioning techniques is to create a navigable fluid mud layer by reducing the strength, density, and settling rate of the sediment (Wurpts and Torn 2005). The thickness of the conditioned, fluidized sediment is then included in the estimates of under-keel clearance, employing the nautical bottom approach (PIANC 2014). Density and yield stress (shear strength) of fluid mud are discussed as criteria for determining the nautical bottom (Wurpts and Torn 2005; Fontein and Byrd 2007; PIANC 2014; Kirichek et al. 2018; Shakeel et al. 2019).

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During conditioning, the strength of the sediment is intentionally weakened by conventional maintenance dredging equipment such as water injection dredgers (WID), bed levellers (or underwater ploughs), and trailing suction hopper dredgers (TSHD). WID is often used for agitation of cohesive sediments by injecting large volumes of water at low pressure and transporting fluidized sediment away from the ports by tidal currents (Wilson 2007; PIANC 2014). WID can also be used for conditioning when the WID-induced density currents settle, forming a navigable fluid mud layer in low-energy regions (Kirichek and Rutgers 2020; Kirichek et al. 2022). Bed levellers can redistribute sediment layers within the port area. Specialized ploughs, I-beams, or old spuds are adopted for bed leveling, reducing the strength of the sediment while ploughing (Rau et al. 2020). Both WID and ploughing processes, as well as the advantages and disadvantages of these methods, are described in Neumann et al. (2024).

Recirculation dredging employs a TSHD for creating low strength, density, and settling rate of the sediment (Wurpts and Torn 2005; Wurpts and Greiser 2007; McAnally et al. 2007). During recirculation, the dredged material is collected by the drag head and transported into the hopper of a TSHD by the suction pipe, while at the same time the bottom door of the TSHD is kept open, ensuring the release of the sediment back into the water shortly after suction. Conditioned material released into the water would go through dewatering and consolidation after the bulk density of mud reaches the structural density near the gelling point (Merckelbach 2000; Winterwerp 2002; Barciela Rial 2019). It has been assumed that as fluid mud is thrust from the suction pipe into the hopper through the air and subsequently settles through the oxygenated water phase, recirculation dredging also oxygenates the sediment, decreasing the settling rate of recirculated mud (Wurpts and Greiser 2007; Kirby et al. 2008). The underlying hypothesis was that recirculation sustains an oxygen-dependent microbial community that excretes extracellular polymeric substances (EPS), creating low-density particle assemblages that settle at a lower rate. For the case of the Port of Emden, this interrelation has been questioned (Gebert et al. 2022), as no correlation between EPS concentration, EPS composition, yield stress, and density could be found, and EPS was not identified as a key regulator. Instead, the study suggested that the density range created by recirculation was mainly determining the favorable yield stress and settling rates.

Surface water hypoxia poses a risk to fish and other aquatic organisms dependent on molecular oxygen (Rogers et al. 2016) and is a frequent phenomenon accompanying the decline in the environmental quality of coastal habitats (Qian et al. 2018). Eutrophication, enhanced primary production, subsequent algae die-off, and organic matter decay contribute to oxygen minimum zones (Rabalais 2010; Geerts et al. 2017; Zander et al. 2022), as does the resuspension of fine-grained organic sediments during dredging interventions (Spieckermann et al. 2022). Hence, it was of particular interest to study the assumed beneficial effect of recirculation dredging on oxygen levels both in the water column and in the fluid mud layer, an aspect not addressed in the earlier study by Gebert et al. (2022).

Naturally muddy sediments in aquatic ecosystems are predominantly composed of fine-grained particles, such as clay and silt, that tend to form flocs and organic matter. The concentration of these suspended cohesive sediments depends on settling velocity, which can be varied over time and place as a result of flocculation. The properties of flocculated matter, including floc density, porosity, cohesion, and settling dynamics, play a critical role in sediment behavior and transport (Mietta et al. 2009; Deng et al. 2019). Furthermore, the interaction between mineral clay particles, microorganisms and their excreted polymers leads to the production of macroflocs (Deng et al. 2019; Shakeel et al. 2020b).

The primary objective of this research is to investigate the effect of recirculation on sediment properties that serve as key indicators for conditioning efficiency (yield stress, density, and settling rate). Furthermore, we tested the hypothesis that sediment recirculation increases the sediment oxygen concentration. The following research questions were addressed:

1. Which operational parameters of recirculation are relevant for maintaining low yield stress, density, and settling rate of fluid mud?
2. How does recirculation affect the yield stress, density, and settling of fluid mud in the Port of Emden?
3. What are the impacts of recirculation on oxygen concentration levels in fluid mud?

2 Materials and methods

2.1 Approach

Six field surveys were conducted before and after recirculation maintenance in the Port of Emden (Germany) in July 2022, August 2022, November 2022, January 2023, June 2023, and July 2023. Two locations, Große Seeschleuse (GS) and Industriehafen (IH) were selected for field surveys since the main recirculation operation occurs in these two areas (see Fig. 1). Measurements of the bathymetry, density, and Bingham yield stress profiles were conducted 7–14 h before (REF) and 3–14 h after recirculation dredging (AD) in the investigation areas on selected points (see Fig. 1). The timing of the last recirculation before each survey was as follows: for the August 2022 survey, recirculation was conducted 5 days before the survey; for the January 2023 survey, recirculation was conducted 1 day before the survey; and for the July 2023 survey, recirculation was conducted

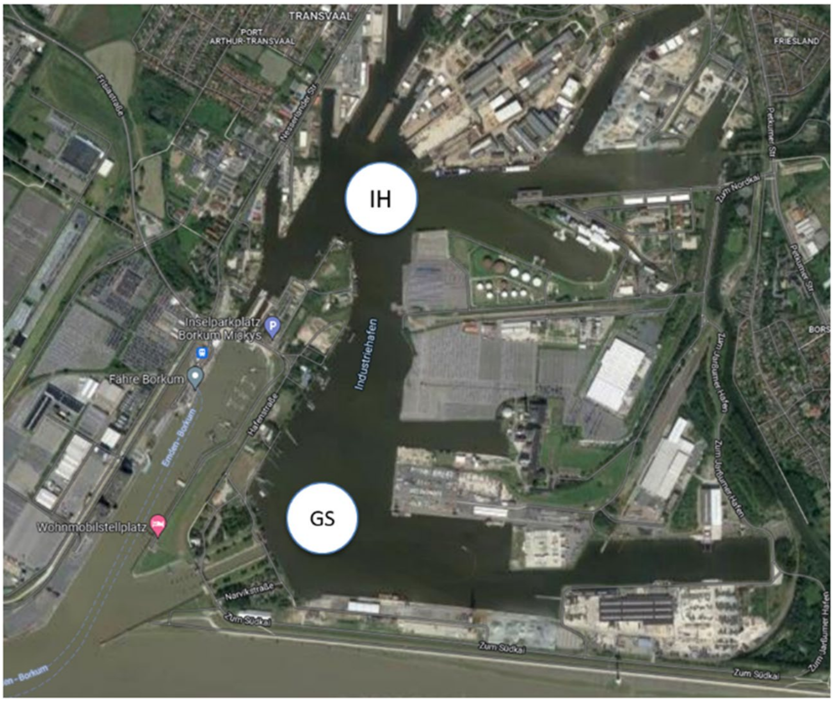


Fig. 1 Monitoring locations: the Große Seeschleuse (GS) and the Industriehafen (IH) in the Port of Emden (Germany). Source of map: Google Earth (2024)

7 days before the survey. Additionally, sediment samples were taken with a Beeker sampler for further analyses and oxygenation experiments in the laboratory.

2.2 In situ measurements

Bathymetry mapping was carried out by the dual-frequency single-beam echosounder Kongsberg EA 440. The lutocline (fluid mud-water interface) and fluid mud-bed interface were detected at 200 kHz and 15 kHz, respectively. The precision of this dual frequency echo sounder depends on the pulse length, which ranges from 64 to 1024 µs for 200 kHz, with a precision of 0.6 cm. For the 15 kHz frequency, the pulse length f ranges from 512 to 8192 µs which equals to the precision of 4.9 cm (Kongsberg 2024). Examples of the echo-sounding data are provided in the supplementary material.

In-situ density and (Bingham) yield stress vertical profiles were retrieved by using a Rheotune probe from Stema Systems. This tool has been frequently used to quantify the strength and density properties of fluid mud for nautical bottom applications (Boer and Werner 2016; Welp and Tubman 2017; Kirichek et al. 2020; Nguyen and Le 2023). The multiprobe MPS-D8/Qualilog8 was used to measure the oxygen concentrations in the water column. Figure 2 shows a schematic of the setup and devices used in the field measurement.

Although exact GPS-supported positioning of the monitoring vessel was intended, spatial variability of at least a few meters has to be accounted for due to limitations regarding precise vessel positioning, introducing spatial variability in the data collection process.

2.3 Laboratory investigations

2.3.1 Gelling concentration

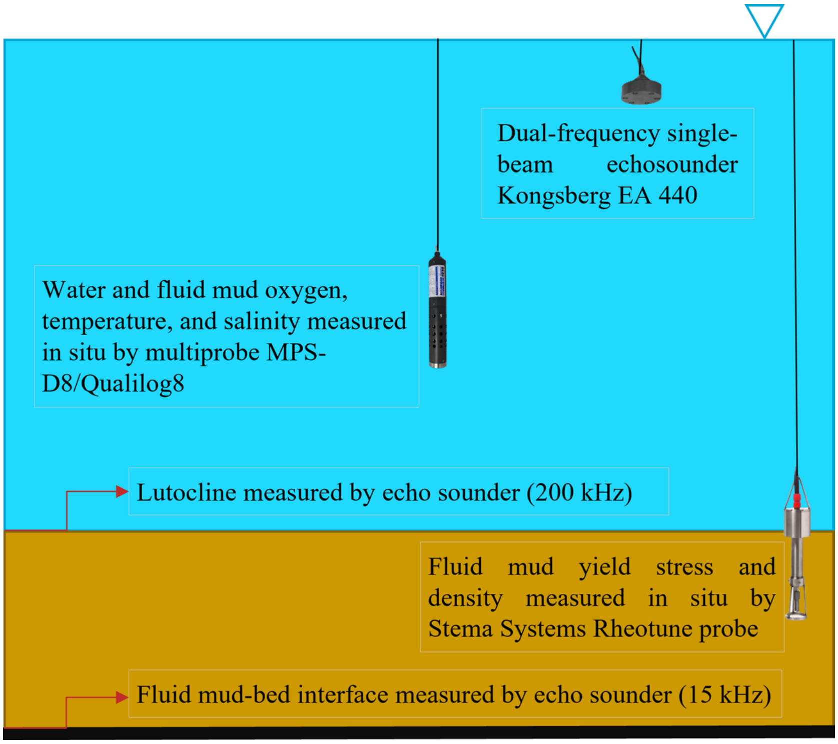
The gelling concentration (φ_g) can be calculated from a series of equilibrium batch settling tests, each initiated with different amounts of solid suspensions, represented by Eq. 1 (Kretser et al. 2003; Nasser and James 2006):

$$\varphi_g\left(h_\infty\right) = \frac{d\left(\varphi_0 h_0\right)}{dh_\infty} \tag{1}$$

where φ_0 and h_0 represent the initial volume fraction of solids and the initial height of the suspension, respectively, while h_∞ denotes the equilibrium height of the sediment bed.

Settling rates were measured using 100 ml borosilicate glass columns, filled with fluid mud samples from GS and IH locations that had been adjusted to four different bulk densities using seawater collected from the field (salinity was 8 ppt). The density of samples from the GS location was adjusted to1149 kg m^{-3}, 1110 kg m^{-3}, 1079 kg m^{-3}, and 1044 kg m^{-3}, the ones from the IH location were adjusted to 1119 kg m^{-3}, 1088 kg m^{-3}, 1069 kg m^{-3}, and 1038 kg m^{-3}. Cameras were strategically positioned for continuous image capture over seven days. These images were subsequently analyzed for changes in the height of the water-mud interface.

Fig. 2 Schematics of the field setup and devices used in the field measurements



The gelling concentration was calculated from the slope of the plot of $\varphi_0 h_0$ versus h_∞ (Eq. 1).

2.3.2 Oxygen concentration in fluid mud

To investigate the hypothesis on the potential increase of oxygen concentration within the fluid mud layer by recirculation, a series of experiments were conducted employing different techniques of forced mud oxygenation (see Fig. 3):

Mixing 1: A mud sample was subjected to a 24-h mixing process using a helical blade mixer operating at a speed of 100 revolutions per minute (rpm), see Fig. 3a. The mixing was performed in a manner that prevented the formation of a vortex, thereby simulating a moderate agitation (see Fig. 3a).

Mixing 2: A three-blade propeller rotating at 100 rpm was used to agitate the mud sample, generating a vortex. This was done to assess the impact of increased shear rates on the process of oxygenation (see Fig. 3b).

Mixing 3: A mud sample was mixed using a wire whisker mixer working at a speed of 200 rpm. Once the maximum oxygen concentration was reached, the mixer was deactivated, and the following decrease in oxygen concentration was observed over a period of time (see Fig. 3c).

Air injection 1: 13.5 L of mud was subjected to air injection using four air pumps from the Superfish Air Kit. The total output of the pumps was 280 L per hour. The purpose of this experiment was to examine the direct oxygenation impact of air pumping over a period of 24 h (see Fig. 3d).

Air injection 2: 300 cc of mud, coated with a layer of oil to hinder the intrusion of oxygen from the laboratory air, was subjected to the injection of air. An air pump was used to inject air at a rate of 70 L per hour for a duration of 24 h (see Fig. 3e).

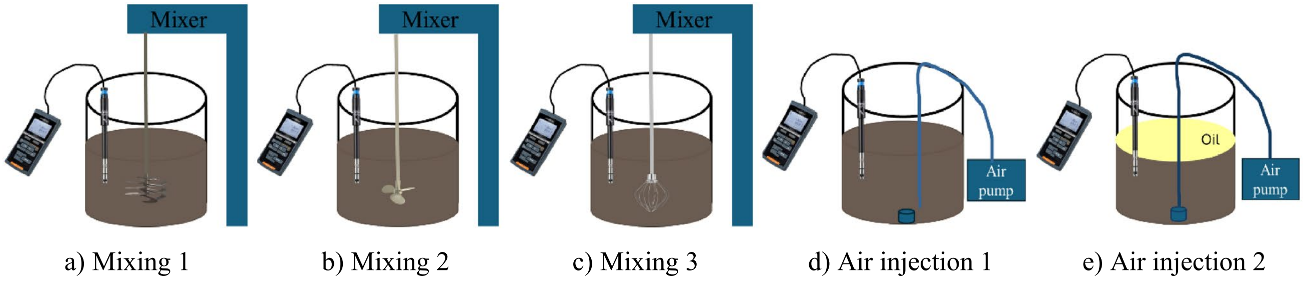


Fig. 3 Schematic of experimental setup of **a** Mixing 1, **b** Mixing 2, **c** Mixing 3, **d** Air injection 1, and **e** Air injection 2

The oxygen concentration was continuously measured during all tests using the WTW Multi 3510 IDS probe.

3 Results

This section presents the findings on the basic sediment characteristics, sediment density profiles, yield stress profiles, thickness of the fluid mud layer, dissolved oxygen levels in the sediment, and laboratory experiments on oxygenation.

3.1 Basic sediment characteristics

In both areas, the particle size distribution of fluid mud is dominated by the silt fraction, with approximately 90% of particles < 63 µm and a d_{50} of 12 and 10 µm at GS and IH, respectively (see Fig. 4). Particle size distribution was also constant in time. Total organic carbon (TOC) ranged between 3.4 and 4.7% of the dry mass, as established in an earlier investigation (Gebert et al. 2023), also showing that the salinity of the water varied seasonally, ranging between 4.3 and 11.9 ppt. Lower values were observed in the season of reduced evapotranspiration and increased precipitation (winter) and elevated values during summer.

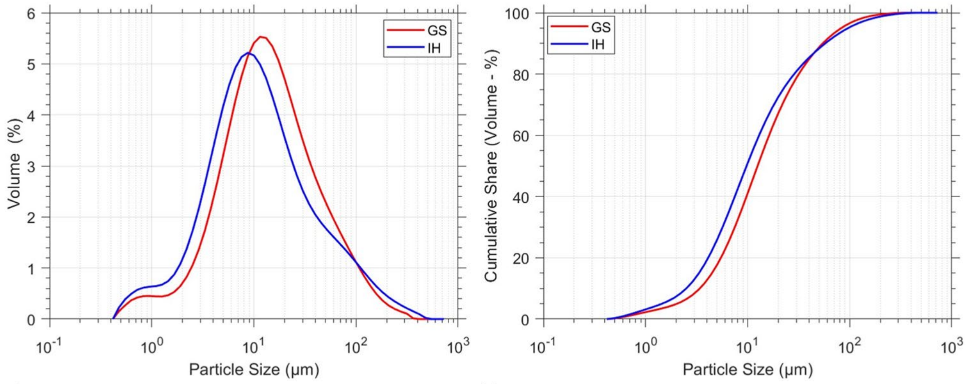
3.2 Density profiles

In field surveys conducted in August 2022, January 2023, and July 2023, the density increased significantly with depth (Fig. 5), which is consistent with the natural settling process observed in fluid mud environments. This phenomenon is attributed to the settling of denser particles towards the bottom by gravity, resulting in a stratified density gradient. A recirculation operation was conducted only one day before the January campaign, which is expected to have caused the observed decrease in the density of fluid mud. The density profiles acquired in July 2023 did not show as steep density gradients as the profiles recorded in other campaigns. This is likely due to an occasional temporary reduction in recirculation frequency due to an operational issue in July 2023. The density of the top fluid mud layer at IH was usually higher than at location GS. Overall, the density profiles showed minimal changes in relation to the recirculation process.

3.3 Yield stress profiles

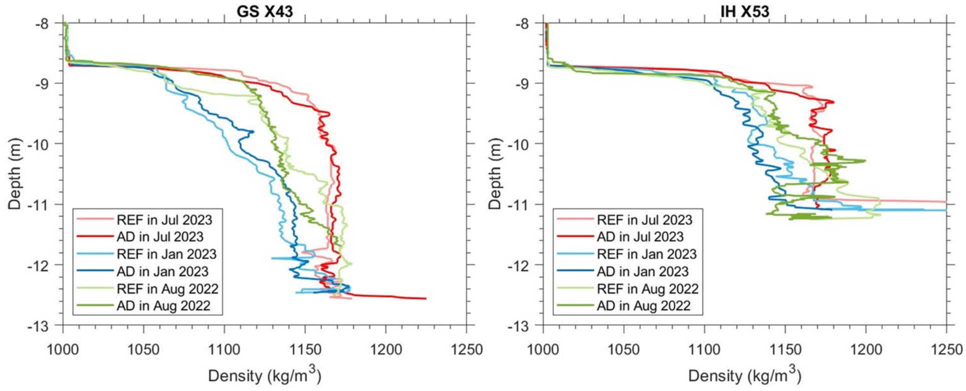
In line with the density profiles, the yield stress profiles increased with depth, both before and after recirculation (Fig. 6). Variations in yield stress were observed before

Fig. 4 Average particle size distribution (**a**) and cumulative share (**b**) at GS and IH, samples collected during six measurement campaigns from July 2022 to July 2023



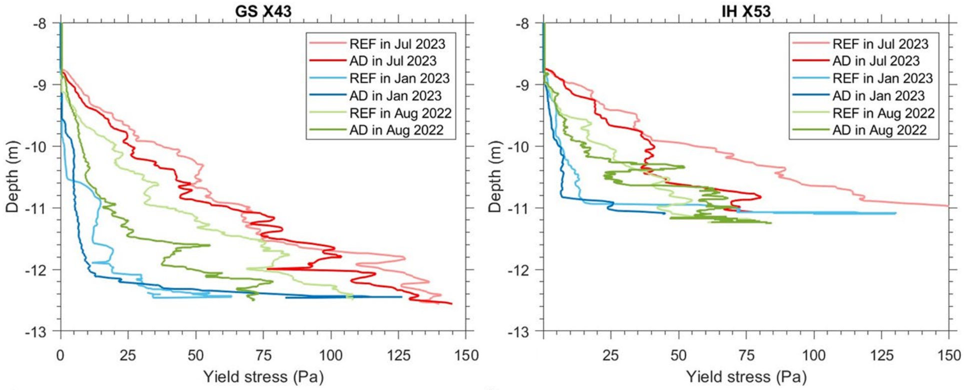
a) b)

Fig. 5 Density profiles measured before (REF) and after (AD) recirculation dredging at GS (**a**) and IH (**b**) in August 2022, January 2023, and July 2023



a) b)

Fig. 6 Yield stress profiles measured before (REF) and after (AD) recirculation in GS (**a**) and IH (**b**) locations in August 2022, January 2023, and July 2023



a) b)

and after the recirculation process. In August 2022, January 2023, and July 2023, at GS, the yield stress decreased by 18 to 51% in depth of 11.9 m, and at IH, it decreased by 36 to 52% in depth of 10.5 m, indicating a recognizable effect of the recirculation process on the yield stress of the fluid mud. In August 2022, a clear difference between before and after recirculation was observed. The lowest yield stress at a depth of 11 m was measured in January 2023 at the GS site. The yield stresses were 20 Pa before and 9 Pa after recirculation. This is assumed to be directly related to the proximity of dredging activities, as the previous recirculation was conducted only one day before the survey. Conversely, the highest yield stress recorded in July 2023 correlates with a longer period since the previous recirculation, which took place seven days before the measurements.

In situ yield stress was directly related to in situ density (Fig. 7), with yield stress increasing non-linearly with increasing density. The relationship between yield stress and density was very similar for both sites. It is seen that for January and July 2023, the data points obtained before and after recirculation dredging align along the same curve. In August 2022, recirculation dredging appeared to have changed this relation at both sites, as after dredging, considerably lower yield stresses were observed for the same density.

3.4 Settling of fluid mud

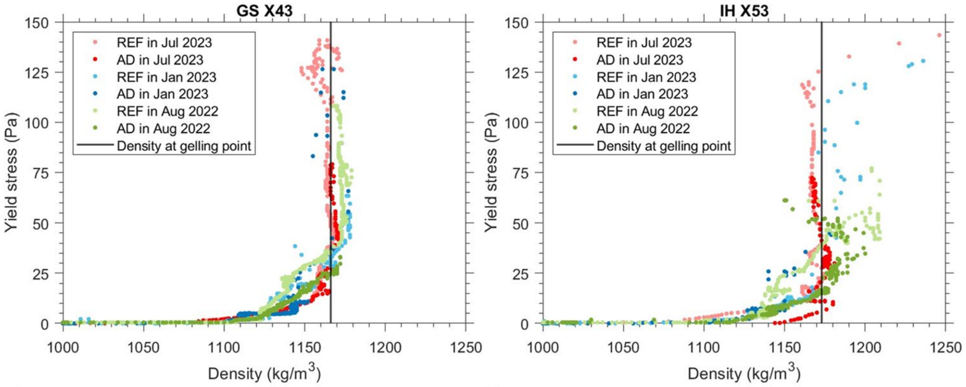
At both locations, the thickness of the fluid mud layer was stable over time (July 2022 to July 2023) and in space. At location GS, the fluid mud layer thickness was found to be between 3.5 and 4.5 m, at location IH it varied between 2 and 3 m. No impact of recirculation dredging on the depth of the lutocline and the fluid mud-bed interface was observed (Fig. 8).

A comparative analysis of settling columns for different fluid mud densities was used to identify the structural density (Fig. 9). The density of the fluid mud at the gelling point for samples from GS and IH locations were estimated to be 1166 kg m^{-3} and 1173 kg m^{-3}, respectively (see supplementary material). The in-situ density measurement showed that fluid mud started developing a non-Newtonian behavior around this structural density (see Fig. 5).

3.5 Oxygen concentration

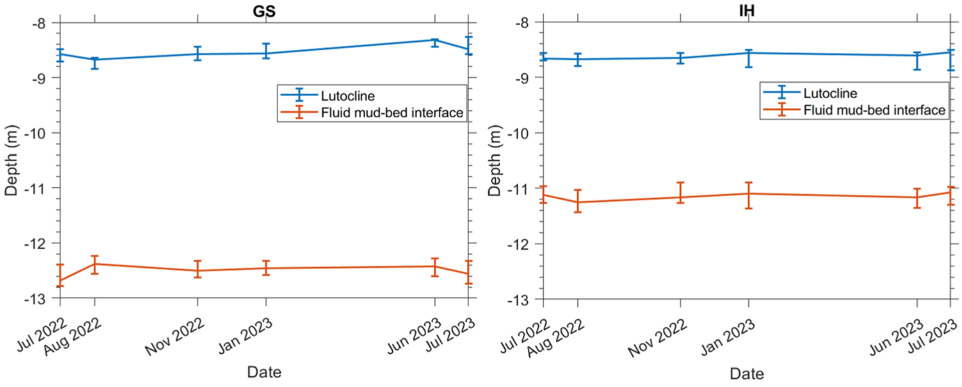
In general, the in-situ concentration of dissolved oxygen declined with depth (Fig. 10). In most cases, a steep decrease was observed above the lutocline, resulting in an oxygen concentration of less than 1 mg l^{-1} at a depth of 3 m below the lutocline. A very subtle increase in oxygen concentration

Fig. 7 Bingham yield stress vs. density measured before (REF) and after (AD) recirculation dredging for fluid mud in a) GSX43 and b) IHX53 in August 2022, January 2023, and July 2023. Black lines show the density of the fluid mud at the gelling point for samples from GS (1166 kg m^{-3}) and IH (1173 kg m^{-3}) locations



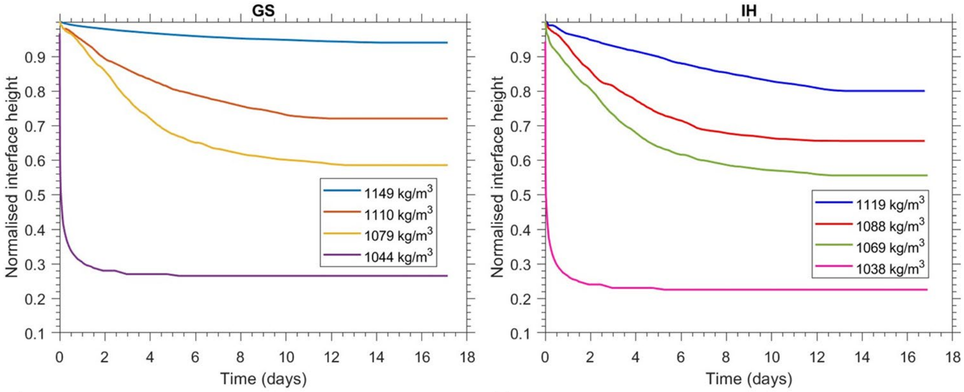
a) b)

Fig. 8 Lutocline and fluid mud-bed interface in GS (**a**) and IH (**b**) location. Error bars represent the range of recorded depths at 6 measurement lines (350 m)



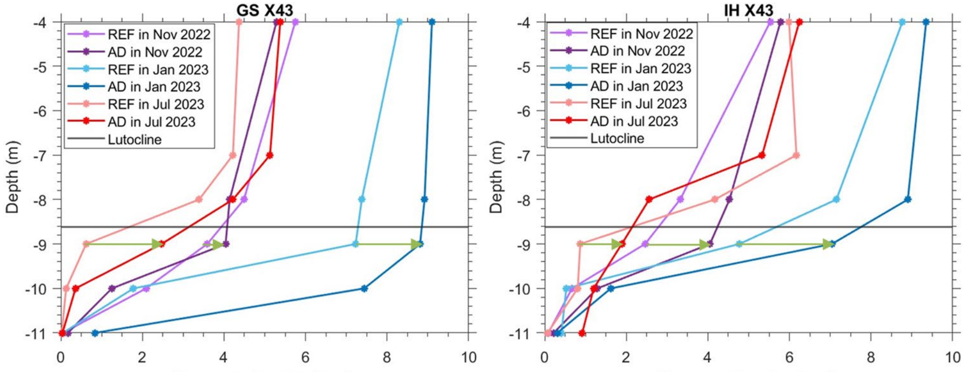
a) b)

Fig. 9 Settling of fluid mud over time at different densities at **a**) GS and **b**) IH location



a) b)

Fig. 10 Oxygen concentration profiles measured before (REF) and after (AD) recirculation dredging in GS (**a**) and IH (**b**) locations between July 2022 and July 2023. The grey horizontal line indicates the depth of the lutocline, and green arrows visualize the shift in oxygen concentration



a) b)

levels after recirculation was detected in the GS location during the January and July 2023 surveys, and in the IH location during the August 2022, January 2023, and July 2023 surveys.

In order to further examine the effect of recirculation dredging on the level of fluid mud oxygenation, a series of laboratory experiments were conducted (Fig. 11) In Mixing 1, the initial oxygen concentration was 0.028 mg l^{-1}, and did not significantly change over a period of 24 h. In Mixing 2, again starting with an initial oxygen concentration of 0.028 mg l^{-1}, the oxygen level increased to 1.44 mg l^{-1} within 30 min and reached 7.7 mg l^{-1} after 3 h of mixing. Mixing 3 also began with an initial oxygen concentration of 0.028 mg l^{-1}, increasing over time and reaching a peak concentration of 9.22 mg l^{-1} within less than 1.5 h of the initiation of recirculation simulation. However, after the

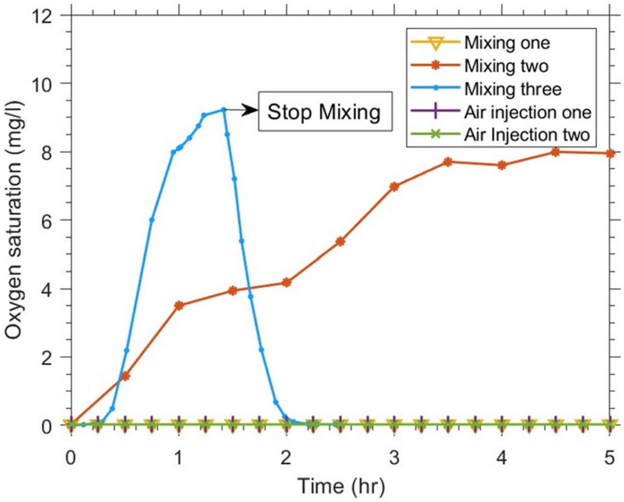


Fig. 11 Development of oxygen concentration in fluid mud during Mixing 1, Mixing 2, Mixing 3, Air injection 1, and Air injection 2

mixing ended, oxygen concentrations decreased rapidly and returned to the initial value within 48 min. In Air injection 1, despite the forced introduction of air bubbles, the oxygen concentration in the mud remained constant at about 0.028 mg l^{-1} throughout the experiment, indicating no significant impact of air injection under these conditions. In Air injection 2, similar results were obtained as no increase in oxygen concentration was observed, and values remained at around 0.028 mg l^{-1}, indicating that air injection alone was not sufficient for oxygenating the sediment.

4 Discussion

The depths of the lutocline and fluid mud-bed interface remained constant over time at both study locations within Port of Emden. Additionally, the in situ density profiles showed minimal changes in density before and after the recirculation process. The recirculation process affected mostly the (Bingham) yield stress of fluid mud. Specifically, post-recirculation measurements revealed a decrease in yield stress. In July 2023, a higher yield stress was observed than at the other dates. This is attributed to the exceptionally long seven-day interval between the recirculation event and the survey, enabling the mud to build up strength in a condition of increased density and hence hindered settling. Fluid mud strength was then effectively lowered by the recirculation process. In contrast, significantly lower yield stress was measured during the survey in January. This can be due to the fact that the recirculation conducted just a day before the January survey did not afford the sediment sufficient time to settle and build up strength. The August 2022 scenario, where recirculation was executed 5 days prior to the campaign, demonstrates an intermediate condition between the January and July observations. The field observations suggest that the frequency of recirculation affects both yield stress and density.

In-situ yield stress was strongly correlated with density, confirming earlier laboratory observations for the same locations (Shakeel et al. 2021; Gebert et al. 2022). For other ports, this relationship was significantly affected by the content of organic matter, enhancing particle–particle interactions and thereby increasing yield stresses at similar densities (Shakeel et al. 2022). As the investigated inner harbor of the Port of Emden is a closed-off system with little hydrodynamic variation and without any spatial gradient of organic matter supply, as opposed to, for instance, the Port of Hamburg (Zander et al. 2022), sediment properties including organic matter content hardly vary in space (Gebert et al. 2022), possibly allowing for the use of density as a single predictor of yield stress throughout all areas of the port. In August 2022, the post-recirculation yield stress was lower than before recirculation at the same density in GS, indicating the possible formation and subsequent disruption of sediment structure due to dredging activities. This deviation was due to the massive recirculation operation conducted prior to the post-recirculation measurements. In this particular campaign, the volume of dredged sediment was significantly higher—60% more than in the subsequent survey in January 2023 and 188% more than in the campaign in July 2023. Therefore, the intensity of recirculation also affects both yield stress and density.

The decrease in yield stress profiles after recirculation, while density profiles remained more constant, can be attributed to the shearing of the sediment during the pumping and back-releasing into the water which induces a reduction in yield stress, reflecting a temporary weakening of the particle–particle interaction and hence the sediment structure (Shakeel et al. 2020a, b; Chassagne 2021). In denser mud, where particles are more concentrated, the settling rate of the particles decreases due to the particles obstructing each other's settling passage, also referred to as ‘hindered settling’ (Chassagne 2021). If the sediment density is lower than the structural densities (1166 kg m^{-3} in GS and 1173 kg m^{-3} in IH), there is no necessity of recirculation dredging since the fluid mud has low yield stress (< 40 Pa, see Fig. 7). Conversely, if the density of fluid mud is higher than structural density, yield stress increases exponentially. From the gelling point, the density alone cannot serve as an adequate criterium for the nautical bottom as material strength can vary significantly. Relying solely on sediment density as the criterion for navigation overlooks the complexity of mud, where similar densities do not guarantee identical yield stresses (Kirichek et al. 2018; Kirichek and Rutgers 2020; Shakeel et al. 2021). Consequently, both density and yield stress are important criteria for the nautical bottom.

The oxygen profiles show low oxygen concentrations beneath the lutocline and levels close to only 4 mg l^{-1} in the overlying water column, which in the Port of Hamburg, for example, represents the limit value for bed leveling and water injection dredging to be carried out during the summer months. Oxygen depth profiles in the investigated Port of Emden showed that oxygen concentrations were highest in the winter campaign, likely due to the combined effect of reduced primary production, lower rates of oxygen-consuming processes, and higher solubility of oxygen at low temperatures. Locally, the oxygen concentration in the fluid mud and in the water was increased slightly by the recirculation process, most strongly so in the winter campaign. However, the consistently low redox potentials measured previously in the fluid mud (Gebert et al. 2023) in combination with the fast decline of oxygen concentrations following forced aeration in the laboratory, suggest that the effect is mainly related to a transient physical mixing of oxygenated water into the fluid mud by recirculation dredging, rather than to a sustainable chemical oxygenation of the fluid mud. The previously measured consistently negative redox potentials suggest that the concentration of reduced solutes and the related oxygen-consuming processes (e.g. oxidation of sulfides, reduced iron and manganese species, ammonium; Spieckermann et al. 2022) preclude maintenance of enhanced levels of dissolved oxygen. The air injection experiments revealed that even rigorous introduction of air bubbles did not increase oxygen levels in fluid mud. In addition to the high biochemical potential for oxygen consumption outlined above, the dense and viscous nature of fluid mud further reduces oxygen diffusion rates. Bubble ebullition transports air swiftly to the surface of fluid mud, allowing for little contact time with the mud and reducing surface agitation of the water compared to other techniques such as recirculation or rotational mixing.

Our measurements show that recirculation of fluid mud led to a reduction in yield stress of 18%—51% (see Fig. 6). The lowest values of yield stress achieved with recirculation were 7–10 Pa. These values are consistent with the lowest yield stresses achieved in WID tests in the Port of Rotterdam (Kirichek and Rutgers 2020). However, the yield stress of the sediment bed before WID was significantly higher (over 170 Pa) than that of the fluid mud before recirculation. The greater reduction in yield stress due to WID is achieved due to the fluidization of sediment. The fluidization of considerable amounts of water into the sediment leads to a reduction in the density of the sediment, so that the yield stress of the fluidized bed decreases faster than with recirculation, where the fluidization process takes place to a lesser extent. Experiments with ploughing have reported that the observed changes in yield stress are minimal (Welp and Tubman 2017). Ploughing results in structural breakup with minimal to no fluidization in the sediment during conditioning. Fluidization is, therefore, one of the key processes that should be considered for effective sediment conditioning in ports.

5 Conclusion

Through a series of field surveys and laboratory experiments, this study has provided insights into the dynamic interplay between recirculation efforts and properties of the generated fluid mud layer, specifically focusing on yield stress, density, settling, and oxygen concentration, in the context of the Port of Emden.

One of the key findings of this research is the consistent depth and thickness of the fluid mud layer observed in the areas of the investigation before and after recirculation. In-situ measurements before and after the recirculation process revealed minimal changes in sediment density. The observed decrease in yield stress post-recirculation highlights the effectiveness of the process in reducing sediment strength. Specifically, yield stress measurements decreased by 18% to 51% at Große Seeschleuse (GS) and by 36% to 52% at Industriehafen (IH) following recirculation. The yield stress varies depending on the timing of the recirculation relative to the measurement period, with significant reductions observed when the interval between recirculation and measurement was short. The study's findings confirm that yield stress is closely correlated with density, reaffirming the importance of considering both parameters when assessing sediment's suitability for navigation and dredging efficiency.

The relationship between density and settling rate supports the definition of a condition that enables the combination of low density with low settling rates, satisfying the navigational requirements (density, yield stress) while minimizing the number of necessary dredging interventions. The interplay between recirculation frequency and settling behavior emphasizes the importance of strategic recirculation scheduling in optimizing sediment dynamics. These findings establish a link between field density and yield stress to the structural density at the gelling point (1166 kg m^{-3} in GS and 1173 kg m^{-3} in IH). From the gelling point, yield stress measurement should be conducted for monitoring the development of strength of fluid mud since yields stress increases exponentially after the gelling point. Future studies could focus on the immediate and temporally sequential evolution of density and yield stress following a dredging intervention to further understand the dynamic processes influencing sediment properties over time.

This study's findings indicate that recirculation dredging can have a modest beneficial impact on oxygen levels, particularly during the winter months when the solubility of oxygen in colder water is higher, and biological oxygen consumption is lower. However, the high concentration of reduced solutes, evidenced by consistently negative redox potentials, precludes a permanent increase in the level of sediment oxygenation. This was corroborated by rapid declines in oxygen levels upon cessation of mixing processes in the laboratory. The transient nature of oxygenation improvements underscores the limited effect of recirculation dredging on sediment oxygen levels and hence the challenges in sustaining elevated oxygen levels in the mud layer. The previously proposed link between an oxygen-dependent microbial community that produces extracellular polymeric substances (EPS) and the observed nautically favourable conditions of low density and low yield stress, therefore, appears unlikely for the case of the inner harbor of the Port of Emden. Future research could address the boundary conditions (e.g. concentration and composition of EPS, microbial community composition and environmental conditions) for the impact of EPS on fluid mud settling rates. Further, the meaning of organic matter properties and its decay for fluid mud density, yield stress and settling rates could be investigated. While recirculation has proven effective in maintaining equilibrium and stability in fluid mud properties, understanding the role of the microbial community and the physical effects of biofilm formation could further enhance comprehension of sediment behavior, enabling optimized sediment management.

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Declarations

Competing interests The authors declare no competing interests.

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