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Agitation dredging of silt and fine sand with Water Injection Dredging, Tiamat and Underwater Plough: a case study in the Port of Rotterdam

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Abstract

Purpose Agitation dredging has gained popularity as an environmentally friendly and cost-effective method for port maintenance. One of the advantages of agitation dredging is the ability to transport sediments out of the port area using natural currents. The effect of the different agitation methods on sediment and water properties has rarely been investigated in a single pilot project. This research aims to study the effects of agitation methods in silt and sand-dominated areas that are frequently maintained.

Methods The effects of water injection dredging, (WID) underwater ploughing (UWP) and Tiamat on sediment properties are investigated in the Port of Rotterdam. In-situ measurements and laboratory measurements are carried out to determine changes in the bed level, the particle size distribution of the bed, the turbidity in the water column and the dispersion distance of the sediment plume due to agitation dredging.

Results The results of the in-situ monitoring of the agitation pilots allow a comparison of the changes in sediment and water properties before, during and after agitation dredging. The production, advantages and limitations of the tested agitation dredging methods are discussed.

Conclusion The in-situ measurements show that WID, Tiamat and UWP can be successfully used for the agitation of sediments and their removal from the silt and sand-dominated areas. The production of the tested agitation methods is higher for silty than sandy sediments. In general, the selection of the agitation equipment can be made based on environmental regulations, sediment properties and hydrodynamic conditions.

Keywords Sediment · Dredging · WID · Bed leveller

1 Introduction

Sedimentation is a common problem in the channels, berths and anchorages of many ports and waterways. As a result, the available water depth tends to decrease, making dredging necessary to maintain the navigable depth. The Port of Rotterdam has a long history of maintaining the navigable depth. The volume of dredged material in the Port of Rotterdam has increased due to the larger container ships and the siltation upstream (Sánchez et al. 2020; Cox et al. 2021). The port is located in the estuary of the Rhine, Meuse and Scheldt rivers, and is affected by the tidal regime of the North Sea (Gandrass and Salomons 2001). Consequently, the Port of Rotterdam is a tide-dominated port, where tides play a crucial role in determining water levels and current patterns. In such ports, the rise and fall of the tides have a significant impact on the sediment transport, nautical depth and access to the port (Wells 1995). In the Port of Rotterdam, the water level can vary up to 2 meters and current velocities can be up to 1.2 m s^{-1}, especially in the narrow parts of the port (Tiessen et al. 2016). Additionally, the Port of Rotterdam is located in the transition zone between a maritime environment and a river environment. Therefore, the port is influenced by both the river and the sea, leading to the sedimentation of both fluvial and marine

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types of deposited sediments (Kirichek et al. 2018). The volume of annual dredged material has already increased by 4 million m^3 since 2011 (see Fig. 1). With the development of the increasing number of container vessels, it is expected that the dredge volumes will continue to rise in coming years (Bhonsle 2022). Another challenge for the port is that around 20 % of CO_2 emissions in the Netherlands come from the use of fossil fuels in the port (PERS 2020). The current situation could pose a long-term challenge due to the emission targets set for the future. The goal is already to reduce 75% less CO_2 in 2025 and 90% less in 2030 than in 2019. By 2030, the use of fossil fuels (especially for dredging) must be reduced by 45% (Ganic 2022). CO_2 emissions in 2019 amounted to 25.4 Mt and the CO_2 emissions in 2021 anounted to 22.4 Mt (Safety4Sea 2020). The development of more sustainable strategies for port maintenance has therefore become increasingly important (de Vriend et al. 2015; Seddon et al. 2020).

Maintenance dredging is usually carried out by relocating the dredged sediment offshore. Trailing Suction Hopper Dredgers (TSHD) are currently the preferred dredging vessels for dredging and relocating the sediments (Kirichek et al. 2018). With this dredging equipment, the sediment is removed from the bottom using a drag head and then transported via a suction pipe into a hopper on board of the vessel. When the hopper has loaded an economically optimal amount of sediment, the dredger transports the material to the designated discharging locations. This port maintenance method is often carried out frequently, therefore it is both costly and time-consuming. In addition, dredging has an impact on water quality and nature and contributes to climate change (Wasserman et al. 2016). Therefore, new more sustainable and efficient dredging strategies have been developed for port maintenance.

Agitation dredging methods use the tidal currents in the estuary to transport the re-suspended sediments away from the dredging areas. Water Injection Dredging (WID) is one of the agitation dredging methods that has gained popularity in recent years (van den Bergs and Bossinade 1987). During WID, the injected water fluidizes the fine sediments creating a density current. This sediment-rich density current moves away from the dredged area under the influence of natural forces. The fluidized sediments move to deeper areas or move to high energy environments, where sediments would not tend to settle and become part of the natural transport again (Wilson 2012; PIANC 2013; Kirichek et al. 2021). Another well-known dredging method used is the underwater plough (UWP), which is used particularly when there are irregularities present in the bed (European Patent Office 1998). UWP (or a bed leveller) is mainly used for relatively small dredging operations and for maintenance dredging in tidal basins where natural sedimentation accumulates. The sediments are displaced to deeper areas within the port basin. UWP is also used in places where other dredging equipment does not have access. The sediment is then pushed to the side where it can be further removed by other dredging equipment (Laboyrie et al. 2018). But as global acclaim for working with nature principles is growing, new agitation dredging methods have been developed for port maintenance. The Tiamat system was developed by the Harwich Haven

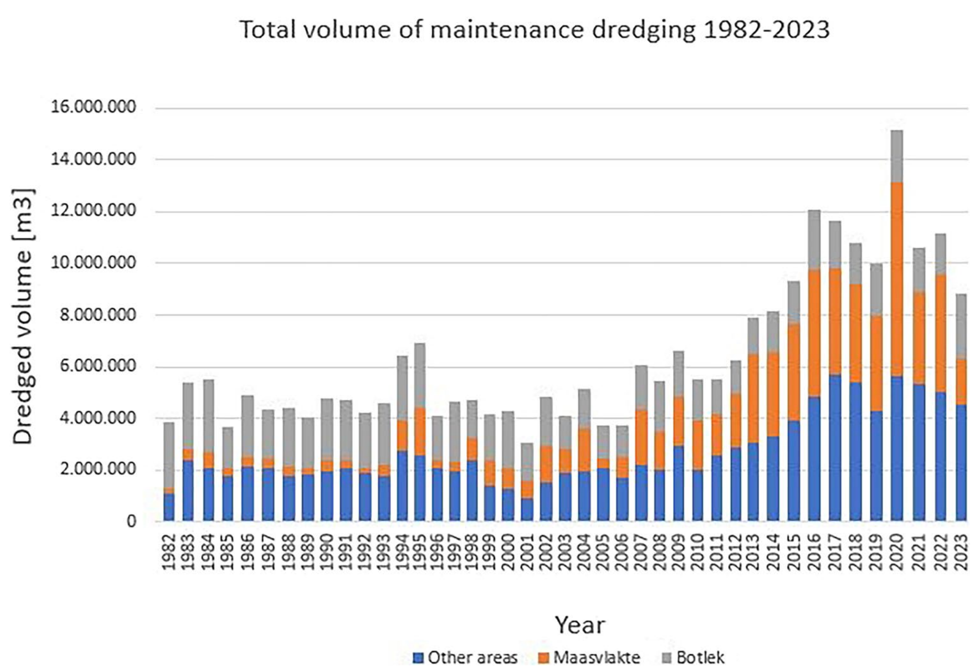

Fig. 1 Dredged sediment volumes in the Port of Rotterdam from 1982 until 2023

Authority. Unlike other techniques, such as WID, which simply inject water into the bottom sediments to fluidize them, the Tiamat system also transports and discharges the dredged sediment higher into the water column, so tidal currents can transport the sediment offshore (Simpson and Vural 2022). One of the advantages of these methods is that they produce fewer emissions during agitation and the sediments remain in the natural processes after dredging (Kirichek and Rutgers 2020; Simpson and Vural 2022).

Although agitation dredging techniques are more frequently used for port maintenance nowadays, the effects of these methods on cohesive sediment proprieties and their environmental impact have not been systematically studied. By testing the agitation methods in different sediment environments, a better understanding of the advantages and limitations of the different dredging methods can be gained. The focus of this research is to investigate the effects of WID, Tiamat and UWP on the bed, particle size distribution, turbidity in the water column and dispersion distance of the sediment plume. The methods are also compared in terms of production rates. The main findings are discussed and the possible outcomes for sediment management in ports are summarized.

2 Methodology

2.1 Location

Two piloting areas are selected for testing agitation dredging in the Port of Rotterdam, the Netherlands (see Fig. 2). The first piloting area, Europahaven (EH) is located in Maasvlakte. This location has a depth of about 19 meters. The bottom sediment distribution in the area consists primarily of fine sand, with a smaller percentage of fines (about 20-25%). The current velocities are relatively low (0.1 - 0.22 m s^{-1}). Due to the proximity of this location to the sea, the salinity levels are relatively high, ranging from 25 to 32 PSU.

The second piloting area, the 2nd Petroleumhaven (PH), is located in Botlek. This area is more strongly influenced by currents (up to 0.6 m s^{-1}). In addition, the area is frequented by many vessels and the bottom consists of a silt layer. At this area, the possible influence of ships navigating the area and thereby affecting sedimentation on the bottom can be investigated. Passing ships can change the path of agitated sediment. Therefore, the experiments were carried out in the study area during the low-traffic period. The depth of this location is around 16 m. The salinity is between 3-22 PSU depending on tides.

Fig. 2 Two piloting locations for testing agitation dredging methods at the Port of Rotterdam: the Europahaven (EH) and the 2nd Petroleumhaven (PH)

Both piloting areas are prone to regular siltation (see Fig. 1), therefore maintenance dredging is often carried out to guarantee the nautical accessibility in these areas. The agitation test areas are located next to each other in both the Europahaven and the 2nd Petroleumhaven. The dimensions of each test area are 200 m by 25 m.

2.2 Agitation dredging methods

In 2022, three agitation methods were tested at both piloting locations during low tide. The Operationele Stromingsmodel Rotterdam (OSR) was used to predict the current velocities and directions during the pilot experiments.

WID was conducted with the vessel 'Mersey'. The Mersey has a length of 43 m and a width of 9.7 m. The jet bar has a width of 12 m (MarineTraffic 2021). There is a row of nozzles on the beam, which are lined up horizontally at equal distances from the jet. The range of the nozzles can vary between 10 and 15 nozzles. The WID process can be divided into three phases (see Fig. 3a). First, the beam is set close to the bottom, and water is injected into the sediment at a low pressure of around 1 to 1.5 bar. The injected water is mixed with the sediment during the fluidization process and the interparticle forces are weakened (Hales 1995). In the second phase, turbulence occurs in a hydraulic jump, whereby the volume of the fluidized sediment increases and the flow velocity decreases (Kortmann 1994). The vertical dispersion distance is limited, which is why the sediments tend to form a density current near the bed without being suspended in the water column. During the third phase of the WID process, the sediment is transported horizontally due to a gravity-driven density current. The balance between injection force, local currents, gravity, and frictional forces determines the behavior of a density current. Various factors, such as sediment density and composition, bottom morphology, and tidal currents, influence the ultimate distance traveled during transport (Sigwald et al. 2015).

The Tiamat system can be used on any workboat equipped with a winch and lifting frame and the appropriate capacity for powering Tiamat Spearman and Benson 2022. In this study, the vessel 'Barney' was used for the agitation with Tiamat. The Barney has a length of 30 m and a width of 13.45 m (MarineTraffic 2021). The sketch of Tiamat is shown in Fig. 3b. The Tiamat version used in the experiment had a width of 8 m. The Tiamat system consists of three hydraulic pumps: two side-mounted water pumps and one suction pump for sediments. Tiamat uses water from the water column, which is injected into the bed via two inlets at a pressure of around 4 bar. The fluidized sediment is then collected and discharged into the water column via the discharge pipe. Due to the different depths at pilot areas, the length of the sediment discharge pipe for the EH and PH sites was set up 12 m and 10 m above the bed, respectively. The discharged sediment was then transported away from the maintenance area by the tidal currents.

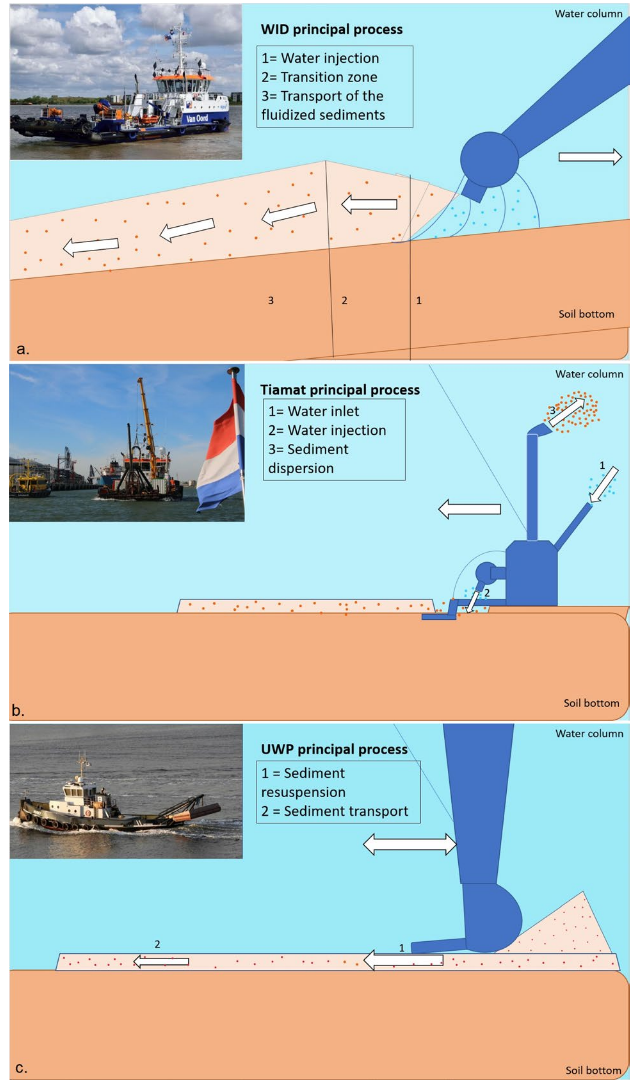

Fig. 3 The working principles of the WID (**a**), the Tiamat (**b**) and the UWP (**c**). See text for details

The vessel 'Husky' was used for UWP agitation. This agitation method was tested only at the PH location. UWP was pulled over the bottom with a tug boat cutting the bottom sediments in layers of about 0.1 m and worked in a back-and-forth movement. The plough has blades that cut through the sediment in front of the frame and push the frame forward until the unit is full or the forces between the sediment is weakened causing the sediment to flow out. (see Fig. 3c). If the sediment remains in front of the device during ploughing, it spreads around moving to deeper areas when ploughing stops.

2.3 Monitoring tools

Sediment properties were monitored before, during, right after and 3 weeks after agitation. A Teledyne Reson SeaBat T50R Multibeam Echosounder was used to detect changes in the bed level. A Swift Turbidity Meter was placed in the outgoing tidal stream for measuring vertical turbidity profiles. A Teledyne RDI WHN Workhorse 600 kHz Sentinal ADCP was used to record the back-scatter data for determining the maximum distance over which the sediment plume can be tracked. The ADCP was only used to track the sediment plume in the water column until the natural sediment variation and the dredged material could no longer be separated. The ADCP data have a blind spot of about 1 meter above the bottom (Dunn and Zedel 2022), so it was not possible to follow the dispersion of the sediment plume at the bed. Density profiles were taken during the study. However, the data was disregarded due to the low accuracy of the measurements. Finally, the Slib sampler was used to collect the sediment samples for the particle-size distribution (PSD) analysis using the Malvern Mastersizer 2000 in the laboratory.

3 Results

3.1 Particle-size distribution (PSD)

The PSD analysis of sediment samples collected before and after agitation dredging showed that WID and Tiamat agitation pilot experiments reduced the amount of finer sediment fraction at the fine sand location (EH), see Fig. 4. Before agitation with Tiamat, the d50 was 183 μm and after dredging the d50 increased to 221 μm. There was also a larger proportion of sediments with a size of 410 μm and more. In the PSD of the WID tests, the d50 value shifted from 123 μm to 175 μm after dredging.

The PSD analysis of the sediment samples at the silt-dominated location (PH) showed minimal changes for both WID and Tiamat pilots (see Fig. 4b). In both cases, the d50 before and after agitation was 19 μm. However, for the sediment samples collected before and after UWP agitation, the d50 value decreased slightly from 18μm to 15μm. The clay flocs on the top of the bed were displaced from the test area, but the total PSD remained relatively unchanged.

3.2 Turbidity

The turbidity measured during agitation dredging of silt was higher than that of fine sand (see Fig. 5). The measured turbidity values varied between the three methods due to the level at which the sediments were displaced. The highest sediment concentrations were found near the bed after WID (see Figs 5a and 5c). However, turbidity values up to 25 NTU were also detected closer to the surface during WID. The turbidity sensor was not able to detect the density currents as the turbidity values in the density currents exceeded the limits of the turbidity sensor (1000 NTU). In contrast, the Tiamat-induced turbidity was detected in the middle of the water column at the depth at which the sediment was discharged (see Figs 5b and d). The turbidity near the bed was highest in UWP tests (see Fig. 5e). Due to the physical mechanism of UWP, where the plough was pulled across the bed, only the sediment at the bed was disturbed, resulting in turbidity near the bottom. This was confirmed by the turbidity profile at depth, as the turbidity changes were detected only 5 m above the bed during UWP agitation. In general, turbidity levels returned to equilibrium within 20-55 minutes after the agitation.

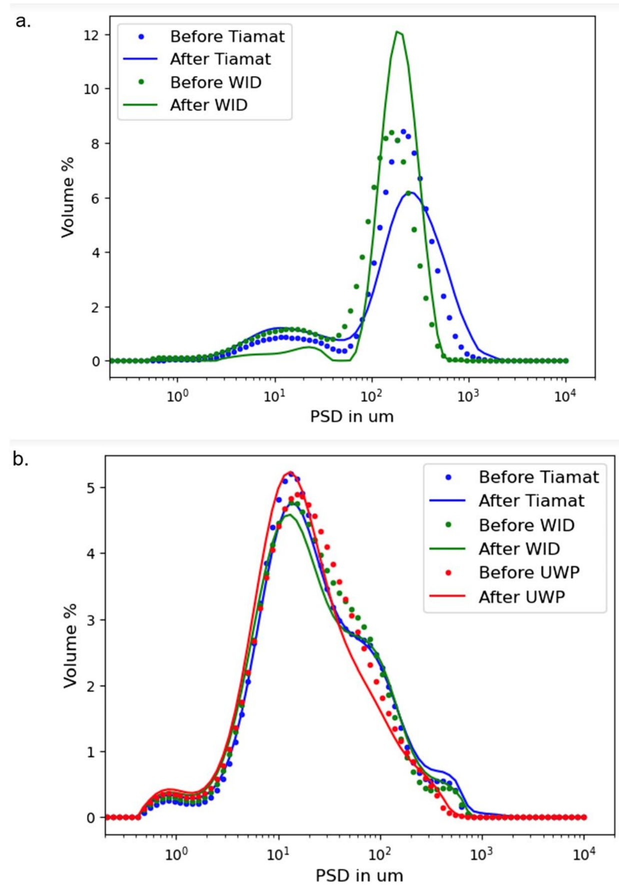

Fig. 4 PSD analysis before and after agitation of fine sand (**a**) and silt (**b**). Green, blue and red lines represent the PSD analyses for WID, Tiamat and UWP pilots, respectively. The dashed line represents the PSD before dredging and the solid line shows the PSD after dredging

3.3 Dispersion distance of the sediment plume

The sediment plume after WID could be tracked 401 m from the sand-dominated area. The width at which the plume was

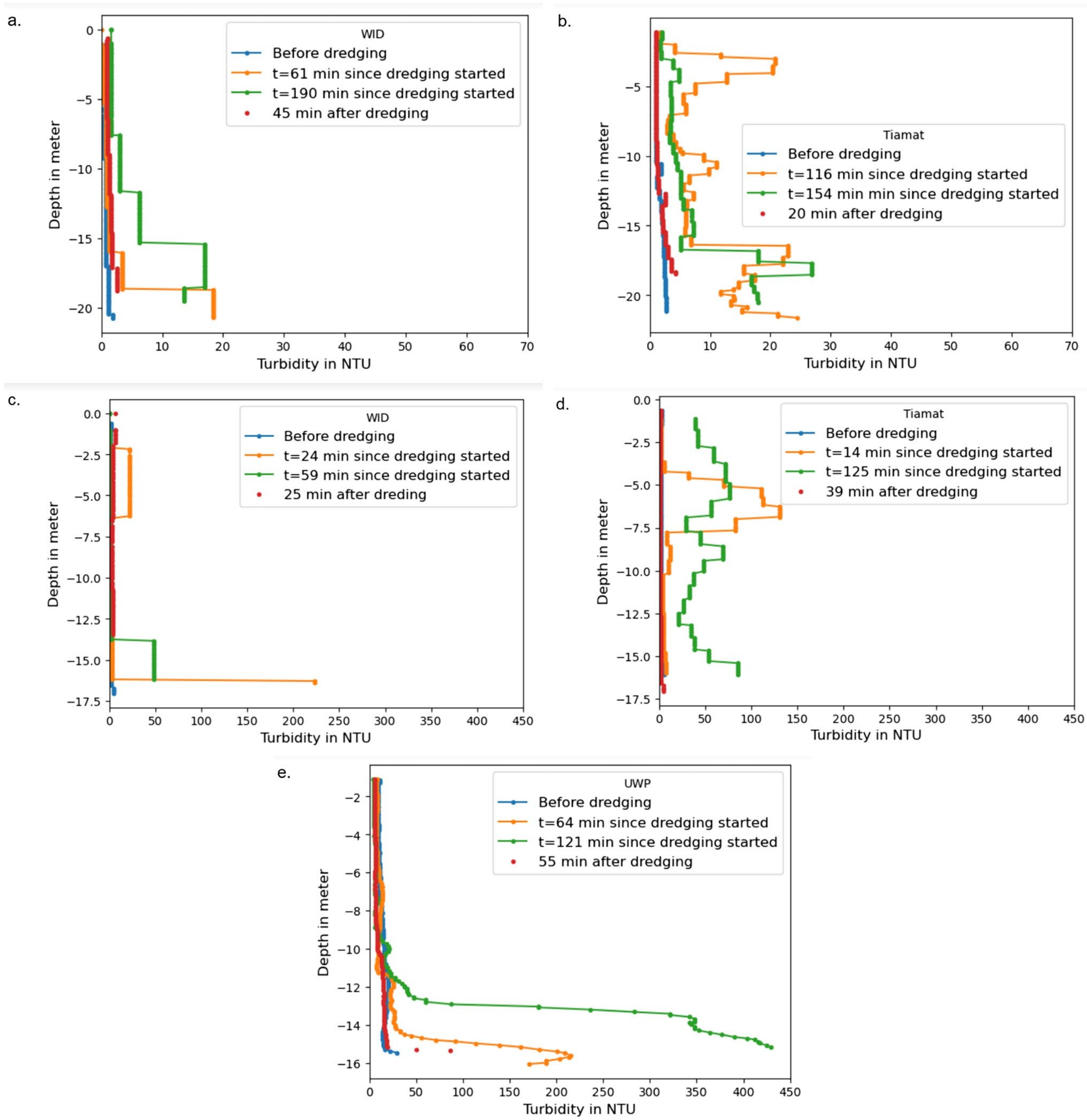

Fig. 5 The turbidity profiles measured before, during and after agitation of fine sand (a,b) and silt (c-e). Blue profiles show the reference turbidity, orange and green profiles show the turbidity profiles during agitation, and red profiles show the turbidity levels after agitation

still recognizable was about 27 m (see Fig. 6a). This was a significantly smaller propagation distance than that with Tiamat agitation at the same location, which was 681 m x 68 m (see Fig. 6b). Although the current velocities were higher with WID compared to Tiamat agitation, the tracked dispersion distance of the sediment plume was also greater with Tiamat agitation compared to WID for the silt-dominated area (see Figs 6c and d). The plume for WID could be detected up to 912 m and 33 m from the pilot area. The Tiamat-induced plume could be tracked up to 3923 m and 227 m away from the testing site as the sediment was discharged higher in the water column. For UWP agitation, the sediment plume could not be detected with the ADCP during agitation. Therefore, a more suitable monitoring method for tracing near the bottom sediment would allow a more detailed comparison.

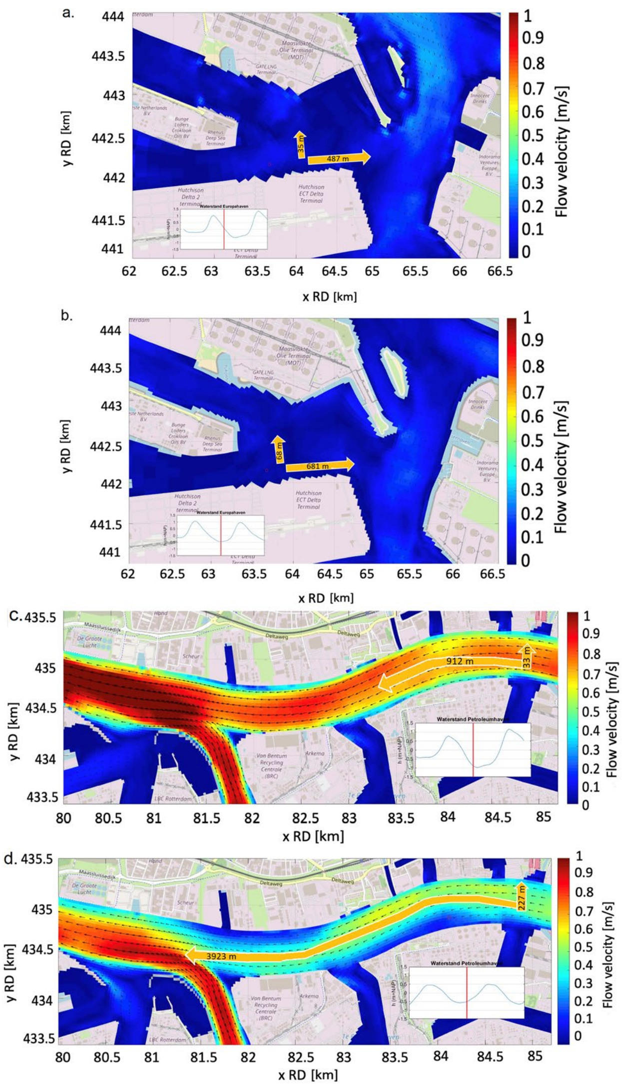

Fig. 6 Current velocities and dispersion distance of the sediment plume after WID (**a**,**c**) and the Tiamat (**b**,**d**) agitations

3.4 Bed level

The bathymetric surveys confirmed the changes in the bed level as a result of agitation dredging carried out by WID, Tiamat and UWP (see Fig. 7). The bottom of maintained areas was flattened during all agitation pilots. These results were consistent with other agitation pilots conducted elsewhere (Kirichek et al. 2021). Agitation with WID resulted in a depth decrease of up to 0.8 m in the sand-dominated area (see Fig. 7a. In the silt-dominated area, the depth decreased up to 1 m (see Fig. 7c). In general, the bed level changes of the agitation dredging with Tiamat were consistent with that of the WID in both areas. Although the surface of the bed level was irregular before dredging, the bed level in sand- and silt-dominated areas decreased up to 1 m and 0.8 m, respectively (see Figs 7c and d). The TSHD trails that were visible on the profiles as pits before dredging were filled with sediments after agitation dredging with Tiamat as it flattens the area similarly to WID. Finally, UWP agitation resulted to a depth decrease of up to 0.8 m (see Fig. 7e). The outcome of UWP agitation was comparable to the other two agitation methods tested in the silt-dominated area. During the third week of monitoring, additional traces were observed in the multibeam echosounder data within the pilot area, indicating that TSHD dredging has taken place.

Sedimentation is found to be lower using Tiamat method compared to WID and UWP agitation during the monitoring weeks after dredging. This is because the Tiamat system discharges the sediment higher in the water column, thus it can be transported farther away. Furthermore, the sediment concentration of the plumes discharged by Tiamat is lower than the concentration of fluidized sediments by WID and of weakened sediment by UWP. Another reason may be due to seasonality and sedimentation from upstream. The Tiamat pilot was conducted in October and the WID and UWP pilots were conducted in December. The amount of sedimentation is typically lower in October than in November in this area, with a potential difference of up to 250000 m^3 in the entire port, with the highest amount occurring at the Maasvlakte (see Fig. 1).

3.5 Production rates

The dredging time and the volume of dredged material are used to estimate the production rate. The volume of dredged material is estimated using the bathymetry data before and after dredging. Additionally, the dredging time is extracted from the dredging log data. The production rate is given in m^3 OH^{-1} where OH is the abbreviation for Operational Hours. The results are shown in Table 1. The production rate is higher for the WID and Tiamat agitation experiments in silty port areas than in sandy locations. The production rate of WID is the highest for agitating both silty and sandy sediments.

4 Discussion

The proportion of fine-grained sediments decreases significantly after agitation dredging in the area dominated by fine sand. This means that more frequent use of agitation in this location can lead to fine-grained sediments being flushed out of the area. This can cause the PSD of the sediment bed to segregate over time as a direct result of the dredging (Kirichek et al. 2021). From the agitation perspective, it will be more difficult to generate density currents after repeated use of agitation. Higher jet pressures may be required to successfully remove these sand-dominated sediments from a given area.

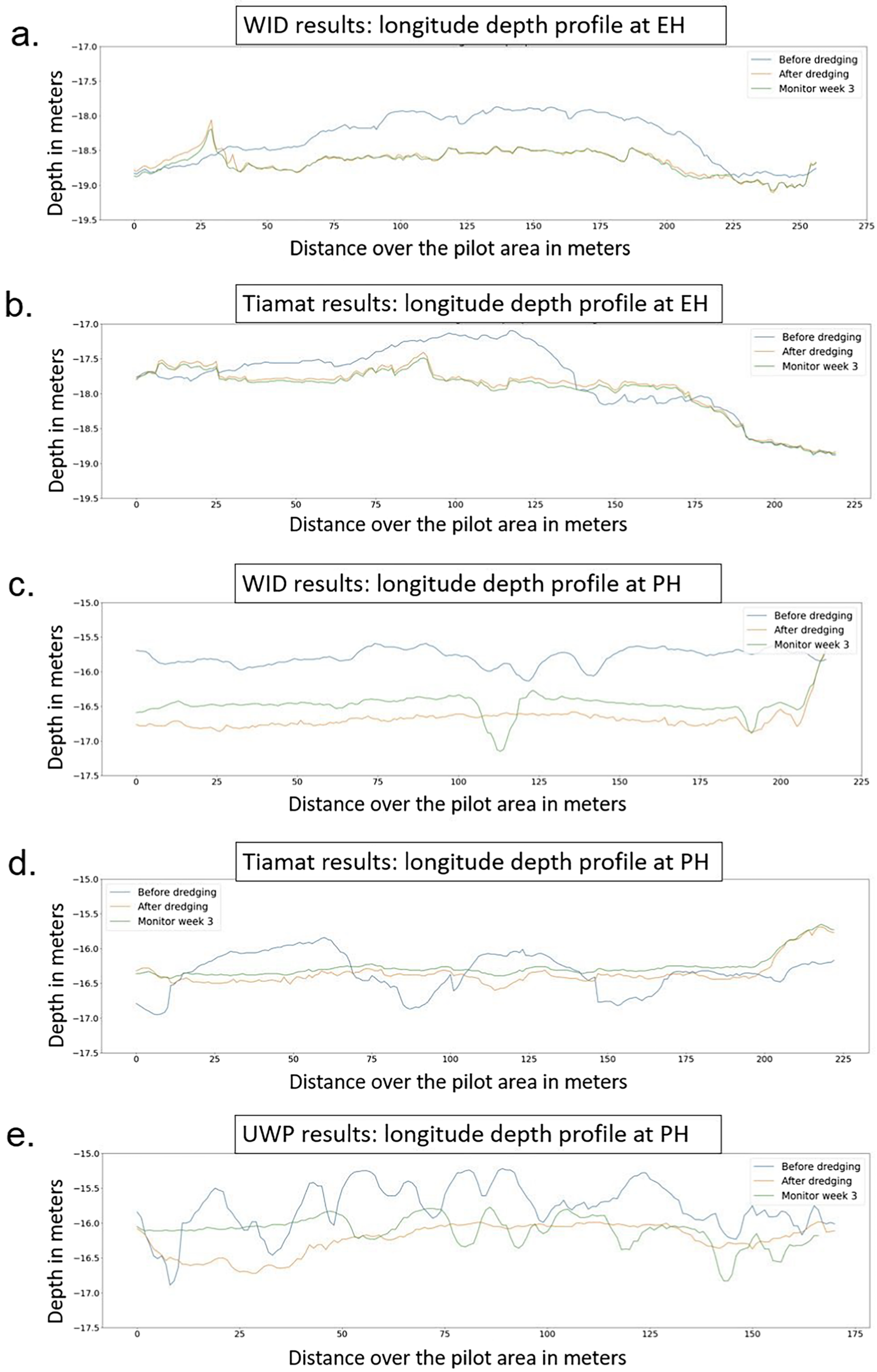

Fig. 7 Depth profiles before and after agitation of fine sand (**a**,**b**) and silt (**c**-**e**). The blue, green and orange lines show the bed level before, after and 3 weeks after dredging, respectively

Table 1 Estimated production rates during WID, Tiamat and UWP agitation pilot experiments

Sediment	WID m^3 OH^{-1}	Tiamat m^3 OH^{-1}	UWP m^3 OH^{-1}
Fine sand	82	46	x
Silt	2673	321	766

The dredging-induced turbidity levels should be managed within levels that will not result in adverse impacts on marine species IADC 2015. For all agitation methods tested, this is difficult to achieve during dredging because all methods require sediment to be brought into the water column close to the bed. For the port of Rotterdam it is important that the turbidity does not exceed the natural variation for a longer time period. Turbidity levels for all methods were shown to gradually return to equilibrium within 1 hour after agitation, this means that they return within the correct time. The turbidity levels caused by UWP occurred close to the bed as the plough cut the bed into sediment layers. Significant turbidity levels also occurred during fluidization of the sediment with WID and Tiamat. With Tiamat, the sediment plumes also rise higher as the Tiamat puts the sediment high into suspension. However, the resuspended sediments quickly settled after dredging and were transported away from the area during dredging, so that the turbidity levels return back to equilibrium.

When comparing different methods of maintenance dredging, it is essential to consider the various factors that can influence the outcome. The agitation outcome can be influenced by a human factor such as the experience of the crew and the operating conditions during dredging. The operational crews of WID and UWP vessels had already carried out agitation dredging in the Port of Rotterdam many times before the pilot. The crews would already know better how to work optimally in the pilot areas and maximize the production rate. Since the Tiamat system is relatively new and optimized for the port areas maintained by the Harwich Haven Authority, the Barney crew needed more time to gain experience with Tiamat agitation in both locations. This factor may explain the difference in the production estimates for WID, Tiamat and UWP. The production rates of WID and UPW in the silt-dominated area are in line with the values reported in the literature for fine-grained sediments (Laboyrie et al. 2018). For the Tiamat, the production rates are significantly lower due to the factors discussed above. In addition, the volumetric approach to production estimates differs from the previously reported production rate in relation to sediment mass removal estimates during Tiamat trials in Harwich Spearman and Benson (2022). In general, the use of the Tiamat results in sediment layers with very low density (<1150 kg m^{-3}), which are then interpreted as the bottom surface by the multibeam echosounder. These sediment layers are considered in the mass production method. However, in the volumetric method used in this study, this layer isn't included in the production estimates as the density data was inconclusive. In general, production rate estimates for agitation methods can be improved by including the nautical bottom, which is defined by density or yield stress rather than by multibeam measurements.

System-related factors such as current velocities and directions, weather conditions, and natural sedimentation may also affect the final comparison of dredging methods. The pilots were planned by taking into account the system-related factors. However, the unavoidable differences between the current velocities during the agitation dredging in the silt-dominated area could influence the dispersion distance of the sediment plume after dredging. The return rate of the agitated sediment should be studied to determine the long-term effects of the agitation dredging on sediment properties. This can be done by incorporating the results of the pilots into sediment transport models or by carrying out long-term monitoring.

5 Conclusion

Three agitation dredging methods were tested in the Port of Rotterdam: WID, Tiamat and UWP. The selection of the agitation equipment can be made on the basis of environmental regulations, morphology and hydraulic dynamics in the port. It has been confirmed that all tested methods perform better with fine-grained sediments, as fine-grained sediments are generally easier to fluidize and have better transport properties than coarse-grained sediments. At the same time, fluidization of coarse sediments leads to the washing out of the fine fraction from the bed, which can lead to a non-cohesive bed in the case of frequent agitation dredging in the area. Tiamat transports the agitated sediment over greater distances than WID and UPW, as the sediment plume from Tiamat is discharged higher in the water column. WID and Tiamat can generate turbidity plumes further up in the water column due to the fluidization of the sediments. On the other hand, UWP only produces sediment plumes close to the bottom due to the physical mechanisms of ploughing. The human factor in performing agitation dredging should also be considered in order to compare the production of the different dredging methods for port maintenance. The way in which the bed level is determined by the surveying equipment should also be taken into account. Specifically, the use of accurate density profilers should be included.

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Declarations

Conflicts of 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.

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