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WATER INJECTION DREDGING AND FLUID MUD TRAPPING PILOT IN THE PORT OF ROTTERDAM

A. Kirichek[1,2] and R. Rutgers[3]

Abstract: As conventional dredging and relocation of sediment deposits is highly expensive, port authorities seek for more efficient solutions for reducing the costs of maintenance dredging. One of the well-known solutions is water injection dredging (WID). In general, WID is proven to be cheaper than the hopper dredging by leaving the sediment in place, thus, eliminating substantial costs for relocation of the dredged sediment.

In autumn 2018, the utility of WID and fluid mud trapping was investigated in the Port of Rotterdam. As a first step, the sediment trap was made in the Calandkanaal. Next, the WID actions were carried out for fluidization of the top layer sediment around the deepening and horizontal transport of the fluidized mud into the sediment trap. The WID actions were monitored by means of multi-beam and single-beam echo-sounding surveying methods at low (15-38 kHz) and high frequencies (200-400 kHz). After WID has taken place, the sediment trap was regularly surveyed for 3 months. Apart of abovementioned echo-sounding surveying methods, different penetrometers were used for monitoring the settling and consolidation processes in the sediment trap. We used Graviprobe, Rheotune and DensX for measuring the shear strength, the yield stress and the density of sediment, respectively. These measurements were compared to the ones in laboratory, where the densities and the yield stresses of sediment samples were measured independently.

It was concluded that the water injection dredging method can be efficiently used for fluidizing and transporting weak fluid mud layers. In-situ measuring tools are available for characterizing the behavior of fluidized sediment. Based on our experimental investigation, it can be concluded that new cost-effective port maintenance strategy is feasible in the port.

Key words: water injection dredging, sediment trap, shear strength, maintenance

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1 INTRODUCTION

The navigation in ports and waterways must be safeguarded by maintenance dredging, which removes sediments deposited by tide, river flows and currents. The volumes of dredged sediment have been substantially increased in the Port of Rotterdam (PoR) over the last 5 years (see Figure 1). In order to keep ports and waterways accessible, more than 11 million m3 of deposited sediment were dredged in 2017. The dredged volumes are almost doubled in comparison with the volumes dredged in 2011. The sediment depositions in these areas consist mainly of fine cohesive minerals forming silt layers, which are periodically dredged by a hopper dredger. As maintenance dredging and consequent relocation of these deposits can be highly expensive, port authorities seek for tailor-made solutions that can help to reduce the maintenance costs and at the same time guarantee safe navigation in the port.

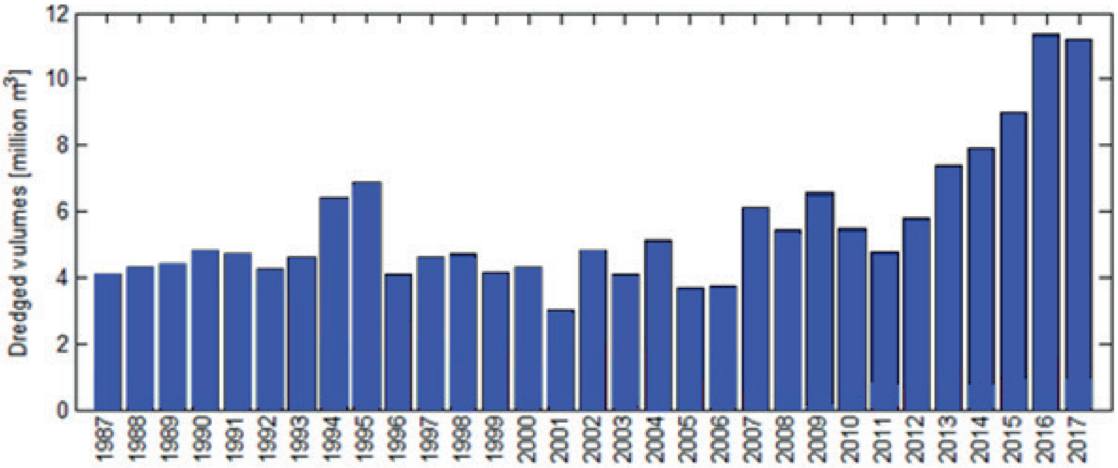

Figure 1. Dredged sediment volumes at the Port of Rotterdam from 1987 till 2017.
Adapted from Kirichek et al., 2018a

There are several measures that can potentially help to reduce maintenance costs in short and long terms. First, revising intervention protocols can be implemented in ports and waterways. Instead of removing sediment, its presence is accepted as ships may sail through mud. Local sediment conditioning may be required to avoid that mud layers become consolidated to allow sailing through them. A conventional way to estimate the navigability in ports and waterways with fluid mud layers is done through the estimation of the nautical depth. This criterion ensures that vessels can safely navigate through areas where thick layers of fluid mud are detected. For practical reasons, a critical density (1200 kg/m3 at PoR) is used for estimating the nautical depth. However, it has long been recognized, that a practical definition of nautical depth should be based on considerations not only of density but should also include the so-called rheological properties of the water-sediment mixture (Wurpts and Torn, 2005). Currently, the yield stress serves as a critical parameter for estimating the nautical depth in the Port of Emden (PIANC, 2014). The description of currently-used criteria for navigation in fluid mud layers and the state-of-the-art of research activities are given in Kirichek et al., 2018b.

Second, smart sediment release is another example of possible solutions which may lead to cost reductions of maintenance dredging. Ongoing SURICATES project is aiming to optimize locations and conditions in which sediment is released. An alternative area for sediment relocation at the Maasmond and natural sediment transport by natural currents to the North Sea are currently investigated within the project (Masson et al., 2019). As a result, the return flow to harbor basins may be minimized. At short term the costs may be large, but long-term benefits may be substantial in the form of reduced dredging volumes.

Finally, optimizing current dredging strategies can substantially reduce the costs for maintenance. Water injection dredging (WID) methods can be efficiently applied for fluidizing and transporting the sediment over long distances within the port area. By applying the WID methods, it is proposed to keep port locations, which are not easily accessible by hopper dredgers, at required nautical depth. Fluidizing the sediment by water injection, homogeneous fluid mud layers of a substantial thickness (up to 2 m) can be created. These fluid mud layers have a week shear strength (yield stress), therefore they can be easily transported by means of natural currents and/or WID actions. Enhancing a natural gravity flow of a silt layer by fluidizing the mud layers can greatly reduce the cost for dredging at locations (e.g. at berths), which are not easily accessible by hopper dredgers.

This paper presents the results of testing the WID actions. The WID and sediment trapping were conducted in order to assess the efficiency of WID, trapping of fluidized sediment and monitoring tools that are available for monitoring the sediment dynamics before, during and after WID actions.

2 DESCRIPTIONS OF THE PILOT

2.1 Location

Several conditions had to be considered before location of the pilot was finally chosen. First, it should be enough sediment to fluidize and transport in the area. This sediment should be cohesive by its nature so that WID fluidizing processes result in formation of fluid mud layers, which can be transported to the sediment trap. Second, the sediment trap should be located further away from the berths to avoid any ship-induced entrainment that can affect settling processes in sediment trap. Third, the hydrodynamic conditions are expected to be favorable for trapping the sediment, therefore preliminary hydrodynamic modelling was done in order to find a right location for the trap. Estimation of bed shear stresses in the area of interest is shown in Figure 2 (top).

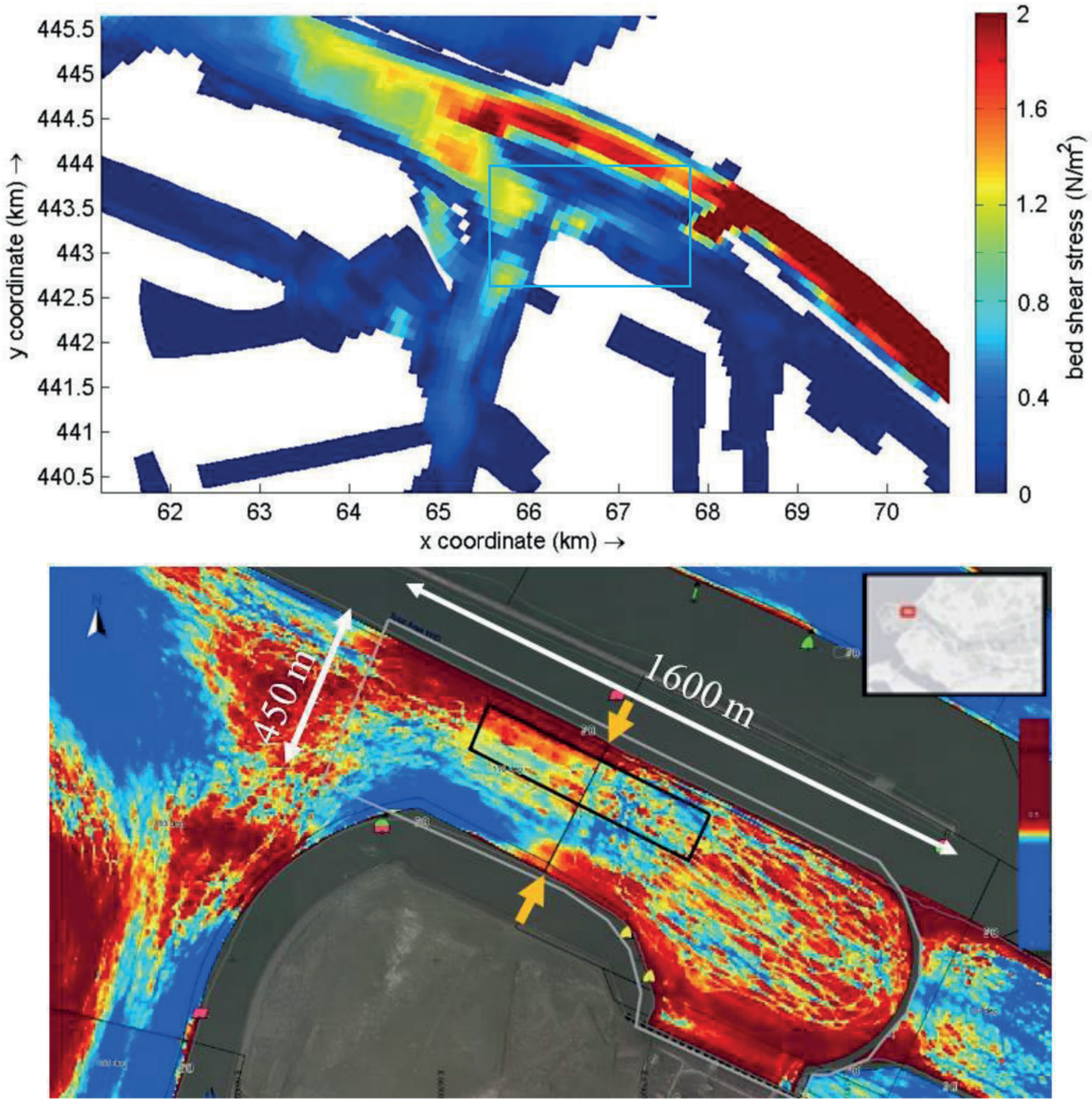

Figure 2. Estimation of bed shear stresses in the area of interest (top). Location of the sediment trap in the Calandkanaal. Black rectangle indicates the positioning and the dimensions of the sediment trap (bottom)

Based on the measured and simulated data, the western part of Europoort was chosen for the WID and sediment trapping pilot.

2.2 Sediment trap and WID actions

Figure 2 shows the location, where the sediment trap was made and the WID actions were executed. The sediment trap was made by the hopper dredger on the norther bank in the Calandkanaal. The dimensions of the trap are 600 m over 120 m. The over depth of the sediment trap varies from 1 m to 1.3 m.

The WID actions were carried out for fluidizing the deposited sediment in the area of the sediment trap over the length of 1600 km, so that the fluidized mud layers would flow into the sediment trap. The WID area is shown by the grey line in Figure 2.

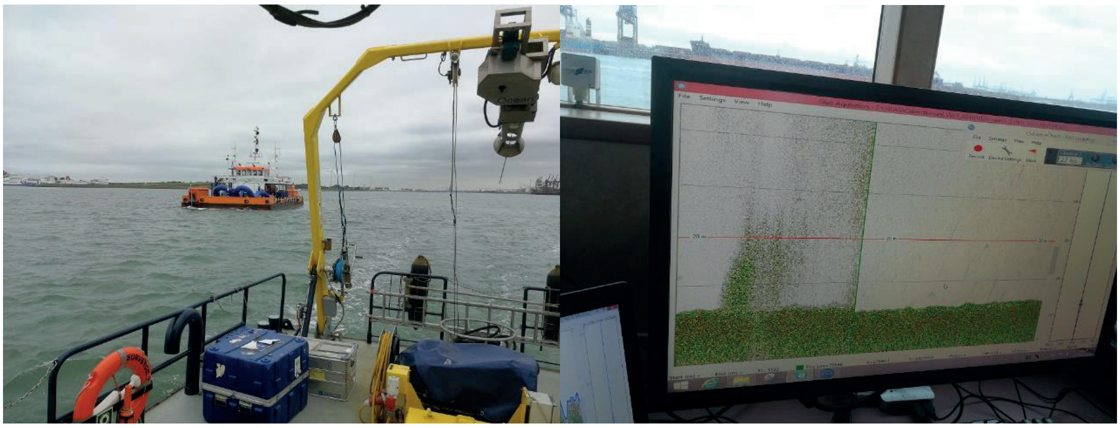

Figure 3. Monitoring during WID actions

2.3 Monitoring plan and attributes

The main goal of monitoring in the pilot was to capture sediment dynamics during WID actions (see figure 3) and settling/consolidation of mud in the sediment trap after WID. The preliminary survey was also conducted before WID actions. The measurements from this survey were used as a reference for monitoring attributes.

The monitoring plan is given in Table 1. The WID actions were performed during week 1. Before WID, the preliminary survey was conducted (referred as week 0 here). The monitoring was carried out on every Wednesday on a weekly basis starting from week 2 until week 13.

Table 1. Monitoring plan for the pilot

Week Pilot	0	1		2	3	4	5	6	7	8	9	10	11	12	13
Weeknummer	42	43		44	45	46	47	48	49	50	51	52	1	2	3
Datum	17-10	23-10	25-10	31-10	7-11	14-11	21-11	28-11	5-12	12-12	19-12	26-12	2-1	9-1	16-1
Dag	wo	di	do	wo	wo	wo	wo	wo	wo	wo	wo	wo	wo	wo	wo
Graviprobe	🟩	WID		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Rheotune	🟩			🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
DensX				🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
SILAS	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Frahmlot	🟩	WID		🟩		🟩	🟩			🟩				🟩	🟩
Rheometers	🟩			🟩		🟩	🟩			🟩				🟩	🟩
Slib sampler	🟩			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Table 2 provides the list of all monitoring attributed which were used during the pilot. The monitoring attributes can be divided in 3 groups:

1. Acoustic/seismic tools;
2. Penetrometers;
3. Laboratory analysis.

There are 2 tools in Group 1. These tools provide a 2D or 3D high resolution mapping systems. Teledyne RESON SeaBat multibeam echo-sounder with RTK GNSS positioning and SILAS system (Diaferia et al., 2013; Werner, 2016) are mounted on the survey vessel that was used for monitoring (see Figure 3). These two systems are used by the PoR surveyors for day-to-day surveys. The high-frequency multibeam echo-sounder is used for mapping the water-sediment interfaces and low-frequency SILAS system is employed in the port areas with mud layers, where the density-based nautical bottom approach is applied for preparing the nautical charts (Kirichek et al., 2018c).

Group 2 consists of three penetrometers, that measure physical parameters in the water-mud column. These tools are shown in Figure 4. DensX provide the vertical profile of density (Kirichek et al., 2018c). The measurements of this device are based on X-ray scattering. At this moment, DensX is used by Rijkswaterstaat and the Port of Rotterdam to map the nautical bottom in muddy rivers and waterways (Kirichek et al., 2018a). Rheotune provides Bingham yield stress and density vertical profiles in water-mud columns (Fontein & Byrd, 2007). This tool correlates the amplitudes, that are triggered by mechanical vibrations at resonance frequencies, to either density or Bingham yield stress datasets, which are collected on various mud samples of different physical properties in laboratory. Estimated by roto-viscometer the Bingham yield tress can be used as a rough approximation of the 'true' yield stress for navigation and dredging purposes. Graviprobe measures the vertical profile of the undrained shear strength and cone penetration resistance (Staelens et al., 2013). Using the force balance equation, the undrained shear strength is estimated from the acceleration/deceleration measurements, that are the primary recordings of Graviprobe. The cone resistance is another parameter that can be provided by this free-fall cylinder.

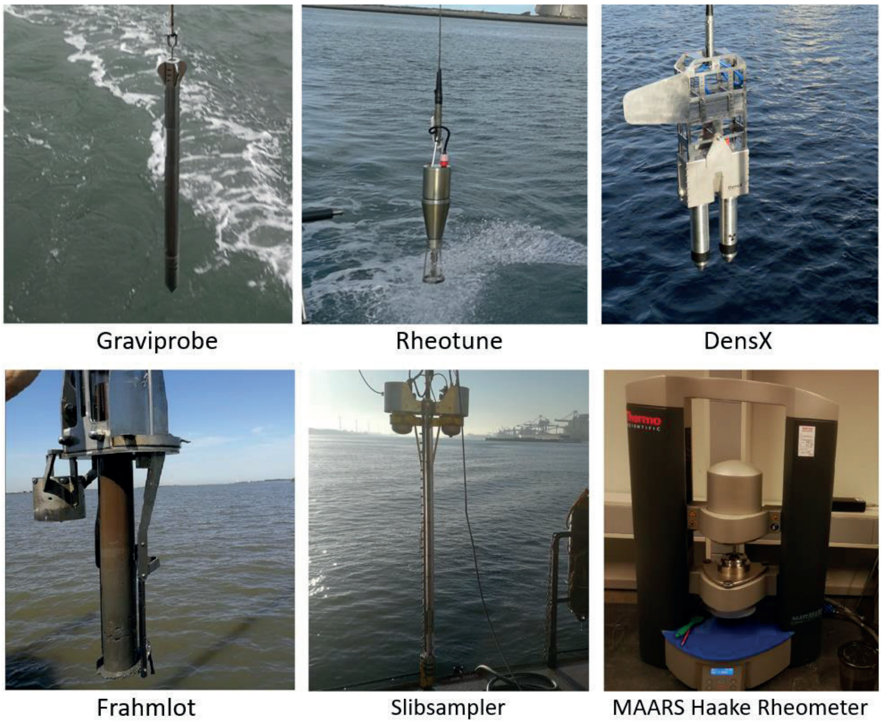
Graviprobe
Rheotune
DensX
Frahmlot
Slibsampler
MAARS Haake Rheometer

Figure 4. Vertical profilers and the rheometer that were used for characterizing the mud layers

Laboratory analysis was conducted by using the equipment in Group 3. Initially, the sediment samples were collected by using Slibsampler or Frahmlot (Reikowski). The former collects sediment core samples by using cylindrical tube with openings on the lateral side. The openings can be used for collecting a fluid mud samples from the core, that can be analysed directly on board using Anton Paar density meter. The latter has a cylinder, that is connected to Frahmlot, and enables to collect soft sediment core samples up to 1 m in length and 0.1 m in diameter. The collected core is then distributed in buckets and transported to a laboratory for further characterization analysis. The density and yield stresses of collected samples were measured in the laboratory. Standard protocols were used for estimating the density of samples. As for rheology, MAARS Haake Rheometer was used for analysing the yield stresses of mud samples. A recently developed time-efficient protocol (Shakeel et al., 2019) was applied for measuring the yield stresses.

Table 2. Monitoring tools used in the pilot

Tool	Working principle	Output	Unit	Usage
Multi-beam	Back scatter	Depth of water-mud interface	m	Before/During/After WID
SILAS	Seismics	2D seismic profiles	m	During/After WID
Graviprobe	Accelerometer	Undrained shear strength	Pa	After WID
Rheotune	Tuning fork	Density, Bingham stress	Pa, kg/m^3	Before/After WID
DensX	X-Ray	Density	kg/m^3	Before/After WID
Frahmlot	Coring	Mud samples	-	After WID
Slibsampler with density meter	Coring and on board density	Density	kg/m^3	After WID
MAARS Haake Rheometer	Rheometer	Yield stress	Pa	After WID

3 RESULTS AND DISCUSSION

Our monitoring results show that current development of monitoring and surveying methods can provide us with useful information on development of mud layers due to WID actions and subsequent settling/consolidation processes. The monitoring tools from Group 1 give a high resolution spatial image during and after WID actions. Figure 5 shows the multibeam echo-sounder measurements before (week 0), during (week 1) and after (week 2 – week 8) WID actions. The indicated depth corresponds to the depth of water-mud interface (a lutocline). By comparing the measurements that are recorded before and after WID actions (week 1 and week 2, respectively), it can be concluded that about 2 m of fluid mud was collected by the sediment trap. Further analysis showed that the mud layer settled in the sediment trap. This conclusion can be justified by the fact that the contours of the sediment trap become more pronounced during week 8 measurements comparing to week 3 measurements, which were collected few days after WID actions. One might argue that the sediment didn't settle but eroded, however the sediment deposited around the sediment trap on week 8 plot suggest that the settling process indeed took place at the sediment trap.

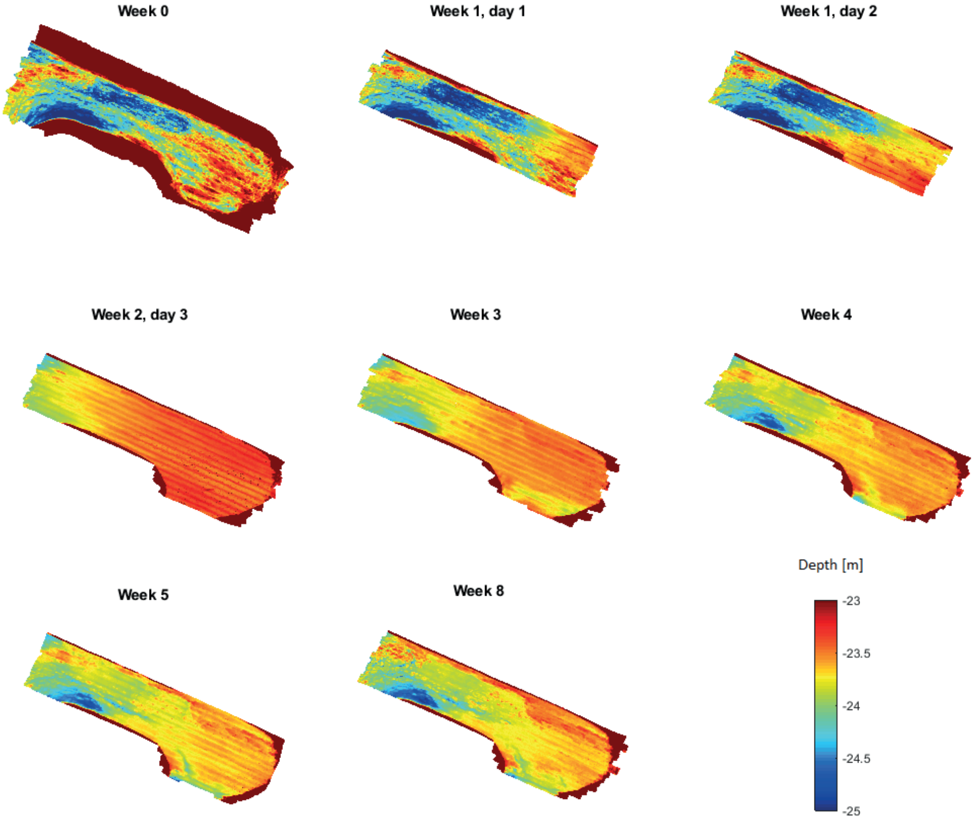

Figure 5. Multi-beam monitoring before (Week 0), during (Week 1) and after (Weeks 3-8) WID actions

Figure 6 shows the seismic profile produced by the SILAS system. Typically, this processed data is used for correlating the density to seismic measurements in order to get nautical bottom horizons, the regions/depth where the density of mud is about 1200 kg/m3. Vertical blue and red lines are the Bingham yield stress and the density profiles that are measured by Rheotune. The change in seismic amplitudes (from light green to dark green) suggest that there is no density gradient indication on the seismic data, only sharp interfaces. These interfaces can't serve as an indication of the fluid mud – consolidation mud interface as it is shown later by analyzing the penetrometers data.

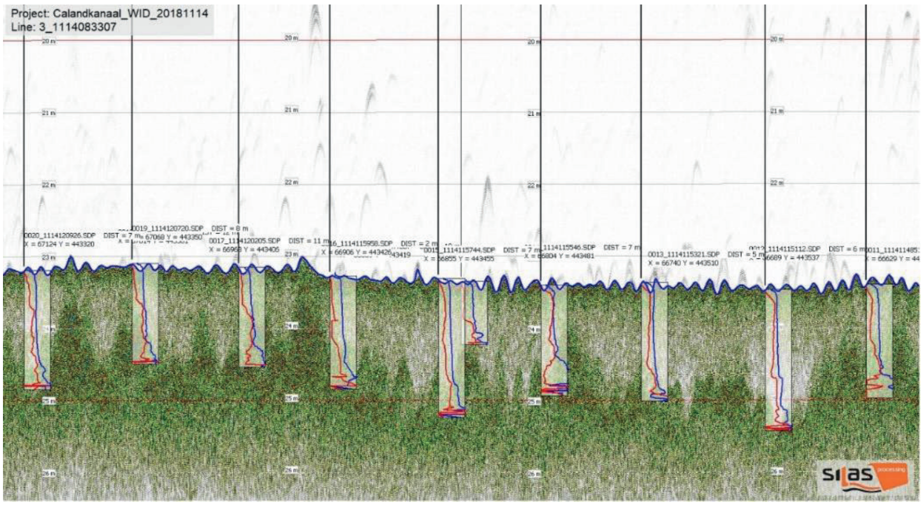

Figure 6. Sonic measurements using SILAS system (Week 4)

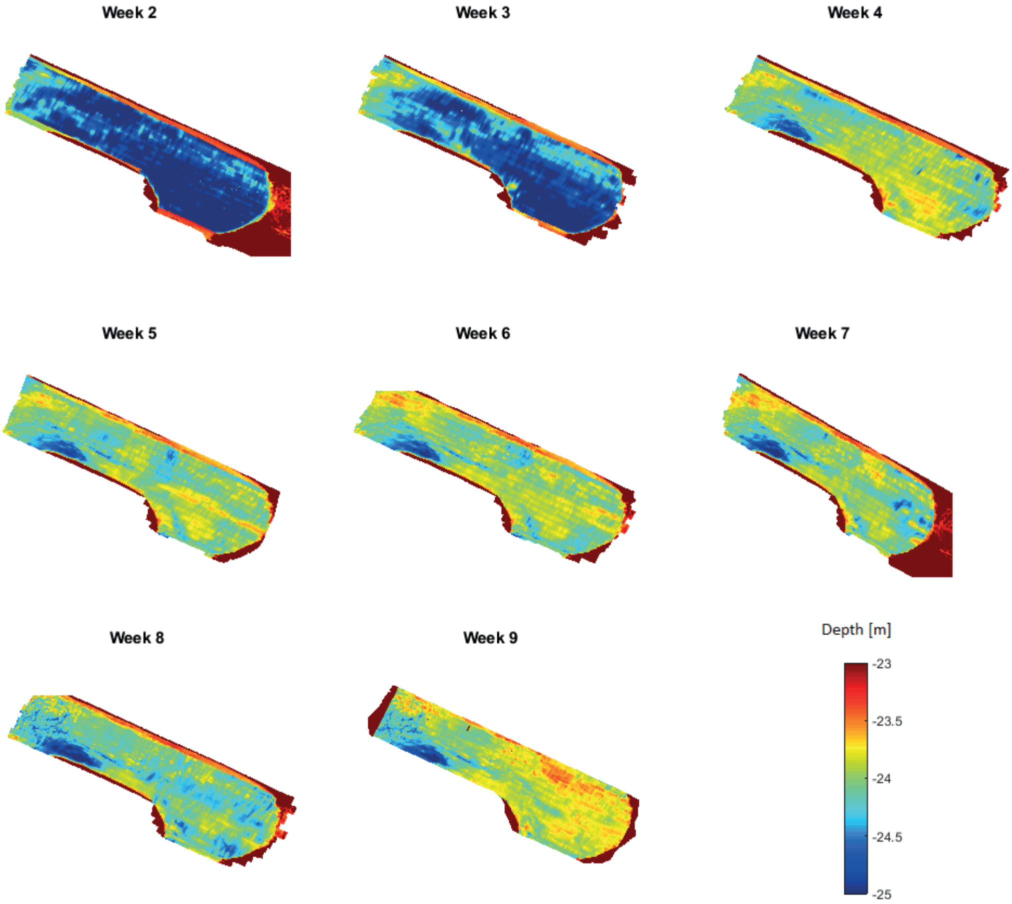

Figure 7. SILAS monitoring after (Weeks 2-8) WID actions at the Calandkanaal

Figure 7 shows the spatial measurements given by SILAS system after WID actions (Weeks 2-8). The colourmap corresponds to the depth, where mud has a density 1200 kg/m3. The figure suggests the fluidized sediment consolidates in the sediment trap and the surrounded area over indicated time. However, the sediment does not consolidate at the South-West area, because this area is eroded due to natural currents. The eroded area is also clearly observed in the multibeam echosounder data (see Figure 5) and in the hydrodynamic simulation (see center of the blue rectangle in the top panel of Figure 2).

Multibeam and SILAS measurements over the cross-section of the Calandkanaal are shown in Figure 8. The SILAS measurements suggest that mud layers in the sediment trap reach high densities (>1200 kg/m3) in 4 weeks. In this case, the over depth of the sediment trap can be used by arriving vessels for 3 weeks after WID actions by following the POR's nautical depth approach (PIANC, 2014). In 4 weeks, the mud in the sediment trap has to be maintained in order to keep the nautical depth that is based on the density of 1200 kg/m3.

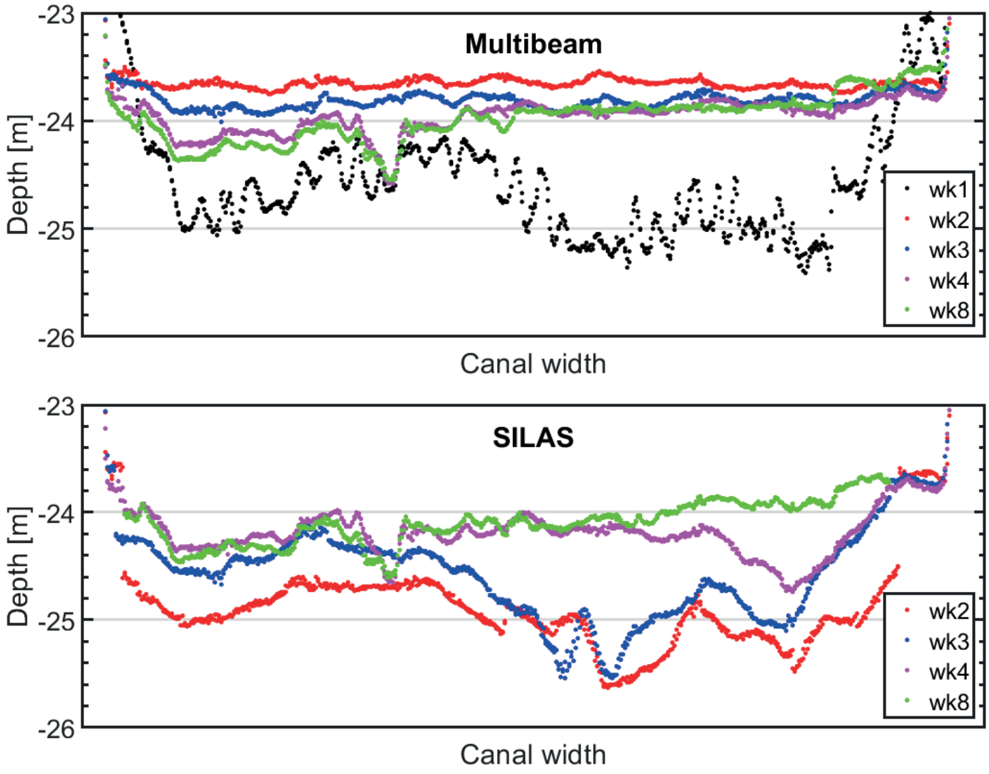

Figure 8. Multibeam and SILAS measurements over the cross-section of the Calandkanaal, that is shown by orange arrows in Figure 2

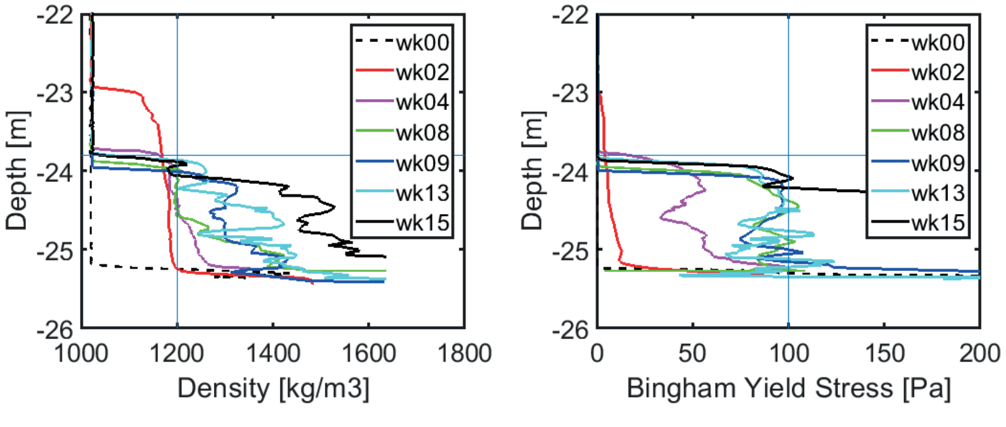

Figure 9. Density and Bingham yield stress profiles measured weakly by Rheotune before (wk00) and after (wk02 - wk15) WID actions at the Calandkanaal

The Rheotune measurements in the sediment trap are shown in Figure 9. Density and Bingham yield stress profiles were made before (wk00) and after (wk02 - wk15) WID actions. The measurements wk00 provide us with the reference. Clearly, there is no fluid mud layers on these profiles. The measurements that are carried out one week after WID (wk02) show that the WID actions created a fluid mud layer of about 2m height. This fluid mud layer has a week strength (the Bingham yield stress is less than 20 Pa) and the density is less than 1200 kg/m3.

Three weeks after the WID actions (wk04), the density of mud reached 1200 kg/m3 at the bottom of the layer due to consolidation process. The Bingham yield stress of the settled layer was less than 60 Pa, suggesting that the mud has a weak strength. Our laboratory analysis of collected mud samples showed a good correlation between laboratory and Rheotune's densities and Bingham yield stresses (see Figure 10 and Figure 11, respectively).

Seven weeks after the WID (wk08), the density level reached 1200 kg/m3. However, the Bingham yield stress of the settled layer was less than 100 Pa. Laboratory analysis showed that collected mud hadn't reached its consolidated phase and might be in a transition from fluid to consolidated phase. Furthermore, the Slib sampler analysis confirmed also the densities of mud at this stage of the pilot. The densities along the Slib sampler were clearly more than 1200 kg/m3. Although the density level reached 1200 kg/m3, the collected mud wasn't in a consolidated phase.

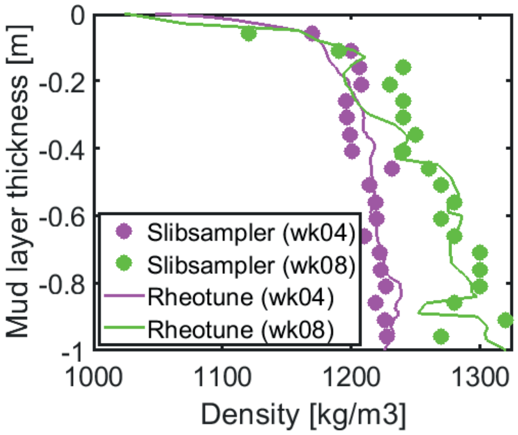

Figure 10. Density measured by Rheotune and Slibsampler during wk04 and wk08

The Rheotune output was further verified by independent density and yield stress measurements. Figure 10 shows the density of the mud layer measured by Anton Paar density meter in Slibsampler and by Rheotune during wk04 and wk08. The protocol of Shakeel et al. (2019) was used to estimate the yield stresses of mud samples in the laboratory. The comparison shows a decent agreement between the measurements.

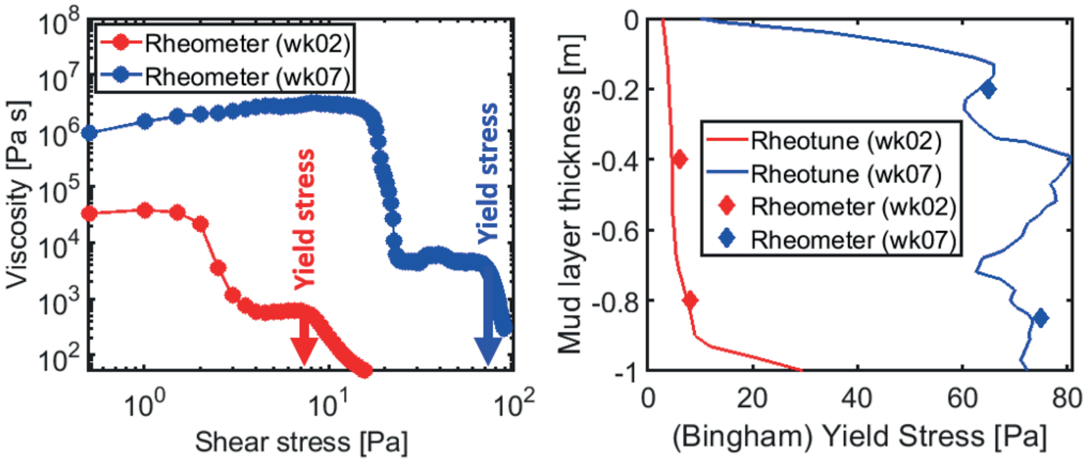

Figure 11. Lab protocol for measuring rheological properties in the lab (left). Rheological properties measured by Rheometer and Rheotune during wk02 and wk07 (right)

The Rheotune measurements wk09, that were conducted 2 months after WID, showed that the measured densities are close to 1300 kg/m3 and the Bingham yield stresses is about 100 Pa. These measurements were further confirmed by laboratory analysis. The measurements that are conducted after week 9 are not presented here.

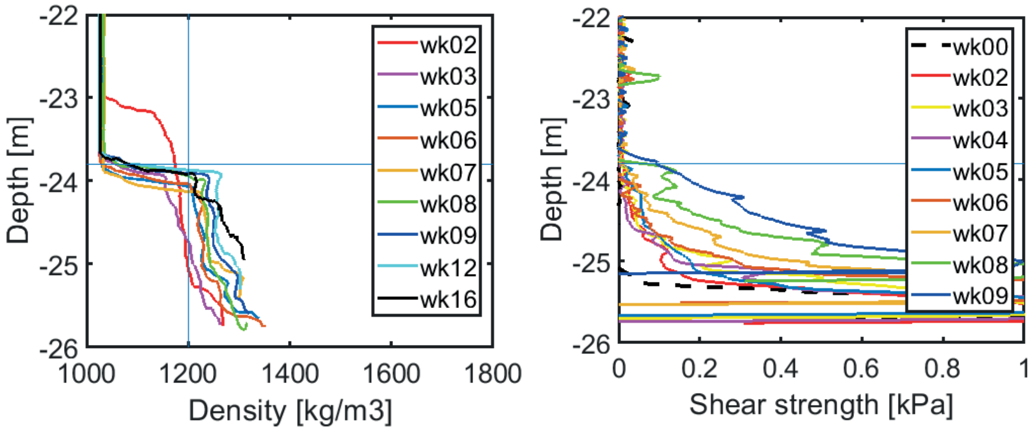

Figure 12. Density and undrained shear strength profiles measured weakly by DensX and Graviprobe before (wk00) and after (wk02-wk16) WID actions at the Calandkanaal

DensX and Graviprobe measurements were used to confirm respectively the density and shear strength development of mud layer in the sediment trap. Figure 12 shows density and undrained shear strength profiles measured weakly by DensX and Graviprobe before (wk00) and after (wk02-wk15) WID actions.

The DensX density profiles are in an acceptable correspondence with the Rheotune density profiles in the density range of 1000-1250 kg/m3 (Figure 9). For the densities >1250 kg/m3, Reotune's profiles have more noise in the data. Most of DensX density profiles have a density cutoff above 1300 kg/m3. One of the reasons is that DensX is operationally used for measuring densities for the nautical bottom approach. Therefore, the data is cut after high densities. Another reason is that consolidated mud layers can limit the penetration of the tool. The measurements that are carried out one week after WID (wk02) show a fluid mud layer with density lower than 1200 kg/m3. The next measurement, that is conducted in two weeks after WID (wk03), shows that a lower part of the mud layer has a density close to 1200 kg/m3, but upper part of the mud layer is still in fluid mud phase. One month after WID actions (wk05), the density reached 1200 kg/m3.

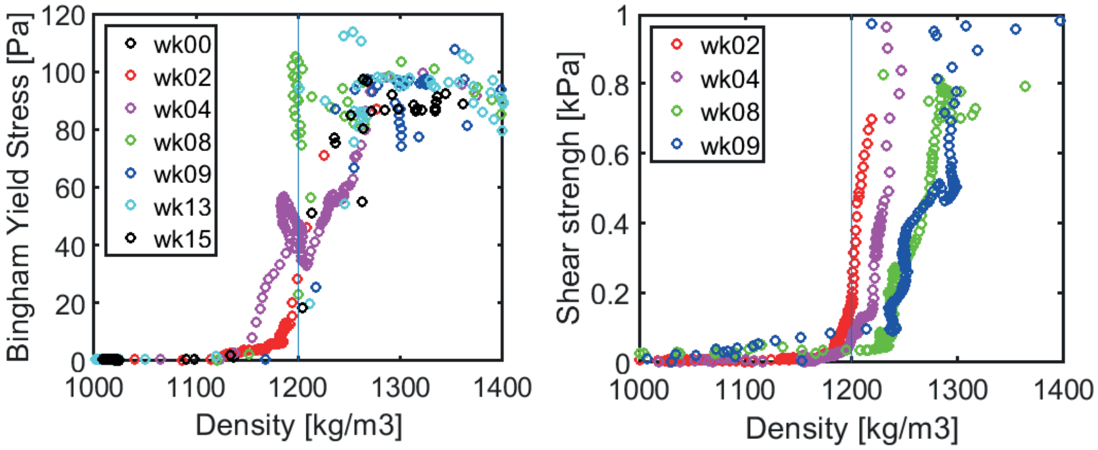

Figure 13. Density – yield stress/shear strength relationship measured by Rheotune (left) as wells as by DensX and Graviprobe (right)

As for Graviprobe, the strength measurements are consistent with the ones of Rheotune. In soil mechanics, mud can be considered as a very soft clay (Atkinson, 2007). From the Graviprobe measurements in the sediment trap, it is concluded that the sediment gains 0.2 kPa undrained shear strength in two month (wk09). This is in line with the Rheotune measurements of the Bingham yield stress profiles shown in Figure 9.

Figure 13 shows a non-linear relationship between density and strength, that is measured by Rheotune (left) as wells as by DensX and Graviprobe (right). This figure demonstrates, that the density of mud can't provide any information about the strength of mud because the strength of mud is time-dependent.
The density-strength relationship that is measured by DensX and Graviprobe (right panel in Figure 13) is more accurate than the one measured by Rheotune (left panel in Figure 10). This is because the density and strength are more closely to direct measurements in the case of DensX and Graviprobe, and more empirical in the case of Rheotune.

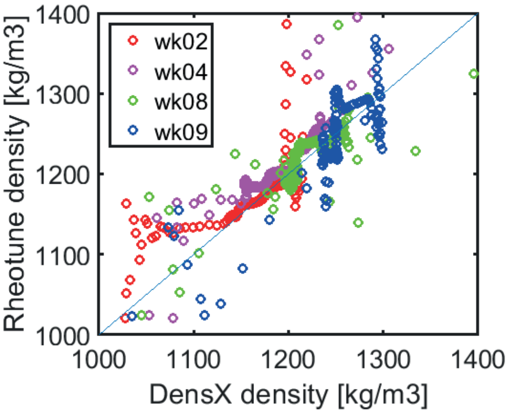

Figure 14. Correlation examples of densities measured by DensX and Rheotune

The density recordings of DensX and of Rheotune are compared. Figure 14 shows the densities of DensX plotted against the densities of Rheotune. Few datasets were randomly chosen for this analysis. It can be concluded from this analysis that the DensX and Rheotune densities are well correlated in the density range 1140-1230 kg/m3 (r ranges from 0.77 to 0.98). There is a big scatter of density values below and above this density range, therefore the densities outside 1140-1230 kg/m3 do not match well.

Similar analysis is not trivial for Rheotune measurements of the Bingham yield stress and Graviprobe measurement of the undrained shear strength because the relationship between these two parameters is not linear. However, the correlation can be done by plotting these parameters on the same plot. From our measurements, it was found that the fluid mud layer thickness is consistent.

The behaviour of mud in the sediment trap can be understood and modelled using settling/consolidation processes (Been & Sills, 1981). The model available for the consolidation of soft mud was applied. Figure 15 shows the estimated water-mud interface and the density and strength profiles. The model prediction reproduces the Multibeam data (see Figure 15a). It was found that the model can partly reproduce the density profiles. In particular, there is a good agreement with the Rheotune data in the density range 1000-1200 kg/m3 (see Figure 15b). The DensX density profiles can be fairly reproduced for densities above 1200 kg/m3 (see Figure 15c). Figure 15d shows predicted strength profile. The strength can also be partly reproduced. Especially, further research is needed for predicting the development of fluid mud layers (< 0.2 kPa).

4 COST IMPLICATIONS

An important part of the pilot was to see how the WID action and trapping of the sediment would influence normal maintenance dredging in the pilot area. The idea was that the WID action and trapping of the fluidized sediment should prevent normal maintenance dredging actions and would have a positive effect on the amount of cost for normal maintenance dredging in the pilot area.

For construction of the sediment trap a Trailing Suction Hopper Dredger lowered the sea bed. The performed action replaced normal maintenance dredging in the area. Therefore, there were no extra costs for making the sediment trap regarding normal maintenance dredging in the area. Performing the WID action to fluidize the sediment in order to let it stream to the sediment trap was extra compared to normal maintenance actions.

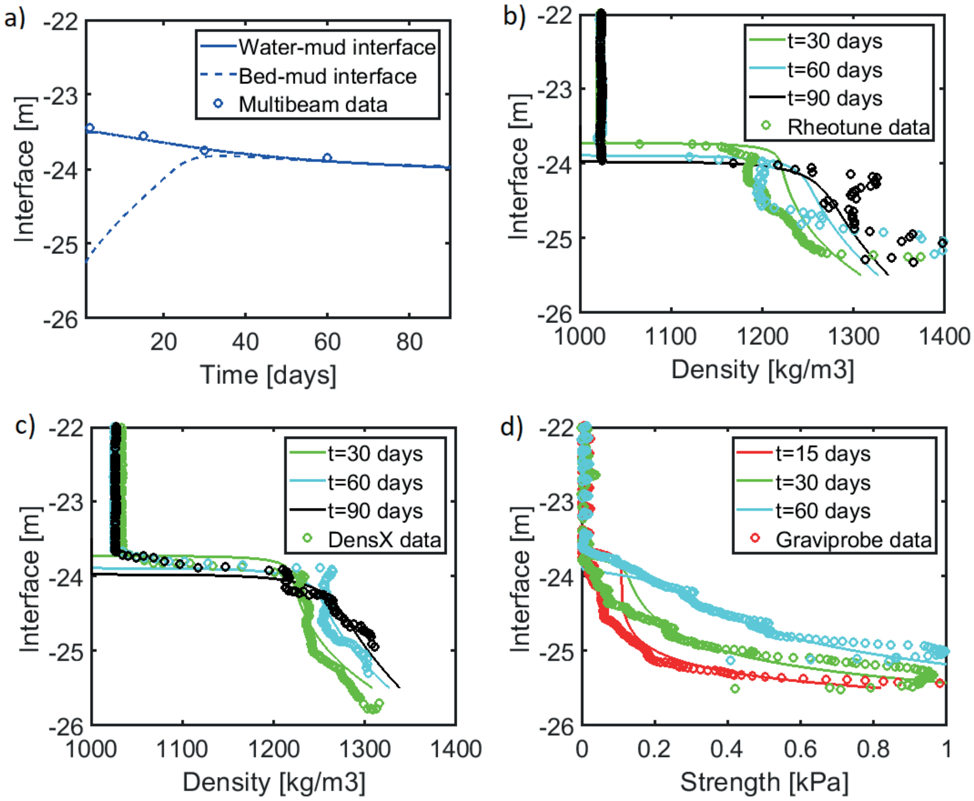

Figure 15. a) Estimated and measured water-mud and bed-mud interfaces. b) Comparison of modelled density profiles with Rheotune data. c) Comparison of modelled density profiles with DensX data. d) Prediction of the strength development and Graviprobe data

After the WID action for more than two months no maintenance dredging was needed in the pilot area. In this area it is normal that every month a maintenance dredging campaign is needed. Regarding the extra costs of the WID action and the rates of operating a Trailing Suction Hopper Dredger (TSHD) for normal maintenance dredging, the total outcome of pilot, in this area, is positive. The rates for a WID vessel are lower than the rates of a TSHD. The extra costs for the WID action where completely compensated by the costs saved for not using a TSHD for two maintenance campaigns. Overall maintenance costs in this area where lowered with 30% - 50% compared to normal maintenance costs.

In two months, it was decided to perform maintenance dredging as normal with a TSHD. The idea is that should a WID have been available for another WID action normal maintenance dredging could again be prevented yet another two months.

5 CONCLUSIONS

It is concluded that WID can be efficiently used for fluidization and mobilizing weak fluid mud layers. To avoid additional siltation in the vicinity and/or strong return flows, WID should be applied in combination with a favorable bed slope, ebb currents or/and a sediment trap from which sediment can be dredged more efficiently.

In-situ measuring tools are available for characterizing the behavior of fluid mud. Measured density and strength profiles can be combined with models in order to predict settling and consolidation of mud layers in ports and waterways.

Based on the results of the pilot, it can be concluded that new cost-effective port maintenance strategy is feasible in the ports with mud layers.

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