Delft University of Technology

Thesis

Analyzing the application of the bed leveller for conditioning of mud

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A laboratory and field research comparing the performance of the bed leveller and the water injection dredger for conditioning pre-consolidated mud in the Botlek (Port of Rotterdam)

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Abstract

Efficient sediment management is crucial to maintain accessibility into the port. This thesis investigates the application of the bed leveller in conditioning pre-consolidated mud, comparing its efficiency and impact on turbidity with that of the water injection dredger. The research is conducted for pre-consolidated mud from the Botlek in the Port of Rotterdam. Instead of traditionally reallocating the dredged material, the mud's properties are modified so that it is safe for vessels to navigate through the mud. The WID is the primary conditioning vessel at the Port of Rotterdam. Since maintenance dredging is a logistical challenge, however, it is attractive to optionally deploy other vessels for conditioning purposes. The bed leveller, a type of plough normally used to level the port's bed, could potentially be used for conditioning. It is cheaper to deploy and more easily accessible for the Port of Rotterdam. Therefore this study investigates if the bed leveller can achieve comparable results as the WID regarding conditioning dredging. To accomplish this knowledge, the research includes the design of a conditioning plough and testing and comparing it to the conventional plough and WID on a laboratory scale. The different treatments on the pre-consolidated mud are measured on density, yield stress and turbidity so the outcomes point out the differences in conditioning effectiveness and impact on turbidity. Furthermore, experiments are executed to discover what is needed to successfully condition pre-consolidated mud and the influence that frequency in a conditioning activity has. To support the findings from the laboratory, field tests are conducted with the bed leveller and the WID as well. This experiment also gives insight into the conditioning efficiency in terms of production rate, costs and fuel consumption. The findings are that an improved design of a new piece of bed levelling equipment, based on research and experience in the field of agriculture, can increase the ability to condition mud. Stirring and mixing, breaking up cohesive bonds within the mud and suspending it, are key for successful conditioning. Increasing frequency in a conditioning activity, increases the effectiveness of conditioning as well, however this relation stagnates. Furthermore, the bed leveller can indeed condition pre-consolidated mud like the WID can. Although in comparison, a higher dredging frequency needs to be applied, for the strength and density of the mud to be reduced just as much. Thus in terms of production rate, the bed leveller is a lot less effective than the WID, resulting in higher average costs and fuel consumption per volume of effectively conditioned pre-consolidated mud. In terms of impact on turbidity, the bed leveller has less effect than the WID and the design of a new plough specifically for conditioning, contributes to reduced environmental impact.

Preface

This report is my graduation thesis project on ’Analyzing the application of the bed leveller for conditioning of consolidated mud’. This graduation thesis finishes my MSc. Hydraulic Engineering at the Delft University of Technology. It was 11 months ago that I first contacted the Port of Rotterdam. Following a period of preliminary communication, the dredging department requested that I conduct research into the potential for conditioning in the port. It immediately caught my interest, since I am very interested in both dredging techniques and managing ports. Combining both subjects was exactly what I was looking for in a graduation project, so I enthusiastically accepted the proposal. As an intern at the Port of Rotterdam, I was going to conduct research for both the port and the TU Delft.

Over the course of 11 months, I happily conducted extensive research for the port company, resulting in the discovery of intriguing findings. This report details my personal journey to achieving these results. I could not have done it without certain knowledge and resources, and for that reason, I want to acknowledge and give my appreciation to some people. To start with my chair assessment committee, Delft University of Technology professors Dr. Alex Kirichek, Dr. José Álvarez Antolínez and Port of Rotterdam employee Andre van Hassent. They provided me with guidance and support throughout the process, offering advice at critical moments. Also, the other employees of the dredging department helped me a lot in order to achieve this. From the Port of Hamburg, I want to give my appreciation to Nino Ohle, who provided me with information on conditioning methods applying the WID and bed leveller. I would like to thank Dr. Marjolein Derks and Ir. Willem Hoogmoed from the Wageningen University & Research for sharing their knowledge on ploughing in Agricultural Engineering. In addition, I would like to express my appreciation to Deltares for giving me the resources to conduct lab tests and to Pepijn Prins and Pieter van Leeuwen, who executed the pre-tests in the laboratory for this research. Finally, I would like to thank the owners of the Husky (Van den Bosch marine), who provided me with resources throughout this study.

Daan van Venrooij
Rotterdam, April 2024

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1 Introduction

1.1 Sediment in the Port of Rotterdam

The Port of Rotterdam is located at the river mouth of the Rhine-Meuse estuary (Nijs de et al., 2009). Such an estuary causes sedimentation since it has both the characteristics of a river system and a tidal system (Bell et al., 2000). In the situation where a port is located at this river's mouth, parts of the port keep filling up with sediment. In the Port of Rotterdam, the sediment is composed mainly of silt and clay (Bruijn de, 2018). Therefore the bed of the Port of Rotterdam consists of mud since the sediment forms a mixture of silt, clay, and water. Mud, located in the bottoms of lakes, rivers, or ocean shores, is a cohesive substance mainly composed of clay minerals, water, and organic matter, with traces of silt and sand (Shakeel et al., 2021a). Figure 1 visualises a schematising of the different layers of mud in the bed of ports and waterways. The horizontal axis shows the concentration in mass per volumetric unit of mud particles present in a layer of the water column, depicted on the vertical axis. Throughout the water column, mud particles play a different role in the dynamics of soil and water. High in the water column, the particles can be categorised as suspended particulate matter. Near the bed, different layers of mud form, growing in density for an increasing depth. The first layer of mud is the fluid mud layer. Fluid mud is a high concentrated aqueous suspension of fine-grained sediment and organic matter. It is often associated with a lutocline, a sudden change in sediment concentration with depth (Chmiel et al., 2021). Fluid mud acts as a liquid, with the ability to flow under certain forces like currents or waves. The next layers consist of pre-consolidated and consolidated sediment, behaving as solid matter.

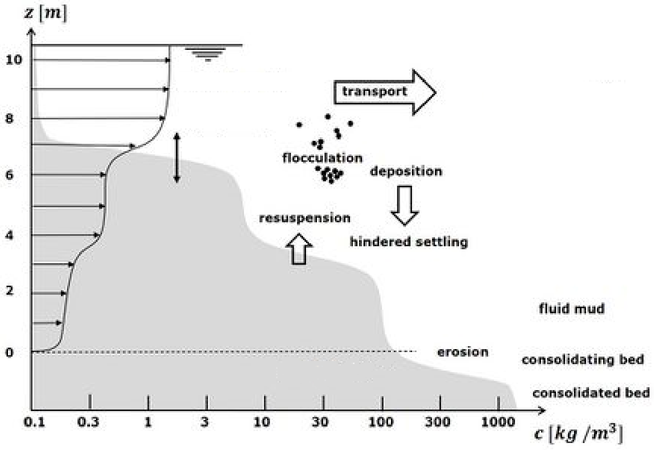


Figure 1: Mud layers in the bed of ports and waterways (Dronkers, 2024b)

The most important factors from Figure 1 that are taken into account in this research are suspension, sedimentation, settling and consolidation. By stirring or mixing the (partially) consolidated mud, the cycle is repeated. Figure 2 visualises this cycle. The fluid mud layer forms in the process between settling and consolidation. Due to interparticle actions, the settling of individual particles is disturbed, which is called hindered settling. The particles float above the bed, creating a mud layer that behaves as a fluid (McAnally et al., 2007).

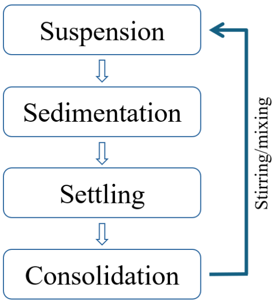


Figure 2: Cycle of mud - suspension to consolidation

Consolidation is the process of sediment bodies getting denser and therefore stronger (Skempton, 1969). There are different stages for the degree of consolidation of mud. In Figure 3 a picture is shown from mud retrieved from the Port of Hamburg in three different stages of the settling-consolidation process. Table 1 belongs to the Figure of the three different stages of the mud. Since consolidation causes an increase in the solids/water ratio, the density increases as well. The values for density and associating state of the mud is dependent on location, so the values in Table 1 are not binding for all mud. Appendix A.2 elaborates on the condolidation of mud.

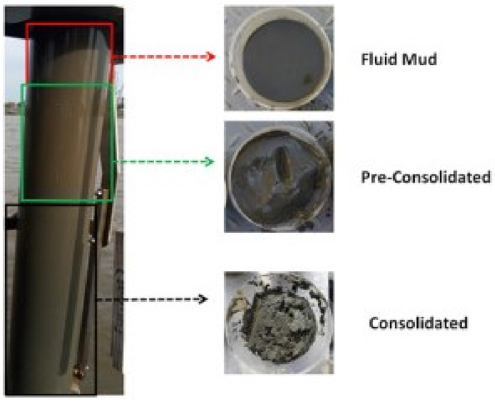


Figure 3: Fluid, pre-consolidated and consolidated mud from the Port of Hamburg (Shakeel et al., 2020c)

Mud layer	**Density** (kg/m^3)
Fluid mud	1134 ± 20
Pre-consolidated mud	1158 ± 20
Consolidated mud	1186 ± 20

Table 1: Table with Figure 3 (Shakeel et al., 2020c)

Mud is a cohesive material that usually exhibits non-Newtonian rheological behaviours like viscoelasticity, thixotropy, and yield stress. Mud experiences this because the material has both liquid and solid characteristics (Shakeel et al., 2020b). This non-Newtonian property causes the mud to behave as a solid, having an initial resistance to deformation, the yield strength, which will further be explained in Chapter 1.4. The magnitude of this factor is partly governed by the density of the mud, where a higher density results in higher resistance (Fontein and Byrd, 2007). As soon as the yield strength is reached the solid behaviour of the material changes to fluidic behaviour. One of the difficulties with mud is that its composition differs per location, resulting in varying yield stresses per location. For example, mud samples from Guyana, in South America, display notably low yield stress even when their densities reach up to 1500 kg/m^3 (Boer de and Werner, 2016). In contrast, mud from harbors in Northern Europe exhibits a marked increase in yield stress when their densities range between 1150 and 1250 kg/m^3 (Fontein et al., 2006).

Daily, large vessels enter the Port of Rotterdam at high tide (Schiereck and Eisma, 2002). The high sea level ensures safe navigation through the port's canals to the assigned berthing pockets for these ships. When the vessels have docked, they stay at this berthing pocket as the tide shifts to a low sea level again. These pockets are deepened out for this reason. When the tide rises again, the vessels can safely navigate out of the port. As soon as the ships can't enter the port at high tide or stay at a berthing pocket at low tide due to a shallow bed, a limiting depth is reached and the port authority needs to make sure dredging activities are carried out. This process of keeping the port accessible through so-called maintenance dredging is a logistical challenge that needs to be reviewed over and over. The precision with which it is carried out must be high, given the consequences could be disastrous, leading to excessive financial setbacks.

The limiting depth of ports has been defined by Nautical Guaranteed Depth (NGD), which is regularly maintained by port authorities. For many ports, like the Port of Rotterdam, the deposited sediment is dredged when its density exceeds a critical value of 1200 kg/m^3 (Peeters et al., 2006). There are some exceptions where this density value differs for the corresponding nautical bottom (Kirichek et al., 2018). The sediment with a density below 1200 kg/m^3 is considered navigable in port areas where this nautical bottom approach is applied (PIANC, 2014). Yield stress is a relatively new measurement value applied for an NGD. Therefore, this nautical bottom concept considers mud safely navigable when density or yield stress of mud is under a certain maximum value since the mud starts behaving like a fluid. Figure 4 shows a sketch of the nautical bottom concept. As mentioned earlier in this sub-chapter, the relation between yield stress and density varies per location because of sediment composition. This variation is associated with the clay content and organic matter content present in the mud (Shakeel et al., 2022). For the port of Emden, a value of 100 Pa is assumed as the maximum yield stress to safely navigate through (Wurpts, 2005). Currently, the Port of Rotterdam is executing research that proves a certain maximum yield stress of mud that vessels can manoeuvre through. The addition of yield stress in the measurement of ports' accessibility opened up possibilities regarding maintenance dredging.

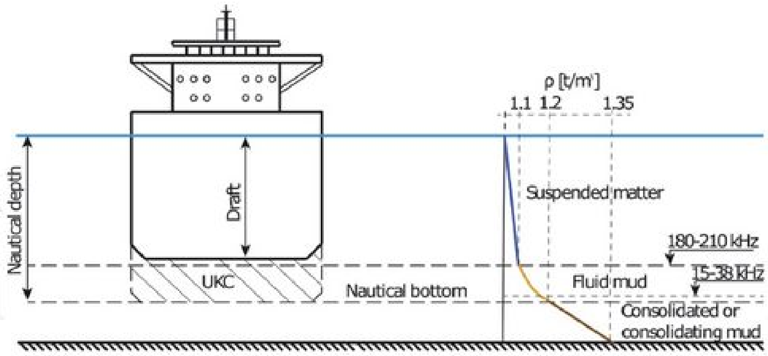


Figure 4: Nautial bottom concept (Kirichek et al., 2020)

1.2 Maintenance dredging

Figure 5 shows the total annual dredged volume of sediment from the past 40 years in the Port of Rotterdam. These volumes represent the amount of sedimentation in the port, as dredging activities are carried out as a result of sedimentation. In the last decade, an increase has been detected, which has to do with several reasons. Besides the estuary characteristics, sedimentation in the port can be influenced by other causes as well, both natural and man-made. Natural causes like storms, for example, can be detected by annual fluctuations in the bar graph. For man-made causes, it can be seen that after the construction of the Maasvlakte 2 in 2013, a redistribution of sediment around the Port of Rotterdam caused the alongshore sediment distribution to change, due to a change in hydrodynamic flow (Bruijn de, 2018). The construction of this structure, perpendicular to the shore, caused a local increase of fine sediments south of the extension (Hendriks et al., 2016). As a result, an annual increase in sedimentation is detected, causing the port authority to adjust their maintenance dredging strategy.

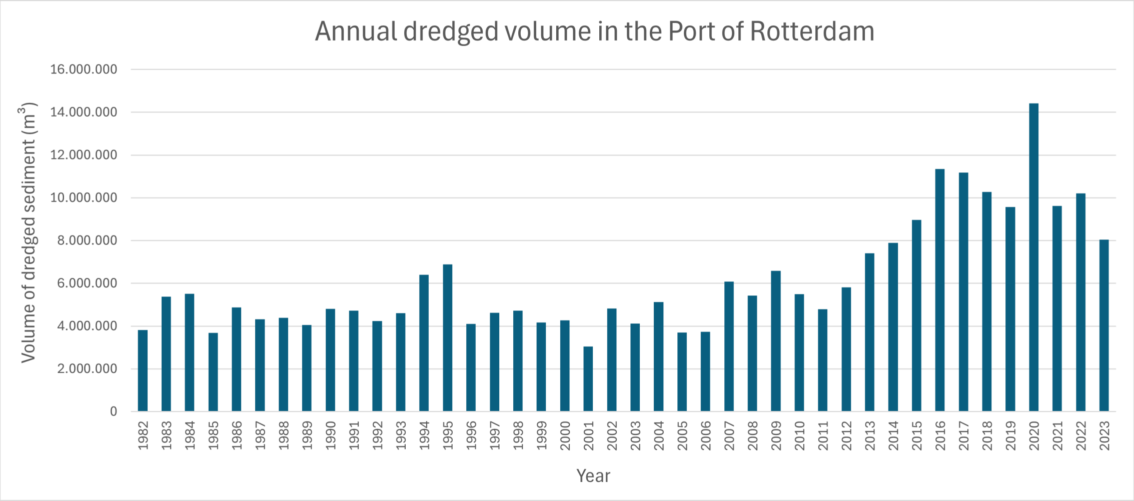


Figure 5: Annual dredged sediment volume in the Port of Rotterdam

In general, maintenance dredging can be split up into two categories regarding the deposition of the sediment (Kirichek et al., 2022). The sediment could:

- be moved or modified in the water or;
- be brought on land.

The first category is the most accessible option since it requires the least effort. The second could be put to use for reclaiming new land or strengthening natural structures like dikes or other ways of permanent storage. In most cases of maintenance dredging in harbors, it is more attractive for financial reasons to keep the sediment in the water rather than bring the dredged material ashore. There are two possibilities considered for this category of maintenance dredging. The sediment can be:

- reallocated or;
- conditioned.

The different categories for the deposition of sediment in ports and waterways are given in Figure 6.

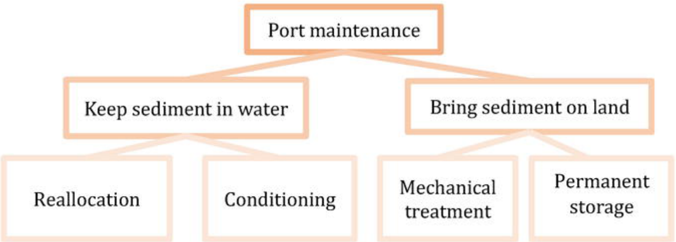


Figure 6: Possibilities for deposition of sediment (Kirichek et al., 2022)

Currently, four different types of dredgers are deployed for maintenance in the Port of Rotterdam. The Trailing Suction Hopper Dredger (TSHD) is the largest dredging vessel applied. The TSHD is a large vessel with a substantial hold, designed to reallocate large volumes of sediment. It is equipped with a large drag-head digging system and hydraulic suction devices to pick up the mud in the port (Bai et al., 2021). For these reasons, the TSHD is difficult to manoeuvre and can not reach sediment near quay walls. The Grab Dredger is a smaller dredging vessel compared to the TSHD. It is equipped with a large grab bucket that is attached to a crane and is solely deployed for reallocation. The bed leveller is the smallest maintenance dredging vessel used in the Port of Rotterdam. It is equipped with a plough that can level the bed or drag portions of mud from one location to another. The final vessel is the Water Injection Dredger (WID), a relatively new piece of equipment that is equipped with a jet system. This system can inject water using low pressure, high volume water jets, into the port's bed, causing fluidisation of the muddy bed. The WID can both be deployed for reallocation and conditioning (Kirichek et al., 2022). By injecting water into the bed, a mixture of upward-flowing water and loose sediment particles is created. As a result, this mixture starts behaving like a fluid. This process of fluidisation of the sediment by water injection can create homogeneous fluid mud layers of a substantial thickness (up to 2 m) (Kirichek and Rutgers, 2019). In Appendix A.1 figures of these four dredging vessels can be found. Currently, the TSHD, grab dredger and bed leveller are all deployed for reallocation of the mud. The WID is used for both reallocation and conditioning.

1.3 Conditioning dredging of pre-consolidated mud

Reallocation of the sediment is currently the prime form used in harbors like the Port of Rotterdam, as mentioned in the previous sub-chapter. However, since conditioning mud takes less effort than reallocation and nowadays the nautical bottom concept is applied, conditioning of mud has become more popular in the last decades. Using dredging equipment that reduces the density and strength of the port's muddy bed, vessels can safely navigate in these parts of the port. Although this is just a temporary solution since the mud will settle again and consolidate, logistically and cost-effectively it can be valuable for the ports. Locations such as berthing pockets alongside quay walls are especially attractive for conditioning dredging. The deep berthing pockets act as sediment traps due to gravitational currents, causing occasional need for maintenance dredging. Conditioning these locations more occasionally would be financially and logistically attractive for ports. Besides conditioning, another option that could logistically and cost-effectively enhance the port's dredging activities is agitation dredging. This dredging method includes suspending sediment into the water column and letting natural forces reallocate the suspended sediment. This would take small effort and could be applied by several dredging techniques. Gravitational forces or currents can reallocate the suspended sediment (Spearman and Benson, 2023). In a research by Neumann (2023) in 2023 was discovered that the WID performs better compared to the bed leveller regarding agitation dredging. Therefore, this research focuses on the testing bed leveler for conditioning dredging.

For conditioning dredging, the NGD should be increased by creating a layer of fluid mud. The cohesive bonds within the mud need to break for such a fluidised layer to be produced. When the characteristics of a fluid mud layer are sufficient, it is safely navigable for incoming and leaving vessels. These characteristic values will be further explained in Sub-chapter 1.4. For now, it is important to realise that cohesion must be overcome to create a fluid mud layer (IADC, 2013). A certain amount of energy needs to be provided to break these cohesive bonds to reduce the strength of the mud. Shear thinning is therefore also a possible method for achieving this. This reduces yield stress according to a study by Zhang and Yu (2017) as well. Therefore all vessels that can either dilute or shear the mud, are applicable for conditioning dredging. In the sub-chapters of this section, each of these vessels used in the Port of Rotterdam is further studied to analyse their applicability in conditioning.

1.3.1 WID

Currently, only WIDs are used for conditioning mud in the Port of Rotterdam. Besides, it is also deployed for reallocation (Kirichek et al., 2022). The WID injects water into the bed at a low pressure (Wilson, 2007). This breaks up cohesive bonds and fluidises the mud mixture. As a result, the WID is the most applicable when it comes to conditioning mud, as it reduces both density and yield stress by breaking down and effectively mixing the mud with one action. In Figure 7 a sketch is given of the working principle of conditioning mud with the WID. So the WID can effectively be put to use regarding conditioning dredging. A downside of the WID is, keeping in mind the dredging capacity per hour, that it can be expensive to deploy in the port. Furthermore, in the case of the Port of Rotterdam, the WID is not easily accessible as there is no such vessel present at all times.

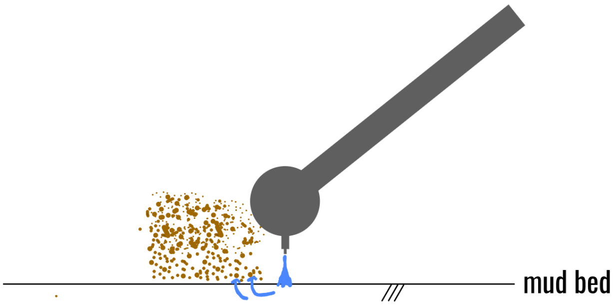


Figure 7: Conditioning mud with the WID

1.3.2 Recirculation using TSHD

A TSHD could well be deployed regarding effectiveness for conditioning where the sediment would be collected into the hopper and immediately released back. For this reason, the conditioning method is called recirculation. In Figure 8 a sketch is given of the working principle of recirculation. In a research for the port of Emden, recirculation was investigated and the outcome was that recirculation reduces the density of the mud (Gebert et al., 2022). Also, the density and the yield stress were closely related. The (hindered) settling of the particles due to recirculation eventually leads to a near-bed fluid mud layer. This would logically decrease yield stress and density, however particles would be spread out over the entire water column. This can have negative effects on the water quality of the direct environment. Furthermore, a TSHD does not have the manoeuvrability to condition the port's bottom near the quay walls, which is unfavorable when conditioning, for example, the berthing pockets. Another large effect that does not suffice to conditioning, is the flowing away of fines due to natural currents. The fine particles settle slowly and tidal forces carry part of these to another location. If a large enclosed area is conditioned this is not an issue, however, for a specific berthing pocket, recirculation is less effective regarding conditioning of mud.

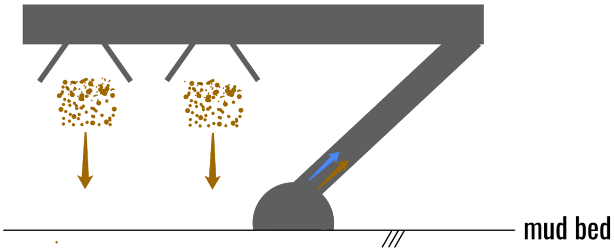
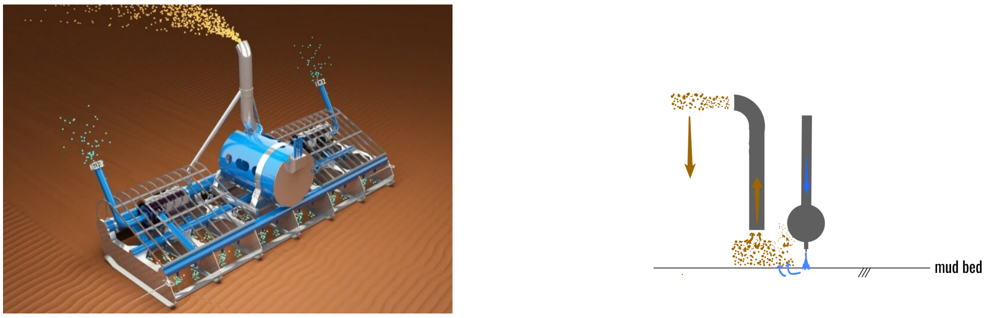


Figure 8: Conditioning mud with the TSHD

1.3.3 The Tiamat

The Tiamat is a new technology in the dredging industry, designed by the Harwich Haven Authority. It is designed so that the dredging activities in this port can be executed in a more environmentally sustainable matter (Harwich Haven Authority, 2022). In Figure 9a, a visualisation is given of the design of the Tiamat. It is a dredging vessel designed mostly for agitation dredging since the Port of Harwich is exposed to many forces induced by natural currents. Making use of these natural forces can make the port's dredging activities more energy efficient. The Tiamat is equipped with a structure of two pump systems. The first system is utilized to inject water into the mud that lies above the port's bed. The second pump system then removes the diluted silt, by a release pipe at 6 m above the bed to encourage the dispersion of the sediment (Haven Dredging, 2023), (Spearman and Benson, 2023). Neumann (2023) researched the Tiamat in her thesis, comparing the new dredging device to a WID and the Bed Leveller. Regarding agitation dredging, the Tiamat and the WID score really well, however, the WID outperforms the Tiamat on production and cost.
The Tiamat could be applied for conditioning purposes as well by recirculation, like the TSHD. However, for the same reasons as the TSHD, it is expected that the Tiamat will spread sediment throughout the water column, which is unfavorable and less controllable. A sketch of the working principle of conditioning with the Tiamat is given in Figure 9b



(a) The Tiamat (Harwich Haven Authority, 2022)

(b) Conditioning with the Tiamat

Figure 9: The Tiamat and its conditioning process

1.3.4 Bed leveller

As pointed out before, the bed leveller is currently put to use in the Port of Rotterdam for two purposes: Levelling the port's bed and shifting mud to deeper or more reachable locations. The bed leveller is equipped with a plough. The technique of ploughing is derived from agricultural engineering. It has been a technique used for a very long time in that field. The bed leveller's main task is levelling the bed after the TSHD has been dredging at a location. Due to the large suction head size and the poor ability to manoeuvre, the TSHD leaves a rather uneven bottom in the port. Large trenches and carvings can be evened out by the bed leveller. In Figure 10 (a) a visualisation of the equalisation of the port's bed is shown. The plough is connected with ropes to a winch from the bow of the ship, that can lower the plough. The ploughs are also connected to the hull of the ship through a chain and a rope. The self-weight of the chain ensures a horizontal pulling force.

Besides the ability to straighten trenches and carvings after TSHD activities, the bed leveller can also be put to use for agitating built-up silt, dragging it into storage areas or deeper, more accessible parts adjacent to a higher area (Jaditager et al., 2014). This secondary application of the bed leveller is visualised in Figure 10 (b).

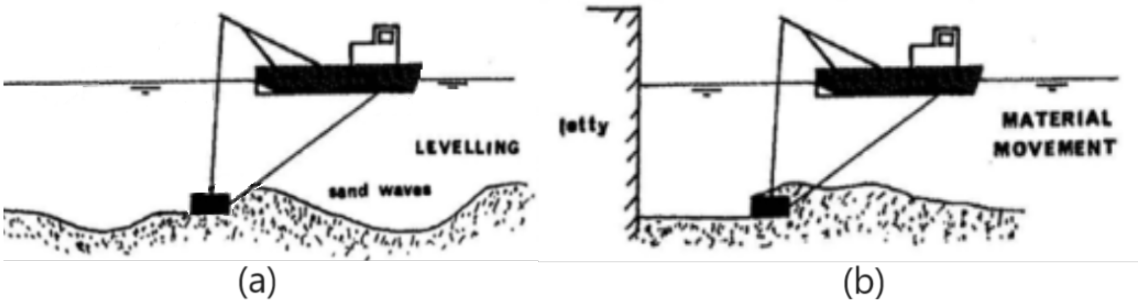


Figure 10: (a) Equalising the bed using the bed leveller; (b) Reallocation of sediment using the bed leveller (Mohammed, 1994)

Applying the bed leveller for conditioning would be very attractive since the vessel is small and thus manoeuvrable and it is cheaper to deploy in comparison with the WID for example. Also, the bed leveller is more accessible for the Port of Rotterdam as there is almost always one at present in the port.

The plough has some teeth intended for digging the whole plough into the bed. To picture the working principle of conditioning with the plough better, a sketch is given in Figure 11. As can be seen, the bed leveller has teeth/shovels that dig the plough in the mud. The aggregates are reduced in size due to these teeth at the front of the plough, and the eddies created in and behind the plough. The large particles settle quickly and fine particles are brought into suspension, forming a fluid mud layer. Theoretically, repeating this action over the same area of mud will further decrease particle size and eventually create a navigable mud layer.

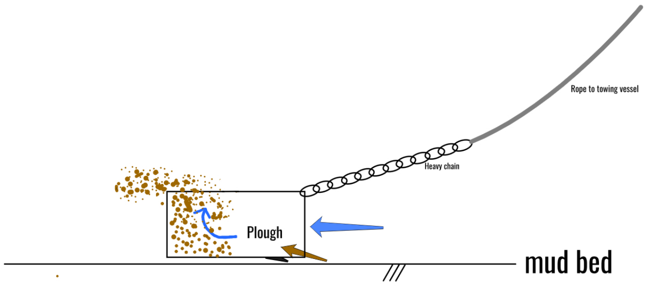


Figure 11: Working principle of conditioning dredging with the conventional plough.

Recirculation with a TSHD and the Tiamat are both difficult for deployment in conditioning dredging in open-flowing basins. As explained, the fines are suspended high into the water column, causing a relatively large settling time. Due to forces such as tidal flow in an open-flowing basin like the Botlek, the fines are transported to other locations, reducing the effectivity of conditioning a certain small area. Therefore, this research continues focussing on the WID and the bed leveller as suitable equipment systems. The bed leveller could be put to use for conditioning like the WID and the possibilities for this are further explored. At present, there is a lack of detailed information regarding the operational principles of the bed leveller. However, investigation into the performance of ploughs has been systematically conducted within the agricultural sector. Therefore, it is of added value to investigate the experiences with ploughing in this field.

Ploughing in agriculture

The plough enhances agriculture by improving soil cultivation, moisture penetration, and crop yields. The main purposes of ploughing in agriculture are the following (Murphy and Sprey, 1986):

- For loosening hardened soil to increase voids through which roots can grow and water can penetrate;
- For turning organic matter under the soil;
- For controlling the growth of weeds which can hinder crop growth;
- For shaping the seedbed (into ridges, beds, or mounds).

The first and main purpose of ploughing in agriculture has a great similarity with conditioning dredging, namely modification of the soil. Consolidated soil needs to be loosened, so a plough is used to cut through the soil, breaking cohesive bonds in the soil. After ploughing, the land is usually harrowed to break up and refine the clods of soil left behind to create a seedbed with finer soil particles. This process ensures optimum conditions for seed planting by creating smaller, more manageable clods of soil, improving the environment for seed growth and development (Murphy and Sprey, 1986). In other words, the soil is further conditioned by loosening soil and thus weakening it. A large difference between the behaviour of agricultural soil and soil in the field of dredging is logically the large water column on top of the soil. Besides being fully drained, this causes constant consolidation which compacts the seabed. In agriculture, consolidation is present as well, however without the pressure of the water column. Evaporation takes a large role in this, causing ripening of the soil if evaporation exceeds the outflux of water by consolidation (Ecoshape, nd). This causes cracks in the soil.

With low-land rice fields, this is different. Here a certain technique is applied that is called puddling. Soil puddling generally refers to the breakdown of near-saturated soil aggregates into ultimate soil particles (Dewanti and Mandang, 2021). It involves turning wet soil into a smooth, mud-like consistency. This process, often done with tools pulled by animals or tractors, breaks down soil clumps and creates a soft layer ideal for planting rice seedlings. Puddling helps conserve water, controls weeds, and makes it easier to transplant rice (Kirchhof et al., 2011). This normally happens after the initial ploughing, leaving about 50 to 100 mm of standing water on the field. Puddling helps maintain water levels within the rice field by generating fine soil particles that decrease soil porosity, thereby minimizing nutrient seepage. Additionally, puddling offers advantages such as weed management, soil surface smoothing, and the creation of a uniform, blended soil texture. It's essential to conduct puddling while there's water present in the field. The standing water on the soil, causing saturation of the soil, affects the mechanical strength of the soil. With such high moisture, the cohesion is at a minimum and shear planes form more easily (Sharma and De Datta, 1985). This makes the breakage of lumps into smaller particles easier. Although the purpose is not the same per se, puddling and conditioning with a plough are comparable since the working method is the same. Both techniques aim to break cohesive bonds in muddy soil. There are two famous techniques used for puddling (Dewanti and Mandang, 2021):

- Traditional plough such as the mould board plough, shown in Figure 12a.
- Rotary ploughs, which appear to be more effective than the traditional plough and are used more often nowadays. An example of such a rotary instrument is the rotavator, shown in Figure 12b.

(a) Mould board plough (Agromaster, n.d.) (b) Rotavator (Tractorkarvan, nd)

Figure 12: Traditional equipment applied for puddling

Previous research on conditioning with the bed leveller

Some research has already been conducted regarding conditioning with a bed leveller. For example, in 2017 the US Army Corps of Engineers studied if the bed leveller could be deployed to further reduce yield stress in fluid mud (Tubman et al., 2017). They used a square beam as a plough. In Figure 13 a graph is given of the results of this research at certain of their testing locations. The graphs show that there is no difference in yield stress between the reference situation and after ploughing. This study concluded that ploughing through fluid mud does not consistently reduce density or yield stress.

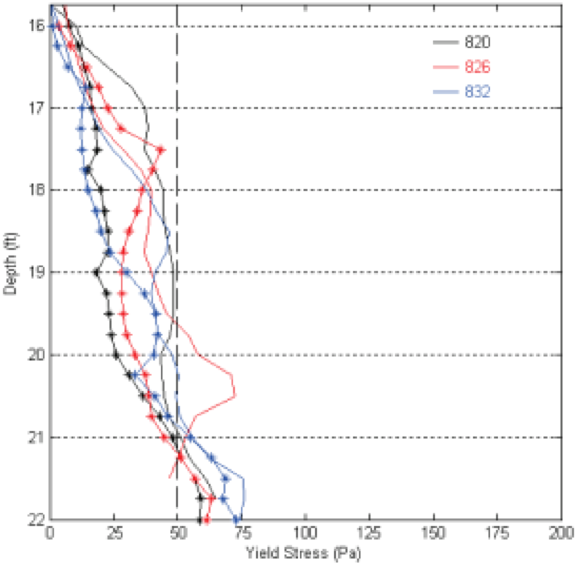


Figure 13: Results of conditioning with a bed leveller from a study of the US Army Corps of Engineers: 'Before (-) and after (-*) plow-barge operations average Rheotune yield-stress profiles at Stations 820, 826, and 832.' (Tubman et al., 2017)

Another study executed by Kirchek et al. in 2023 has a similar outcome (Kirichek et al., 2023). In this research four different conditioning methods were tested and compared regarding impact on density and yield stress reduction. This laboratory study conducted measurements on mud samples from the Port of Hamburg for several weeks, repeatedly conditioning the mud. In Figure 14 the outcome of the study is given. As can be observed, the WID clearly has the greatest impact on both density and yield stress. Recirculation by the TSHD has rather similar results as the bed leveller. Both do not reduce density but do reduce yield stress, although this is also a minor difference over the total testing period of one month.

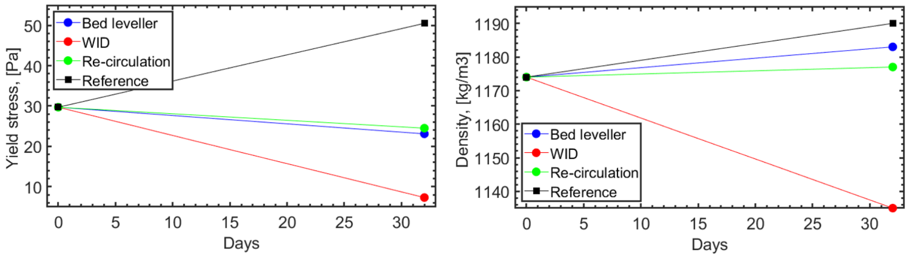


Figure 14: Lab comparison of Kirichek et al.'s study comparing different conditioning methods: 'Effect of conditioning methods on (fluidic) yield stress (shear strength) and on density of mud.' (Kirichek et al., 2023)

For conditioning preconsolidated and consolidated mud with the plough, no studies have yet been executed. From an interview with a dredging expert from the Port of Hamburg, Nino Ohle, came out that in Hamburg tests were conducted with the bed leveller on pre-consolidated mud (Pana, 2022). Through trial and error, they slowly gain experience with using the conventional plough for conditioning. The findings are that with a high ploughing frequency, the bed leveller can replace the activities of a WID.

1.4 Characteristic values

To measure the performance of each type of conditioning equipment, the characteristics of the port's bed and water need to be determined. Several values are of importance to establish knowledge of these characteristics. Some values have already been pointed out and in this section, they will be elaborated. Some other factors are determined and examined.

Yield stress

Yield stress contributes to the navigability of vessels sailing through the port. The term yield stress was first introduced by Bingham and coworkers for plastic yielding in metals (Bingham, 1922). They concluded that a Bingham plastic is a material that acts as a solid under low stresses and starts flowing and acting as a fluid when the stress increases. The yielding point is the point at which materials become plastic. The plastic deformation of the material starts at this point and the material will start to harden. The relation between stress to strain becomes higher until the ultimate strength of the material is reached. The yield stress is dependent on shear strength and viscosity, two so-called rheological parameters. Rheology is the study of deformation and flow of matter under the influence of an applied stress. Ideal solids deform elastically, which means that the solid body deforms due to an applied stress and returns to its original state after the stress is removed (Björn et al., 2012). In hydraulics, this behaviour is that of a Newtonian fluid. A Newtonian fluid is defined as one with constant viscosity, with zero shear rate at zero shear stress, that is, the shear rate is directly proportional to the shear stress (Lever, 2005). Body's of mixtures containing sediment however, don't deform elastically and have a non-Newtonian behaviour, meaning that shear stress and shear rate are related non-proportionally. As a result of an applied force, shear stress starts acting from one body to another in opposite directions. In port management, a vessel and the sediment bed are exposed to shear stress when in contact with each other. When the yield stress of the bed is high, the sediment body does not deform for shear stresses applied by the vessel. This can result in damage to the vessel, for example in the form of cracks. This is obviously not acceptable, therefore the yield stress needs to be under a certain value. For the Port of Rotterdam, this value for yield stress is currently set at 100 Pa however, this is still to be verified by research. Legally, the port authority can only allow this method of measurement if it has been proven to work in practice. In this research, it is assumed that this value will be the limit value for yield stress for fluid mud.

Two types of yield stresses are considered within the rheology of mud, static and fluidic yield stress. This double-yielding process is the process of intergranular bonds breaking down two times in soft materials (Ahuja et al., 2020). In Figure 15, an example is given for the shear stress to rate graph for a soft material. The static yield stress is considered the yielding point which corresponds to elasticity and the fluidic yielding point corresponds to the viscosity break-down. These two critical yield stresses mark the points where the natural mud shifts from a solid to a solid-fluidic state and from the solid-fluid state to a fully fluidic state. They can be identified directly from the apparent viscosity curve by observing two distinct sharp declines (Wang et al., 2022). This can be seen in part A of Figure 15. A visualisation of the possible mechanism for two step yielding is shown in Figure 16. When the static yield stress is reached the network of flocs is broken down to individual flocs. At the second yielding point for fluidic yield strenth, the individual flocs are broken up into individual particles (Shakeel et al., 2020c). As soon as the fully fluidic state is reached, the mixture can be considered as fluid, so this is the critical yield point that determines the nautical bottom.

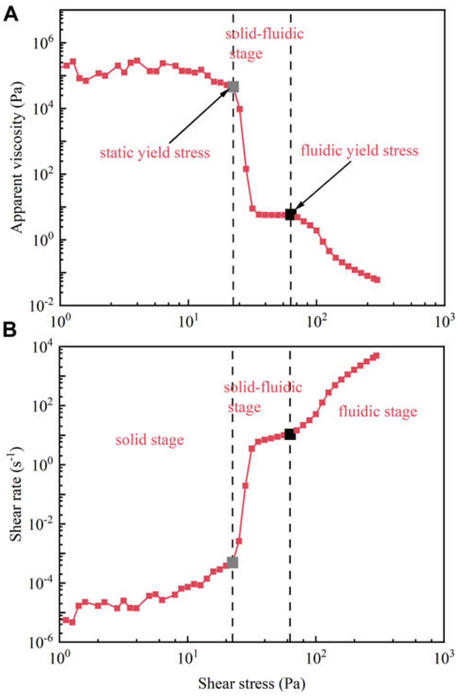


Figure 15: Shear stress to rate graph for soft materials, in which two-step yielding is found (Wang et al., 2022).

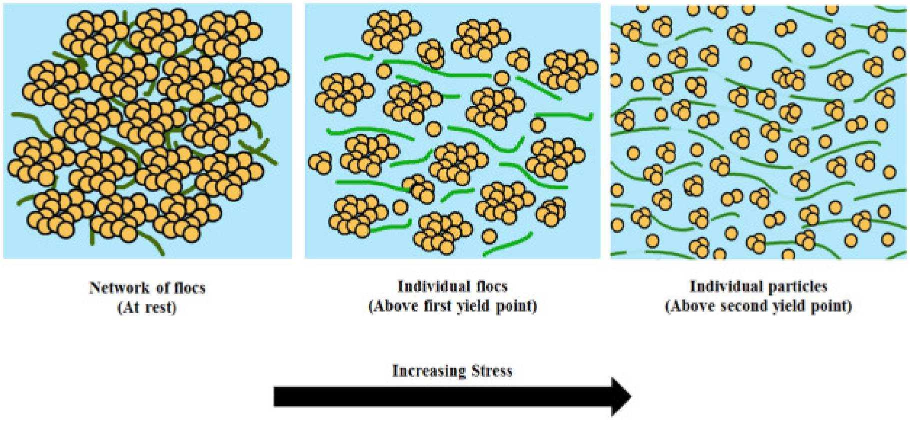


Figure 16: Possible mechanism for two step yielding in mud (Shakeel et al., 2020c).

Bulk density

Bulk density represents the density of a body of mud and water. In this research bulk density is referred to as 'density'. The mud's yielding process is dependent on both density and particle size distribution (Wang et al., 2022). The less dense the mixture of water and grains, the smaller the concentration of sediment in the water. One can imagine that a denser mixture, containing heavier material per unit volume, is tougher for an object to move through. As this is already explained, this is due to the shear stress created. Figure 17 shows several graphs for mud samples with different densities. The figure is copied from a study of Shakeel et al. (2020b) that proves that yield stress is strongly dependent on density. This can be seen in the graph below as well.

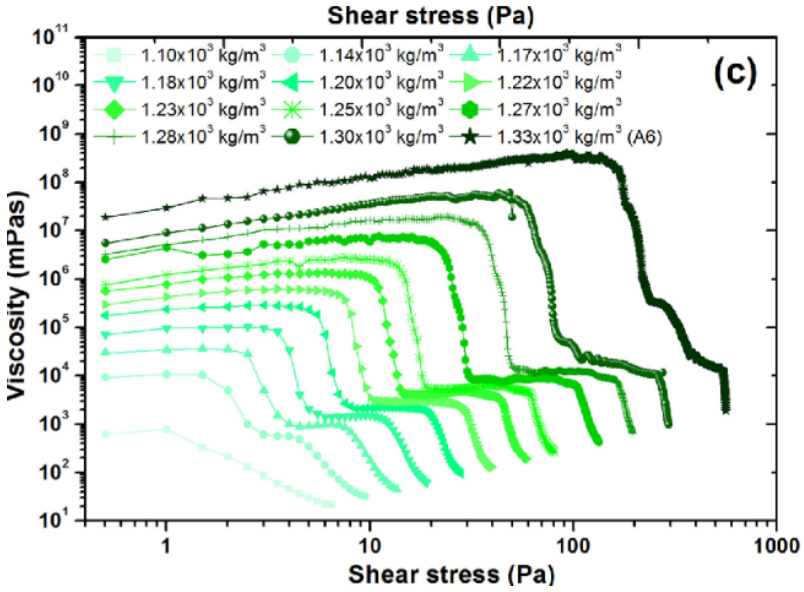


Figure 17: Shear stress figures showing two-step yielding for graphs from a study on diluted mud samples with different densities (Shakeel et al., 2020b).

Therefore, density is the second characteristic of the mud that contributes to the nautical bottom concept.

Turbidity

Turbidity serves as an indicator of particle levels like sediment, plankton, or organic by-products within a water body. With increasing turbidity, water density rises and clarity diminishes due to higher concentrations of light-blocking particles (Grobbelaar, 2009). The unit in which turbidity traditionally is expressed is Nephelometric Turbidity Units (NTU). The Turbidity does not influence the ability of a vessel to move and manoeuvre through the port. However, turbidity is a factor that does need to be taken into account regarding the environment of the port's water. The higher the turbidity in the water, the lower the water quality and marine fauna. Due to dredging activities, the turbidity is disturbed. The amount of distortion relative to the natural turbidity should be minimized at all times.

1.5 Problem definition

Currently, the Port of Rotterdam only uses the WID for conditioning of the port's sediment, however, the WID is often unavailable and expensive to deploy. Therefore, the port authority aspires to find an alternative vessel to deploy for conditioning the sediment. Especially for silt traps, it would be favourable to condition them more occasionally rather than deepen them. Recirculation with the TSHD and the Tiamat are not suitable because of local hydrodynamic conditions in the port. The objective of this research is to evaluate the application of the bed leveller for conditioning purposes in the Port of Rotterdam. The bed leveller and the WID are compared in terms of **effectiveness**, **frequency** and environmental impact in terms of **turbidity**, including the **cost-effectiveness** of the operation as well. This research compares these two conditioning methods for the Port of Rotterdam. Since previous research concluded that conditioning fluid mud with the bed leveller has a minor effect, this research will focus on pre-consolidated mud. Therefore the main research questions in this thesis are:

Q1. *How can the conventional plough design be improved to minimise impact on turbidity, while maintaining effective conditioning efficiency for port maintenance with the bed leveller?*

Q2. *In what way can the bed leveller effectively achieve comparable results to the WID regarding conditioning of pre-consolidated mud?*

Q3. *Does the frequency in a dredging activity with the bed leveller at a certain area influence the effectiveness of conditioning for pre-consolidated mud?*

Q4. *How does the bed leveller perform compared to the WID in terms of the environmental impact regarding conditioning dredging?*

1.6 Structure of this report

The structure of this report is as follows. First, an overview is given of the activities performed in this study. The approach is chronologically divided into different phases; the design phase, the lab tests phase and the field tests phase. Second, the results are presented of the various activities in each phase of the Methodology. Following, flaws that were faced in the methodology and results are discussed. Then, conclusions on the study are formed altogether and finally, recommendations are given on follow-up research.

2 Methodology

This chapter gives an insight into the methodology used to answer the research questions that were raised. The first Sub-chapter 2.1 gives a general overview of this methodology. In the design phase a prototype for a conditioning plough needed to be designed and developed. The execution of this development is explained in detail in Sub-chapter 2.2. Following, in Sub-section 2.3.1, the pieces of measuring equipment used in the field tests phase and lab tests phase are described to comprehend their working mechanism and output. This is followed by a description of the experimental set-up for the laboratory and tests in Sub-chapter 2.3. Then, in the Sub-chapter 2.4, an overview of the performed field tests will be given.

2.1 General overview

To obtain answers to the research questions stated in the problem definition, the research was divided into three different phases. Following, the phases are listed and briefly explained in chronological order:

Design phase

The design phase gives knowledge on improving ploughs specifically for conditioning purposes, which could make the deployment of the bed leveller for this purpose more attractive. Since no other reported studies can support the suggestion of a conditioning plough design, the design phase took effort and time. In this phase, the different options for creating a new conditioning plough design were explored. Supported by experiences and research with ploughs in the field of agriculture and dredging, a design was developed, reviewed and iterated. Various design options were considered and assessed on set criteria to carry out a Multi-Criteria Analysis (MCA) which determined the final features that were included in the design. Using a 3D-modelling program, this design was worked out and a 3D print was manufactured. After some initial testing of the working principle, the design was iterated and a final design was created. Due to limited time, only one design was created and manufactured. Besides, for this reason, only limited modifications could be made to this single design.

Lab tests phase

The first set of experiments was performed in the laboratory. This setting was crucial for conducting experiments for analysing the conditioning technique and comparison of three prototypes; a manufactured prototype of the conventional plough, the newly designed conditioning plough and a prototype of a WID. All three prototypes were present at the laboratory and were tested in small tanks. The tanks were filled with mud and water from a certain location in the Port of Rotterdam, to recreate field conditions as much as possible. Using specifically water from this location is important since salinity and organic materials in the water affect the amount of flocculation (Deng et al., 2022). Before using the mud in each experiment, the mud was gently mixed into a homogeneous mixture. The reason for this is that the mud consolidates after some time and needs to be returned to its original state. There should be noted that each experiment is replicated once. In the lab tests phase three experiments were executed; the technique transition tests, the frequency tests and the comparative tests:

- *Technique transition tests*: This experiment simply mimics the bed leveller and the WID, by shear-thinning and dilution respectively. The experiment was designed to check what is needed to successfully condition pre-consolidated mud. The hypothesis of this experiment states that shear-thinning pre-consolidated mud reduces the strength of the mud just like diluting does. This is based on the theory that shear-thinning reduces yield stress Zhang and Yu (2017), predicting that the strength is reduced for shear-thinning, however, not as much as for dilution. The amount of stirring and dilution are varied throughout the experiment as different treatments, collecting samples of the mud after each alteration to check the influence of these treatments. Post-experiment, both methods are compared on density and yield stress to check if results point out that shear-thinning indeed reduces strength just like dilution.

- *Frequency tests*: This experiment applies both the conditioning and conventional plough prototypes, to check if the frequency in a conditioning activity influences the effectiveness of conditioning of pre-consolidated mud. The hypothesis of this experiment states that a higher frequency in a conditioning activity results in a higher effectiveness of consolidation. This is assumed based on a study by Kirichek et al. (2023), in which was found that increasing the frequency of dredging activities also increases the degree of conditioning. It is predicted that an increasing frequency in one dredging activity also increases the degree of conditioning. The tests are carried out using both the conditioning plough and the conventional plough, applying different treatments by varying the frequency of the dredging action. Mud samples were collected for both tests after each increasing step of frequency. Post-experiment, the samples were analysed on density and yield stress to check the effectiveness of conditioning.
- *Comparative tests*: The goal of this experiment is to obtain knowledge about the conditioning effectiveness and impact on the turbidity of pre-consolidated mud for both ploughs of the bed leveller and the WID. The hypothesis of this experiment states that the bed leveller can successfully condition pre-consolidated mud and the conditioning plough minimises impact on turbidity, however, the conditioning effectiveness of the WID is higher. Partly, this is based on the study by Kirichek et al. (2023), which found that the WID has a larger effect on conditioning fluid mud than the bed leveller. The assumption is made that this is also the case for pre-consolidated mud. Furthermore, the assumption is made that the conditioning plough has a smaller impact on turbidity, as it was designed specifically for this. This will be elaborated in Sub-chapter 2.2. It is predicted that the WID is more effective regarding conditioning than the bed leveller and the conditioning plough minimises impact on turbidity. The prototypes for the conditioning plough, conventional plough and WID are used to execute the conditioning activity. Over a period of two weeks, mud samples were collected and analysed for density, yield stress, and turbidity under different treatment conditions using four types of dredging equipment. Post-experiment, the analyses of all mud samples were compared to check if the predictions were correct.

An experimental overview is given in Table 2, including their hypotheses, conditioning methods applied, scale, varying variables and analysed variables. Further details about the test setup and measurements will be addressed later in Sub-chapter 2.3. Keeping in mind that certain lab conditions leave out components that could play a major role in reality, initial conclusions can be formed about the conditioning methods treated in this research.

Field tests phase

The field tests were performed in the Port of Rotterdam, using a bed leveller and a WID. This experiment would confirm the findings of the comparative tests. In this way, the outcomes of the laboratory experiments are supported by the outcomes of experiments in the field. If the results were similar, acceptable conclusions could be formed about the performance of the dredging devices. Furthermore, due to the application of more accurate measuring equipment, the volume of effectively conditioned pre-consolidated mud can be predicted. This leads to an estimated production rate and can give insight into the cost-effectiveness and fuel consumption of each dredging method. The hypothesis of this experiment states that the bed leveller can effectively condition mud while having a smaller impact on turbidity then the WID, however, the WID is more effective. This is based on research by Kirichek et al. (2023) and Berendt et al. (2013) that found that this is the case for fluid mud. The assumption is made that this also applies to pre-consolidated mud. The bed leveller and WID perform conditioning activities in a designated area at the same location where the mud was retrieved for the lab tests phase. A surveying vessel conducted measurements prior to, directly after and a week after. Post-experiment, the obtained data was analysed and a comparison was made between both conditioning methods. Also, the outcomes were compared to the findings from the comparative tests. An overview of the lab experiment is implemented in Table 2 as well.

Experiment	Hypothesis	Conditioning methods	Scale	Treatment	Analysed variables
Technique transition tests	Shear-thinning pre-consolidated mud reduces the strength of the mud just like diluting	Shear-thinning & dilution	Lab	Amount of stirring and dultion	Density & yield stress
Frequency tests	Higher frequency in a conditioning activity results in a higher effectiveness of consolidation	Bed leveller (two ploughs)	Lab	Frequency	Density & yield stress
Comparative tests	The bed leveller can successfully condition pre-consolidated mud and the conditioning plough minimises impact on turbidity, however, the conditioning effectiveness of the WID is higher	Bed leveller (two ploughs) & WID	Lab	Conditioning method	Density & yield stress & turbidity
Field tests	The bed leveller can effectively condition mud while having a smaller impact on turbidity than the WID, however, the WID is more effective	Bed leveller & WID	Field	Conditioning method	Density & yield stress & turbidity

Table 2: Experimental overview

The silt trap in the Botlek is chosen as the research location. Figure 18 shows a map of the Port of Rotterdam with a red mark on the location of the Botlek silt trap. For the lab tests, mud and water were retrieved from this location. The field tests were carried out at this location themself.

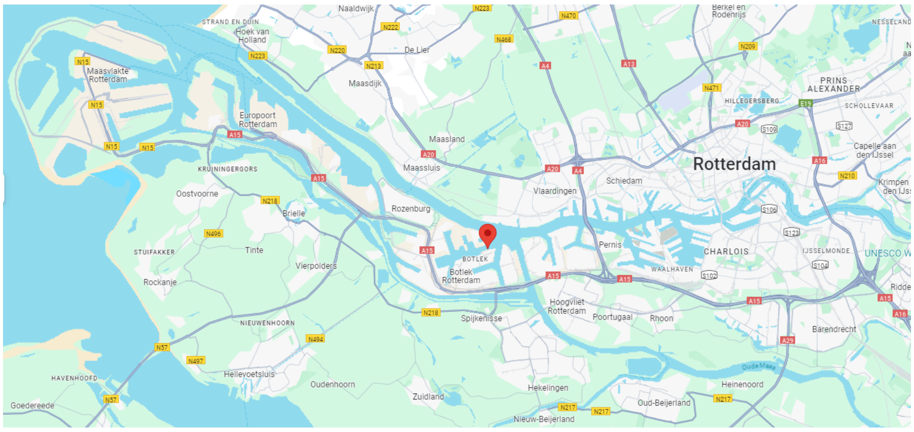


Figure 18: Research location - Botlek silt trap

2.2 Design phase

In this sub-chapter, an overview is given of the methodology for designing the conditioning plough. To determine how the conditioning plough will differ from the conventional plough, certain steps were taken that are shown and explained in Table 3.

Step	**Details**
Defining key elements	During the initial part of the design phase, various essential elements were identified, each contributing to maintaining effective conditioning, while minimising impact on turbidity.
Exploring design options	Following the identification of the key elements, several design options were explored.
MCA	Finally, criteria were set and a set-up was given for an MCA, which would eventually point out the most optimal design options for the conditioning plough.

Table 3: Overview of the methodology for designing the conditioning plough

2.2.1 Defining key elements

For the design of a conditioning plough specifically for conditioning dredging, it was important to identify key elements to include in the design. Taking in mind the current methods for ploughing, WID, puddling and environmental requirements, the following were determined:

- An element for breaking cohesive bonds in the mud. As explained in Sub-chapter 1.3, the cohesion within the mud must be overcome to produce fluid mud. This requires a certain energy source, like water injection in a WID system. In this research, this component is called 'the breaking element' from now on.
- An element for the suspension of the particles. The smaller particles need to be suspended so that a fluid mud layer is formed near the seabed. As explained before in Chapter 1.1, the fluid mud layer is formed when particles are mixed and suspended and do not settle due to hindered settling. When injecting water into the muddy bed, the particles are mixed and suspended by the liquid. The suspension of the particles high in the water column should be minimized though. It is known that the particles are suspended more throughout the whole water column with the WID technique, than with the bed leveller (Berendt et al., 2013). For environmental reasons, this should be minimized.

2.2.2 Exploring design options

For each of the two explained key elements that needed to be included in the design of the conditioning plough, several solutions were created. In this sub-chapter, these solutions are given and described.

Breaking element

For the breaking element, different mechanisms could be used. Since puddling is a technique that's been used for many years and the goal is similar regarding the modification of clayey and muddy soils, the different techniques in this field can be applied. As explained in Section 1.3.4, rotational ploughs are widely applied for puddling of rice fields. Most experience with puddling comes from India and rotary puddles appear to be the most effective puddling technique. However, small farmers still use traditional ploughs drawn by bullocks as well, such as the mould board plough or the cultivator. This seems to be a more laborious and time-consuming job. So creating design options that ensure the breaking down of aggregates, can copy the mechanism used in:

- The traditional plough like the mould board plough in Figure 12a. The principle of such a plough is cutting through hardened soil and turning it. Cutting is meant to reduce aggregates in size and turning the soil is meant to bring nutrient-rich soil to the surface while burying weeds and leftover crop to decay. In its simplest form the moldboard plow consists of the share, the broad blade that cuts through the soil; the moldboard, for turning the furrow slice; and the landside, a plate on the opposite side from the moldboard that absorbs the side thrust of the turning action (Britannica, The Editors of Encyclopaedia, 2024).
- A rotary plough like the rotavator in Figure 12b. Rotary plows or tillers (sometimes called rototillers) have curved cutting knives mounted on a horizontal power-driven shaft (Britannica, The Editors of Encyclopaedia, 2024).

Suspension element

Suspension of small aggregates and particles can be reached by various methods, so one can be quite creative regarding this. There are two factors given in the previous section that should be taken into account regarding suspension. The first factor points out that suspension is necessary for creating fluid mud and the second factor is that suspension should be minimised to reduce environmental impact. Therefore a method should be used in which suspension of particles is maximised near the bed. So particles get suspended but not blown throughout the whole water column. The following options are considered:

- Water injection: Install water injection component on the plough to suspend the loose aggregates near-bed. Figure 19a gives a sketch showing the working principle of a plough combined with a water injection system to suspend particles. The conventional plough breaks down the aggregates into smaller pieces by cutting. The water injection system also breaks down inter-particle bonds and penetrates deeper into the mud. Its main goal is to suspend them and it is already known to be effective for that purpose from current WID activities.
- Funnel: Create a plough with a funnel-like shape that pushes the plough. A funnel-shaped plough has the ability to suspend particles and also to break up inter-particle bonds due to the acceleration in velocity of the water pushed through the funnel-shaped plough. This growth in energy will help break cohesive bonds in the mud. The eddies created behind the plough also break up the mud. A sketch of the funnel-shaped plough is shown in Figure 19b.
- Recreate the WID technique with a plough accelerating water downward to the bed. In Figures 19c and 19d two examples are given of such a water plough. Figure 19c has a linearly sloped downward facing plough and Figure 19d has a parabolically shaped downward facing plough. In both designs, the method includes accelerating the flow of water to break up the mud and suspend particles, just like with WIDing.

(a) Conventional plough with a WID system

(b) Sketch of a funnel-shaped plough

(c) Water plough, option 1

(d) Water plough, option 2

Figure 19: Sketches of design options for the suspension element

2.2.3 MCA

To execute an MCA to determine which features would be included in the design, certain criteria needed to be set:

1. Criterion on the ability to break down pre-consolidated mud.
2. Criterion on the ability to suspend particles.
3. Turbidity criterion. Minimising the turbidity is of importance for the conditioning plough.
4. Feasibility criterion; in terms of production and iterations of prototype. Due to time restrictions, it is not doable to create, manufacture, test and recreate a complicated design of a conditioning plough.
5. Criterion on alignment with scope.

The MCA rates each criterion for the suggested design options for the key elements on a scale of $1-5$, 1 being not suitable at all, and 5 being very suitable. All components weigh the same, so no multiplication factor is added for any criterion.

When the outcome of the MCA was known, a 3D model of the conditioning plough was made in a 3D-modelling program. AutoCAD Autodesk was used for this. A 3D print of the design could then be manufactured. After the manufacturing of this initial prototype, the final iterations of the design were worked out. This was achieved by performing some simple tests to check if the working principle of the design was met. Finally, 3D prints of the finalized conditioning plough and conventional plough were manufactured and used in the lab tests phase.

2.3 Lab tests phase

The lab tests phase consisted of three experiments conducted on a small scale in the laboratory. Measurements were conducted on the characteristic values from Sub-chapter 1.4, with the lab equipment that is described in Sub-section 2.3.1. The first experiment that was executed was the technique transition tests, in which shear-thinning and dilution are compared to check what is needed to successfully condition pre-consolidated mud. The second experiment investigates if the frequency in a conditioning activity influences the effectiveness of conditioning of pre-consolidated mud. The third experiment compares three different conditioning methods, the conditioning plough, the conventional plough and the WID, and analyses them on conditioning effectiveness and impact on turbidity.

2.3.1 Measuring equipment

An overview of measuring equipment deployed in the field tests phase is shown in Table 4. Below the table, an explanation is given for each type of measuring equipment.

Equipment name	**Brand**	**Parameter(s) measured**	**Units**
Rheometer	Haake Mars	Yield Stress	Pa
Portable Density meter DMA35	Anton Paar	Density	kg/m^3
Portable Turbidity Meter	Extech	Turbidity	NTU

Table 4: Equipment for measurements deployed in laboratory experiments

Haake Mars Rheometer

The Haake Mars, a flexible Modular Advanced Rheometer System, is a lab-scale rheometer that can measure resistance of sediment species to an applied shear rate. Depending on the type of test, the Rheometer can perform a test on a material by either a rotating or oscillating test (Thermo Scientific, nd). The simple shearing flow is attained and by controlling the strain rate in terms of applied strain rate, the resulting couple or torque can be measured. Vice versa, applying couple or torque results in the strain rate. this determines the viscosity of the sediment-water mixture. Different kinds of tests can be executed using the rheometer. In this research, only the stress ramp-up test is used, in which the rheometer constantly increases stress on a mud sample until its structure is completely destroyed (Shakeel et al., 2021b). Graphs can be obtained from which both the static and the fluidic yield stress can be observed.

Anton Paar Portable Density Meter DMA35

The portable density DMA35 meter of Anton Paar is a small device that can measure density and concentration of a sample directly on site. The device requires a sample that is retrieved from the sediment mixture. A U-shaped tube of borosilicate glass will be vibrated untill the natural frequency of the sample is reached. Since the natural frequency is based on the density of the sample, this density can be calculated (Anton Paar, nd). So by determining this frequency, the density of the sample can be accurately determined. Density depends on temperature as well, so it is of vital importance to know the precise temperature of the sample. The concentration of the sample is dependent on the concentration of both the water density and the dry density of the sediment particles. Knowing the density of the mixture results in the concentration of sediment in the mixture as well.

Eventually, a different method was applied to measure the density of the samples. Since the mud consists of quite consolidated mud, the Anton Paar Portable Density meter could not be applied. The substance of the mud was too thick for this meter. Therefore another method needed to be applied to determine the density of each sample. Figure 20 shows a picture of a small tub, of which the empty weight is $g_{empty} = 13.41gr$. Together with the precise scale and the known volume of the container, the density of the mud samples could be determined by filling the container with a mud sample and topping it off evenly.

Figure 20: Container for measuring density

The density of the water used to determine the volume of the container is measured with the Anton Paar Density meter. Then equation 1 is filled in to determine the density of the mixture ρ_m of each sample. It is important to note that each measurement with this method was conducted three times and an error margin of 0.2-0.3% is implemented due to the lack of accuracy.

$$\rho_m = \frac{(g_m - g_{empty}) * \rho_w}{g_w - g_{empty}} \tag{1}$$

Where:

- ρ_m, ρ_w = the density of the mud sample and the density of the water, respectively.
- g_m , g_w = the weight of the container filled with the mud sample and the water, respectively.
- g_{empty} = the weight of empty container = 13.41 gr

Extech TB400 Portable Turbidity Meter

The Extech portable turbidity meter was used in the laboratory. It is a portable device that can measure the turbidity of a taken sample. The operational principle of a turbidity sensor is based on assessing the interaction between light and suspended particles in a liquid. This interaction impacts the light primarily through two processes: scattering and absorption (Bin Omar and MatJafri, 2009). The turbidity meter comes with two calibration samples, two liquids with 0 and 100 NTU, respectively. The meter measures up to 1000 NTU (Nephelometric Turbidity Unit) with 0.01 NTU resolution (Teledyne Flir, nd).

2.3.2 Technique transition tests

This experiment simply mimics the bed leveller and the WID, by shear-thinning and dilution respectively. The experiment was designed to check what is needed to successfully condition pre-consolidated mud. Density and yield stress were tested in the technique transition tests so the Portable Density meter and the Rheometer were utilized. There should be noted that for the Rheometer's geometry, a vane was used in this experiment. The tests were carried out by applying different treatment conditions by varying the amount of time of shear-thinning and adding water to dilute the mixture. The test was replicated one time.

Shear-thinning

In the shear-thinning test shearing forces of the bed leveller were imitated by stirring the mud with a small spatula, breaking cohesive bonds. The frequency of shear-thinning is expressed in time and is set up in the order as shown in Table 5.

Dilution

To imitate the principle of the WID, the pre-consolidated mud mixture was diluted in the order shown in Table 6. As this form of dredging creates a fluid mud layer by reducing density and yield strength, dilution mimics this performance regarding the change of solids to water ratio. The mud sample was diluted and stirred gently so that the mud sample diluted evenly.

Treatment	**Shear-thinning [s]**
Reference	0
Sample A	10
Sample B	20
Sample C	30
Sample D	60

Table 5: Bed leveller; amount of shear-thinning

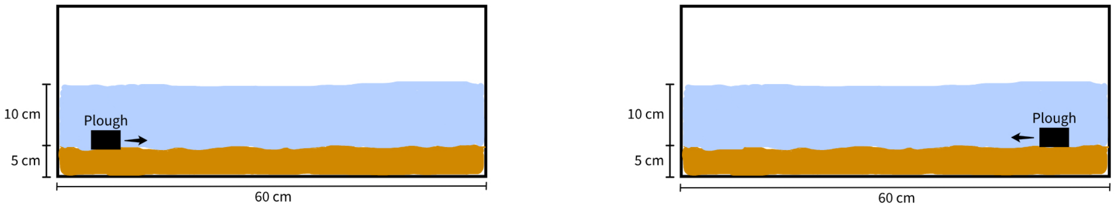
WID	**Dilution [mL]**	**Density [kg/m^3]**
Reference	0	1326
Sample A	100	1244
Sample B	200	1200
Sample C	300	1151
Sample D	400	1120

Table 6: WID tests; amount of diluting

2.3.3 Frequency tests

The goal of the frequency tests experiment is to check if the frequency in a conditioning activity influences the effectiveness of conditioning of pre-consolidated mud. To check this the mud is tested on changes in density and yield stress. The hypothesis of this experiment states that a higher frequency in a conditioning activity results in a higher effectiveness of conditioning. The tests were carried out using both the conditioning plough and the conventional plough, applying different treatments by varying the frequency of the dredging action.

Tanks of 60 x 35 x 40 cm, present at the Deltares laboratory, were filled up to 4-5 cm in height on average with the Botlek's mud. Another 10 cm was filled with the Botlek's water on top of this. Pictures of the tank and plough setup can be found in Appendix C.2. Figure 21 gives sketches of a simplified demonstration of the lab tests. One of the ploughs was lowered into the tank and the mud was treated by dragging it the plough through it from left to right and from right to left with a constant speed of 0.12-0.15 m/s. This is equal to 4-5 seconds over the entire length of the tank. This dredging speed was based on an assumption, which was obtained through a process of trial and error. The downward force of the ploughs was only dependent on the additional weights. The ploughs both needed to have a similar weight to accurately compare them. In appendix B.1 this is elaborated. The treatment conditions varying for frequency, are shown in Table 7. First, a reference sample was taken and then after each treatment, another sample was. The samples were taken with a syringe in this experiment, with the location of retrieving the sample being the top 1 cm of the mud in the middle point of each tank. Therefore, each tank was not emptied and refilled for each sample taken. The Portable density meter, container and Rheometer were applied to conduct measurements to check changes in density and yield stress. The density measurements were conducted three times to reduce the error margin on the method of the container. A cone was used as a geometry for the Rheometer in these tests. Furthermore, the development of the fluid mud layer was visualised and read from the tanks' height dimension, a few minutes after each action.



(a) Pulling plough from left to right

(b) Pulling plough from right to left

Figure 21: Sketch of testing method for the frequency tests

BL	**Frequency [#]**
Reference	0
Sample A	5 times
Sample B	10 times
Sample C	20 times

Table 7: Frequency test; Scheme for dragging each plough through it's corresponding tank

To sum up the frequency tests, the experimental parameters can be found in Table 8. It was important to clearly define these parameters before the tests so that the activities in the experiment were executed similarly.

Experiment characteristic	**Value/description**
Varying treatment condition	Dredging frequency
Mud samples retrieved	Top 1 cm of the mud layer; middle of the tank
Measurements conducted	• Measure the density of the mud, using the Rheometer • Measure the yield stress of the mud, using the Portable density meter and the container. • Visualise the thickness of the fluid mud layer a few minutes after dredging.
Replicates of experiment	1

Table 8: Experimental characteristics of the frequency tests

2.3.4 Comparative tests

The goal of this experiment is to obtain knowledge about the conditioning effectiveness and impact on the turbidity of pre-consolidated mud for both ploughs of the bed leveller and the WID. The hypothesis of this experiment states that the bed leveller can successfully condition pre-consolidated mud and the conditioning plough minimises impact on turbidity, however, the conditioning effectiveness of the WID is higher. The execution of the comparative tests is rather similar regarding test setup to that of the frequency test, only in this case, there are four tanks with different types of tests that need to be carried out. The application of a certain conditioning method is set as the varying treatment condition. All proceedings for the different treatments were done in the same manner and measurements were conducted in the same period for all conditioning methods. The treatments with or without prototypes represent the following dredging methods:

- Reference situation.
- Water injection; prototype of research of Chamanmotlagh et al. (2023). A picture is shown in Appendix C.3.
- Bed leveller using the conventional plough; 3D print of conventional plough.
- Bed leveller using the conditioning plough; 3D print of the conditioning plough.

Like the frequency tests, tanks with dimensions of 60 x 35 x 40 cm are filled up to 4-5 cm with homogenized mud and about 10 cm with water from the Botlek silt trap. For these tests, there was one day in between filling the tanks and executing dredging works. The tank with the reference situation was to remain untreated in this experiment.

The WID prototype is connected to a small pump at the water laboratory. It pumps water through the tubes of the WID prototype to its nozzles. The nozzles are held slightly, about 1 cm, above the bed for the entire experiment. Since this is a simplified prototype mimicking the working principle of a WID, the pressure and discharge of the prototype do not correspond to a real WID. Therefore, it was chosen to execute the experiment until a similar layer of fluid mud was formed as the conditioning and conventional plough methods. This happened at $t = 350$ s, corresponding to 7 times crossing the entire length of the tank. Pictures of this treatment are shown in Appendix C.3.

The dredging works for both the conventional and conditioning plough were done in the same manner as the frequency tests, as Figure 21 shows. The frequency of dredging with the ploughs was set at $N = 10$. The experiment of the frequency tests will point out that the higher the frequency, the bigger the effect on conditioning. This frequency was chosen, however, since it was the most convenient to also apply in the field tests.

The measurements after the dredging activities in each tank were conducted as follows:

- Measurements were conducted directly after (t_0), 1 day, 3 days, 7 days, and 14 days after conditioning activities. The measuring moments are expressed in $t_0 + n$, with n representing the number of days after conditioning activities,
- At each measuring moment all tanks were emptied, samples were taken from the top layer (top 1 cm) and the bottom layer (lower 1 cm) of the mud and the tanks were filled with the same water again. Emptying and refilling were executed with the same pump system as used for the WID. It was important to minimize the impact of the water hitting the mud when refilling.
- Each sample was used to determine density and yield stress using the Portable density meter, container and Rheometer. For density, measurements with the container were conducted three times to reduce the error margin. A cone was used as a geometry for the Rheometer in these tests.

- Each measuring moment a water sample was taken from all tanks at 2 cm below the water surface. These samples were analysed on turbidity using the Portable turbidity meter.

Table 9 gives an overview of the set-up of the comparative tests.

Experiment characteristic	**Value/description**
Varying treatment condition	Conditioning method
Mud samples retrieved	Top 1 cm and lower 1 cm of the mud layer; middle of the tank
Water samples retrieved	2 cm below the water surface
Measurements conducted	• Density of the mud, using the Portable density meter and the container. • Yield stress of the mud, using the Rheometer. • Turbidity, using the Portable turbidity meter.
Replicates of experiment	1

Table 9: Experimental characteristics of the comparative tests

2.4 Field tests phase

The third phase of the research, called the field tests phase, consisted of an experiment executed on a large scale as field tests in the Port of Rotterdam. The Husky, a vessel used for bed levelling, and the AquaDelta, a WID vessel, were deployed in the Botlek's silt trap for this.

2.4.1 Measuring equipment

An overview of measuring equipment deployed in the field tests phase is shown in Table 10. This equipment was present on board of the surveying vessel. Below the table, an explanation is given for each type of measuring equipment.

Equipment name	**Brand**	**Parameter(s) measured**	**Units**
Multibeam Echosounder	Teledyne Marine	Bed level	-
Rheotune	Stema	Density & yield stress	kg/m^3, Pa
SWiFTplus	Valeport	Turbidity	NTU

Table 10: Equipment for measurements deployed in laboratory experiments

Multibeam echosounder

The multibeam echosounder is a piece of equipment widely used to map the seabed. It does so by an advanced sonar system, emitting sound waves. These sound waves are captured again and an accurate 3D mapping of the seabed can be developed. The sound waves are reflected on the lutocline layer, which represents the water-mud interface. It thus maps the layer of fluid mud. Many vessels nowadays feature such a multibeam echosounder. The width of the surveyed area depends on the depth surveyed and the acoustic frequency used (Infomar, nd). For the multibeam echosounder, the SeaBat T50-R from Teledyne Marine is deployed on the surveying vessel.

Stema Rheotune

The Stema Rheotune is a field version of the Rheometer. It is a probe that is lowered in the water. The RheoTune rheometric profiler determines nautical depth through the measurement of yield strength and viscosity. This versatile system provides density and yield stress profiles of fluid mud simultaneously. Designed as the successor to the Densitune, the RheoTune utilizes both yield strength and viscosity data to set the nautical depth accurately (STEMA, nd). The RheoTune was used for supplying density and yield strength profiles throughout the water column and mud mixtures at the bed. The Rheotune is connected to an electrical winch on the surveying vessel.

Valeport SWiFTplus

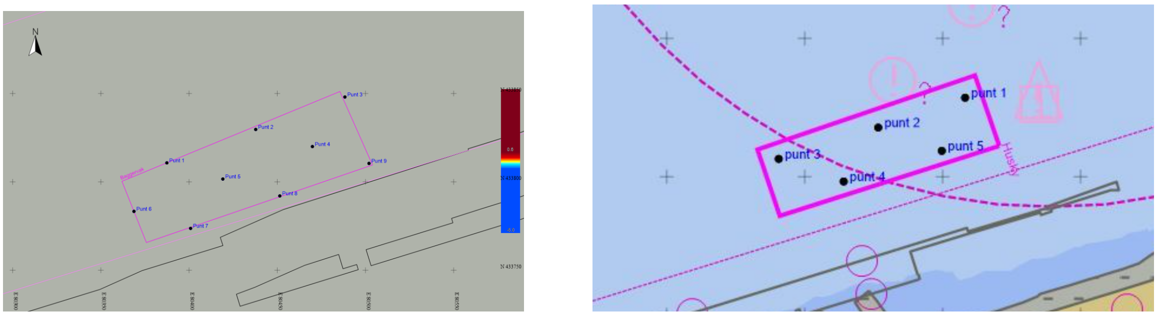
The Valeport SWiFT is in this research the in-field substitute of the Extech TB400. The measuring device is equipped with sensors for sound velocity, temperature, pressure, and optical measurements. The optical sensors are mainly of use in this research. This sensor can measure turbidity by using light. It emits light, which interacts with particles in the water column and detects the scattered light. This is converted into an electrical signal, which is then processed to an output for turbidity in NTU (Valeport, nd).

2.4.2 Field tests

The goal of this experiment is to confirm and support the outcomes of the lab tests phase. Furthermore, due to the application of more accurate measuring equipment, the volume of effectively conditioned pre-consolidated mud can be predicted. This leads to an estimated production rate and can give insight into the cost-effectiveness and fuel consumption of each conditioning method. The hypothesis of this experiment states that the bed leveller can effectively condition mud while having a smaller impact on turbidity than the WID, however, the WID is more effective. Two tests were executed on two different testing days in the Botlek silt trap. One with the WID and one with the bed leveller, using a conventional plough. Also, a surveying vessel was deployed for both testing days to conduct measurements. All vessels used a Global Positioning System (GPS) to ensure that they crossed intended paths and measuring points and to ensure that overlaps between adjacent runs were completed. In Table 26 an overview is given of the three vessels deployed for the field tests and the dates they were deployed on. For the field tests the areas shown in Figures 22a and 22b were assigned to the WID and the bed leveller respectively. The testing area of the WID (35*130 m) had nine measuring points (1-9). The testing area of the bed leveller (20*75 m) was smaller and had five measuring points (1-5), as can be seen in the figures. As mentioned in 2.3.4 the frequency of the conditioning activity was set to $N = 10$ for both ploughs in the comparative tests at the laboratory. Therefore the frequency for the Husky's conditioning activity is also set to $N = 10$. The plough was lowered 10 cm for every time the area was dredged to create a fluid mud layer. The frequency of the AquaDelta was set to $N = 3$. The estimation was made that both vessels would have to work the same amount of time in this way. The Surveyor 2 initially executed measurements in the area on depth, density, yield stress and turbidity. These were conducted at the measuring points shown in the figures.

Vessel type	**Testing surface area**	Number of measuring points
Bed leveller	1500 m^2	5
WID	4550 m^2	9
Surveying vessel	-	

Table 11: Vessels for Field tests



(a) WID

(b) Bed leveller

Figure 22: Testing areas with point measurement locations

As given in Table 26, the WID test was executed initially and the bed leveller test 7 weeks later. Accordingly, the setup of both tests was similar:

- The Surveyor 2 does baseline measurements that function as a reference, using the Multibeam echosounder, RheoTune, and SWiFTplus.
- The dredging vessel executes appointed dredging activities.
- The Surveyor 2 does a second measurement, using the RheoTune and the SWiFTplus.
- The Surveyor 2 does a Multibeam analysis one week after dredging activities.

The Rheotune, SWiFTplus and Multibeam data retrieved on the Surveyor 2 were converted to figures showing profiles for depth, density, yield stress and turbidity. From the combined density and yield stress profiles, differences can be detected for changes in density and yield stress for each location. Some of the figures indicate that density decreases a little bit more than yield stress and vice versa. The combination of the layer between values of > 0 and $100 Pa$ for yield stress and $>$ 0 and $1200 kg/m^3$ is representative regarding the creation of fluid mud:

- As soon as the density profile starts increasing, the water-mud interface is reached. This is where the fluid mud layer starts.
- When both values for density exceeds $1200 kg/m^3$ and yield stress exceeds $100 Pa$, the fluid mud layer ends.

An overview of the experimental characteristics is given in Table 12.

Experiment characteristic	**Value/description**
Varying treatment condition	Conditioning method
Measurements conducted	• Bed level, using the Multibeam echosounder. • Density of the water/mud column, using the Rheotune. • Yield stress of the water/mud column, using the Rheotune. • Turbidity of the water/mud column, using the SWiFTplus.
Replicates of experiment	1

Table 12: Experimental characteristics of the comparative tests

2.4.3 Efficiency Analysis

When profiles for depth, density and yield stress are obtained, the volume of effectively conditioned pre-consolidated mud can be predicted. This production rate of fluid mud can be determined for each dredging vessel and with this, a financial analysis can be executed. The production of fluid mud is calculated by analysing the obtained profiles for density and yield stress. Averaging each measuring point's created fluid mud layer gives an estimation of the thickness of the produced fluid mud layer. This is calculated by Equation 2. By multiplying this value by the total area dredged, the total volume of produced fluid mud can be determined. By then taking into account the time of the dredging activity, the production rate can be calculated. Equation 3 gives the calculation for production rate, which is eventually expressed in fluid mud volume produced per hour m^3/h. The WID is manufactured specifically for fluidisation of mud and the knowledge about applying the vessel for conditioning is far more advanced than the bed leveller. Further research needs to be conducted to investigate the optimal application of the bed leveller for conditioning. In this research, however, this is not taken into account.

$$\Delta h_{fm,av} = \frac{\Sigma \Delta h_{fm,MPi}}{\Sigma MPi} \tag{2}$$

$$Production\ rate = \frac{\Delta h_{fm,av} * A_t}{t} \tag{3}$$

Where:

- $\Delta h_{fm,av}$ is the average thickness of the produced fluid mud layer (m)
- $\Sigma\Delta h_{fm,MPi}$ is the sum of the thickness of the produced fluid mud layers at each measuring point (MPi)
- ΣMPi is the total number of measuring points
- A_t is the surface area of the testing area (m^2)
- t is the total time of the dredging activity (h)

With the contracting costs of both the Husky and the AquaDelta, the hourly rate of the vessels and the production rate of fluid mud can be compared, resulting in a certain amount of costs per m^3 of effectively conditioned pre-consolidated mud. Since the actual costs of contracts with both vessels need to be kept anonymous, a certain fictional currency needs to be introduced. This currency is called DredgeCoin (DC). This coin reflects the real value of the contract costs, as they have been based on these and multiplied by a factor that shall remain secret. Equation 4 shows the calculation of the costs per m^3 of effectively conditioned pre-consolidated mud.

$$Costs\ (DC/m^3) = \frac{Hourly\ rate}{Production\ rate} \tag{4}$$

The fuel consumption can be calculated as well. Knowing the amount of fuel consumed by each vessel to create fluid mud, and comparing this to the production rate, results in a certain amount of fuel consumption per m^3 of effectively conditioned pre-consolidated mud, as shown in Equation 5.

$$Fuel\ consumption\ (L/m^3) = \frac{Hourly\ fuel\ consumption\ rate}{Production\ rate} \tag{5}$$

3 Results

3.1 Designing phase

In this part of the results, the design for the conditioning plough is worked out and the technical drawings of the final design are shown. Also, for the conventional plough the technical drawings are given. Eventually, both designs for the new and conventional plough described in the previous sections were 3D printed to be used as prototypes in the lab tests phase. A picture of the prototypes and information about additionally installed weights is described in Appendix B.1.

3.1.1 The conditioning plough design

The two key elements that are to be included were identified in the methodology; a breaking element that could break down cohesive bonds in the mud and a suspension element that could suspend particles that will then form a fluid mud layer. Through an MCA, the design options of both elements are weighed on set criteria to form the outcome of the design of the conditioning plough. There should be noted that some assumptions were made while creating this design, due to limited time. These assumptions will be appointed throughout this chapter. In Section 4 this is pointed out as well. In Table 13 below, the results of the MCA are given.

Criterion	**Breaking down mud**	**Suspension**	**Environmental impact**	**Feasibility**	**Alignment with scope**	**Total**
			Breaking element			
Traditional plough	4	N/A	3	4	5	**16**
Rotary plough	5	N/A	3	2	5	15
			Suspension element			
Water injection	3	5	2	2	3	15
Funnel	1	4	4	5	5	**19**
Water plough	2	5	2	4	5	18

Table 13: MCA

The outcome of the MCA suggests that the new design should consist of a funnel-shaped plough, including a cutting mechanism based on that of the traditional plough used in agriculture. There should be noted that a factor like feasibility in terms of succession of the model is excluded from this research. It would be more accurate to use certain flow modelling software to determine the impact of certain designs on flow and sediment behaviour. As stated earlier, this research focuses on the rough design of a new plough to test the working principle.

Breaking element: Cutting mechanism based on the traditional plough

As pointed out in chapter 1.3.4, traditional ploughs such as the mould board plough function for cutting and turning the soil in agriculture. Since in this design, the soil only needs to be cut before it enters the funnel-shaped plough, the turning mechanism of these ploughs can be omitted. A harrow-like design needs to be made, that is suitable for 3D printing. Therefore, it is chosen to set a row of small teeth at the front of the plough. These have the same form as the cutters on a mould board plough 12a. After conversations with 3D printing company coastruction, these cutters were not suitable for 3D printing, due to the parabolic curve in the cutters. Therefore the final design of the cutters was made, where these parabolic curves were excluded. Snapshots of both 3D designs are shown in Appendix B.

Finally, an initial design was made, of which the technical drawing and 3D snapshots are shown in Appendix B. In this Appendix, the iteration after initial testing is described as well. In Figure 23 and the final design of the new plough is shown, with specifics in Table 14. 3D snapshots of the final design of the conditioning plough are shown in Appendix B.

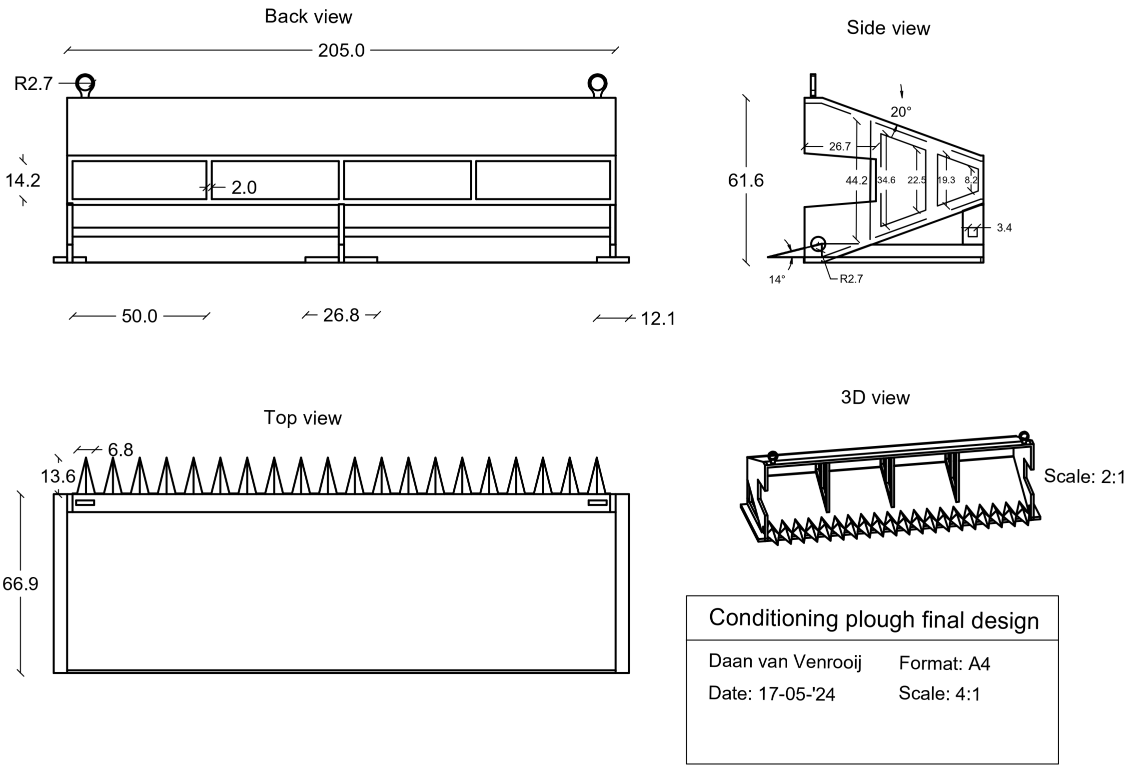


Figure 23: Technical drawing of the final conditioning plough design

Name prototype	Final design new plough
Process	3D Printing SLS - Selective Laser Sintering
Material	Nylon PA12 Gray / White (SLS)
Density material	1010 kg/m^3
Thickness plates	2 mm

Table 14: Details of initial prototype new plough

There are a few things to notice in this design:

- The row of teeth at the front of the plough that is used for cutting the mud.
- The funnel-shaped form of the plough will suspend the particles and further break down cohesive bonds in the mud. The angle of the funnel has been set at 20 °. This value is based on the assumption that the acceleration of the seawater through the funnel needs to be high to create energy by having a large angle, but on which the larger clods could still slide up and through the funnel.

- The three sledges are put under the plough so that the plough does not fall backwards.
- Rings on top and holes on the lower front sides of the plough, which can be attached to a rope for towing the plough.
- Three vertical reinforcement components inside the funnel. The presence and dimensions of these components are not technically supported. These were determined together with the 3D printing company Xometry, who were very experienced with the stability of 3D printed prototypes.

3.1.2 The conventional plough

For the conventional plough the current design needed to be reproduced from the plough attached to the Husky. In Figure 24 below, the 3D model of the prototype design is visualised. It is a scaled-down version of the Husky plough. The dimensions of this prototype are given in the technical drawings in Appendix B. The specifications of this prototype are the same as those of the new plough and are given in 14.

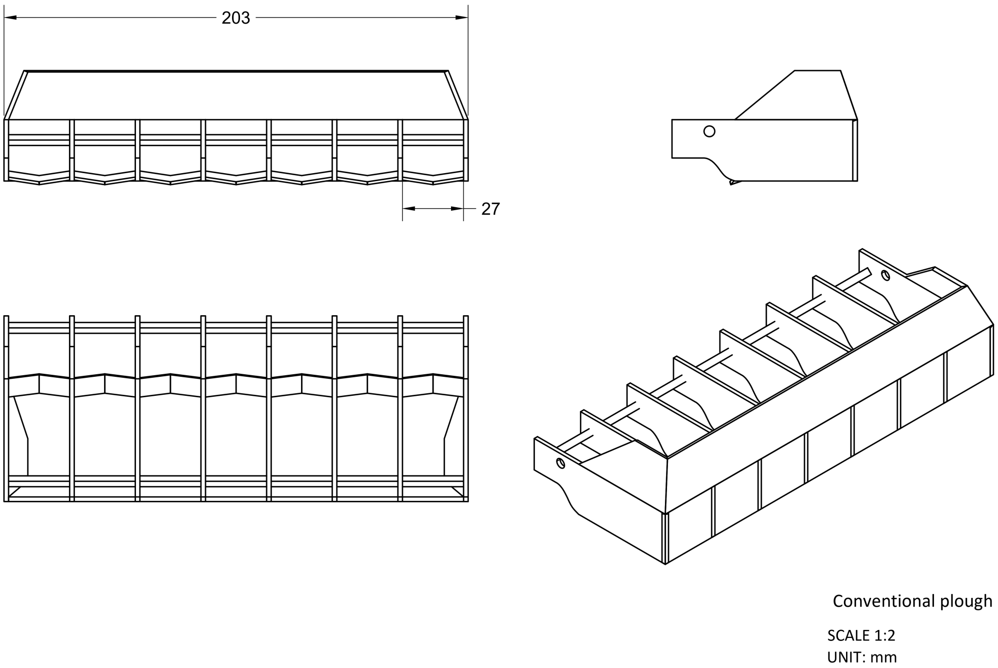


Figure 24: Technical drawing of the conventional design prototype

3.2 Technique transition tests

The experiment results for the shear-thinning and dilution treatments of the samples, representing the bed leveller and the WID, respectively, are shown in 15. The rheological graphs from which these values are derived are shown in Appendix C.1. It should be noted that due to the use of the vane as a fixture in the Rheometer, the second yielding points of some of the mud samples were not obtained properly. Therefore, the value is set at > 350 Pa.

Treatment	**Density**	**Static yield stress**	**Fluidic yield stress**
Shear-thinning			
0 s (reference)	1326 kg/m^3	225 Pa	$>$ 350 Pa
10 s	1326 kg/m^3	200 Pa	$>$ 350 Pa
20 s	1326 kg/m^3	235 Pa	$>$ 350 Pa
30 s	1326 kg/m^3	180 Pa	310 Pa
60 s	1326 kg/m^3	190 Pa	330 Pa
Dilution			
0 ml (reference)	1326 kg/m^3	225 Pa	$>$ 350 Pa
100 ml	1244 kg/m^3	5 Pa	220 Pa
200 ml	1200 kg/m^3	1 Pa	70 Pa
300 ml	1151 kg/m^3	$<$ 1 Pa	3 Pa
400 ml	1120 kg/m^3	$<$ 1 Pa	2 Pa

Table 15: Density and yield stress values

What can be noticed is, that the lower the density due to mixing mud with water, the smaller the yield strength becomes. At 200 ml dilution, for a density of 1200 kg/m^3 the fluidic yield stress is already 70 Pa.

The shear-thinning test has significantly less effect on the rheological parameters in comparison to the dilution test. Simply stirring the mud will not change the density of the material and as a result, the yield strength does not change much either. It is hard to tell by fluidic yield stress if there is a clear decreasing trend line, however for the final two treatments it can be spotted. For the static yield stress, in comparison with the reference sample apart from the sample of 20 seconds, the other samples do have a small trend in decreasing for the treatment conditions. So for the hypothesis of the experiment that states that shear-thinning pre-consolidated mud reduces the strength of the mud just like diluting does, can be concluded that this is not the case. Apart from the situations after stirring 20 seconds having higher yield strength values than the reference, and the yield strength for the situation for 60 seconds being higher in comparison to 30 seconds, it is safe to make this valid conclusion. Dry shear-thinning alone minorly affects the strength of the mud. Looking at the WID results, it is safe to conclude that the strength does decrease when water is added to the mixture and then stirred. It is plausible that stirring the mud with water on top of the mud layer could certainly decrease yield strength and density.

3.3 Frequency tests

Some difficulties were faced with this experiment. Taking samples with a syringe was difficult and affected the accuracy of the tests since some water was added to the mixture. Furthermore, due to little unintended stirring and mixing of the mud with the water mainly due to filling, and executing the test directly after, the values came out a little different in comparison to the comparative tests. However, with a reference situation and these tests being purposed for determining the influence of frequency of dredging activities on the effectiveness of conditioning, they can still be considered reliable.

3.3.1 Density

The samples were each weighed three times and averaged out to determine the density. In Figure 25 the progress of the density for the increasing frequency is given. An error margin of 0.25 % is added to the figure. There can be observed that the density is reduced due to ploughing, however, the frequency has a minor influence on this.

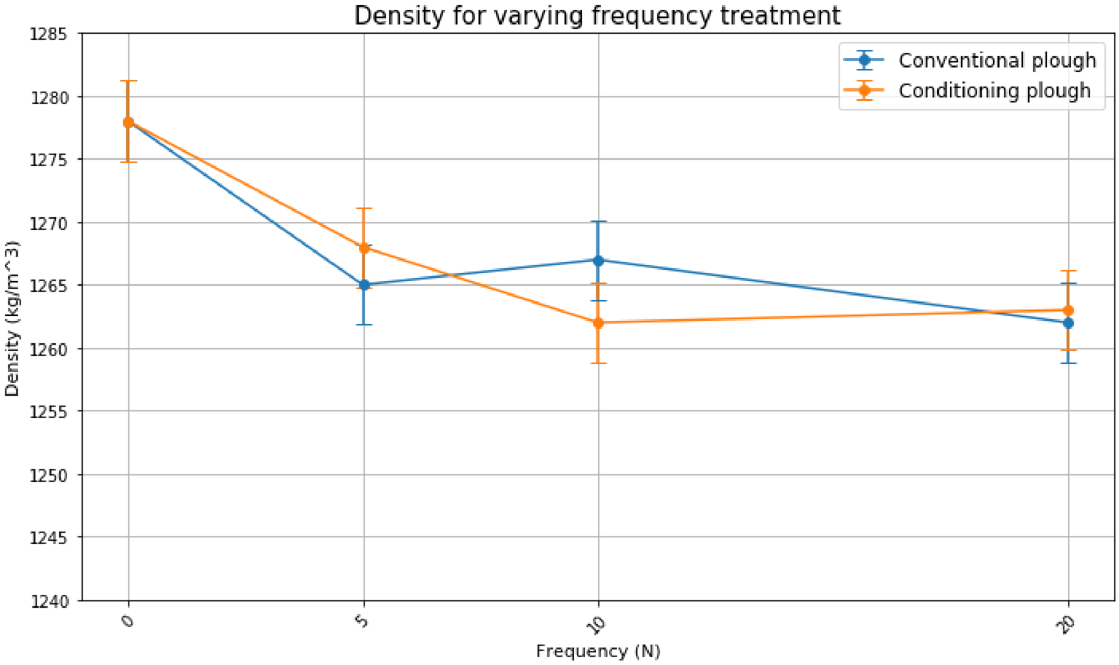


Figure 25: Density values for varying frequency treatment

3.3.2 Yield stress

The progress development of fluidic yield stress for the varying treatment conditions of frequency is shown in Figure 26. The graphs from the Rheometer where these values are read from are shown in Appendix C.2. The fluidic yield stress of the reference situation is $>$ 150 Pa and can not be seen in these results, since the Rheometer was set to perform a stress ramp-up test until 150 Pa. Due to measurements in the other experiments being about 300 Pa or higher for the untreated mud, it is assumed that this value exceeds 150 Pa widely in this experiment as well, however, the graph does not show this. A clear reduction in the static and fluidic yield strength is assumed for the initial treatment of the mud until N = 5. After this decrease, no further reduction in fluidic yield stress is detected. This is not what is expected, as has been proved in other studies mentioned in 2.1. Also, the visual observations point out otherwise. A reason for the yield stresses in this experiment to have this outcome, is the application of the syringe for retrieving mud samples. Lower parts of the mud were likely retrieved than intended.

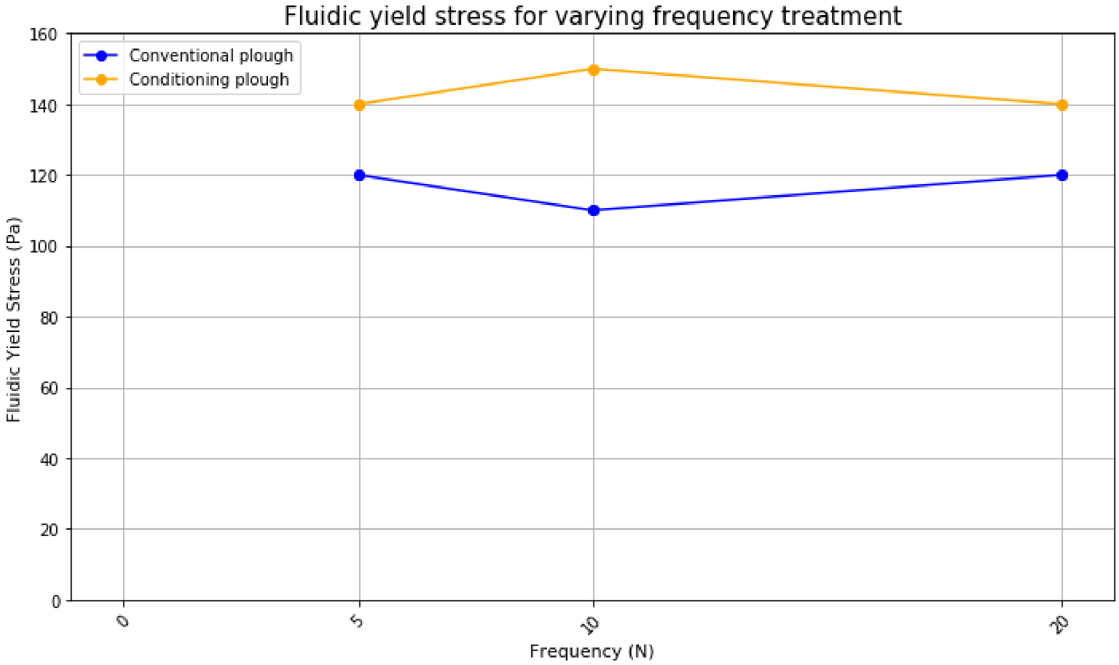


Figure 26: Fluidic yield stress for varying frequency treatment

3.3.3 Visualisations

Visualising the fluid mud layer thickness is of importance in this experiment. In Figure 27 the progress of the fluid mud layer, based on visual observations, is shown. These values were read from the dimensions of the laboratory tanks a few minutes after conditioning. Pictures of this are shown in Appendix C.2. It was clear that the fluid mud layer kept increasing for a varying treatment condition of increasing frequency N.

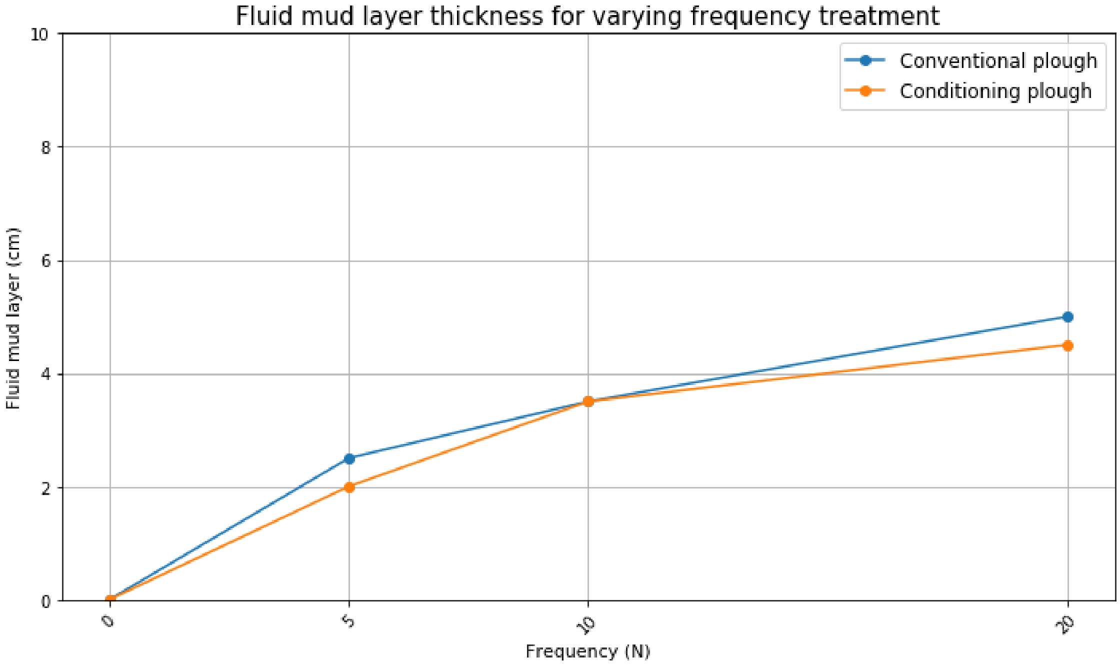


Figure 27: Fluid mud layer growth based on visual observations

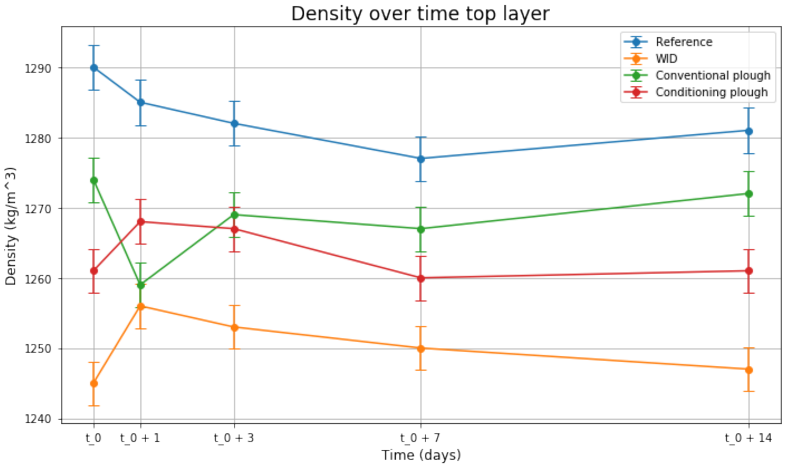
The density and yield stress of the top 1 cm mud layer are reduced for the initial treatment with a dredging frequency of N = 5. For further increasing frequency, the density and yield stress changes seem zero. The fluid mud layer kept increasing for increasing frequency from visual observations. The latter is of large importance in this experiment. Regarding the reduction of yield stress of the top layer of the mud, the conventional plough seems to have a bigger impact on conditioning than the conditioning plough. The comparative tests will investigate this further. For now, we can conclude that the hypothesis that a higher frequency in a conditioning activity results in a higher effectiveness of conditioning is correct.

3.4 Comparative tests

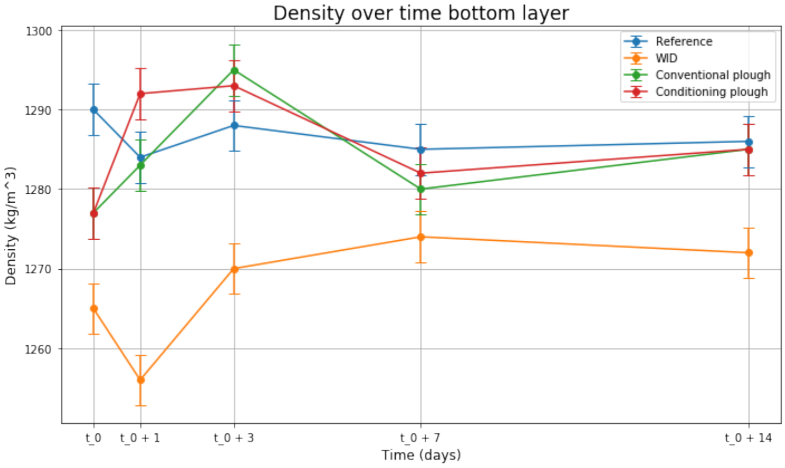
The results of the comparative tests are given in this chapter, in the order of density, yield stress, and turbidity.

3.4.1 Density

The density of the top and bottom layer was measured for each sample from the four different treatments at the given intervals. The measurements were conducted three times and the average value was applied. An overview of these weights is shown in Appendix C.3. Figure 28a was obtained, in which the error margin is set at 0.25% for the error bars in the figure. As noted before, the reference situation is valid for the three other dredging types researched in these tests. At t_0 every dredging activity was executed in its basin and immediately after, measurements were conducted.



(a) Top layer



(b) Bottom layer

Figure 28: Density over time for both top and bottom layers of the mud

From Figure 28a for the top layer, the following observations can be made:

- For the reference situation an initial decrease in density is detected. The reason for this is the refilling of the tank. Although stirring due to refilling was attempted to be minimised, it was unpreventable that it would impact the density. Especially the top layer is sensitive to this.

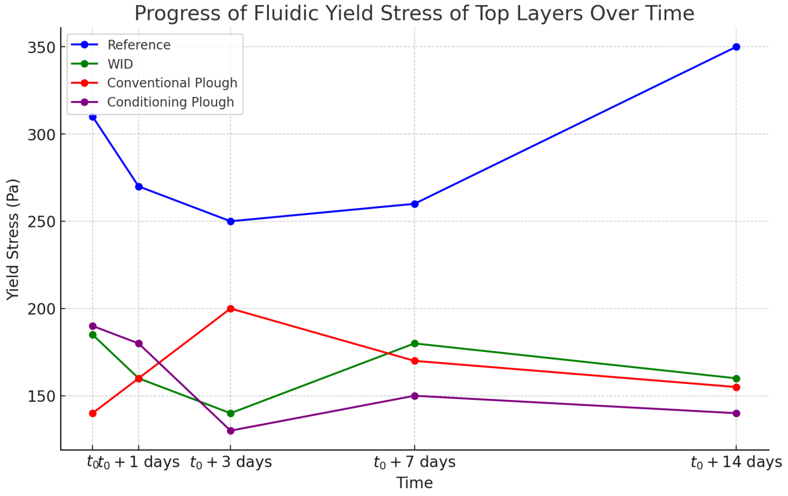
- For the top layer the WID performs best in terms of diluting the sample and creating fluid mud. At each measuring moment, the density value is the lowest. As a lot of the particles settle on the first day, an increase in density is detected at $t_0 + 1$, however it is expected that in the measuring moments after, the density further increases due to consolidation. Just like the reference situation refilling likely has had an impact on this.
- For the conventional plough, the density decreases at $t_0 + 1$. This is likely incorrect, so the density at t_0 was lower and the density at $t_0 + 1$ higher. Like the WID, the particles settle increasing density and further consolidation is hindered due to refilling the tanks. The trajectory of the conventional plough would then be similar to the trajectories of the WID and conditioning plough.
- For the conditioning plough, the trajectory can be explained in the same was as for the WID. The efficiency of conditioning in terms of density is lower than the WID, but likely higher than the conventional plough.

From Figure 28b for the bottom layer, the following observations can be made:

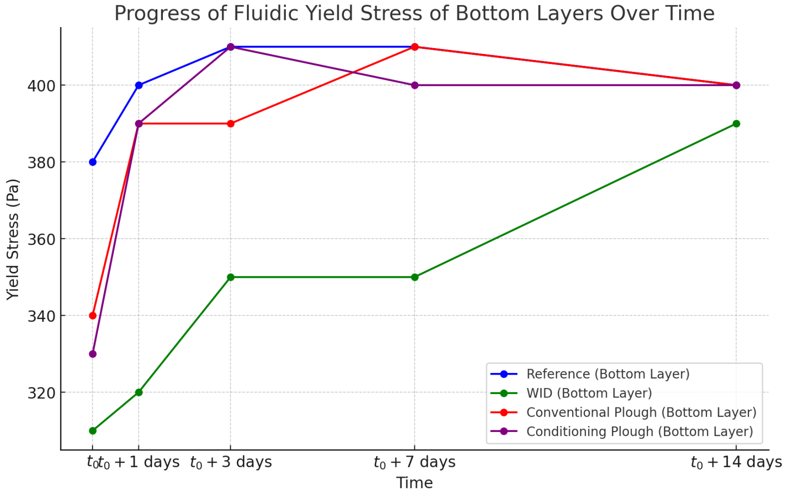
- Both bed levelling ploughs have a similarly small effect on the bottom layer of the mud. At t_0 the ploughs do cause a small decrease in density, however, at the other measuring moments this is not the case.
- The WID does influence the bottom layer of the mud. The explanation for this is the penetration of the water injection into the mud.

3.4.2 Yield stress

With the same samples used to measure the material's density, the rheological parameters were measured as well. In Figure 29a the progress of the yield stress for the top and bottom layer of the mud are given. Appendix C.3 shows the graphs developed from the data of the Rheometer, from which the values in the figure were derived.



(a) Top mud layer



(b) Bottom mud layer

Figure 29: Yield stress progress of the comparative tests

The following observations can be made regarding the results for the top mud layer in Figure 29a:

- There is an initial decrease in yield stress for the reference situation. As said in the density section this is likely due to the refilling of the tank.
- Although the conventional plough has a lower yield stress than the WID and the conditioning plough directly after ploughing, as time progresses, the opposite is apparent.

For the bottom mud layer, shown in Figure 29b, the following observations can be made regarding these findings:

- Both the conventional and the conditioning plough have a lower yield stress than the reference directly after dredging at t_0. As time progresses the trajectories for yield stress for the ploughs reach the same values as the reference situation. This means that ploughing has a minor penetrating effect in the mud.
- The WID has fluidic yield stress values that are consistently lower than the other conditioning methods. This means that water injection has the ability to penetrate deep into the mud.

3.4.3 Turbidity

An overview of the turbidity values is shown in Table 16. The water samples for measuring turbidity were constantly retrieved from 2 cm below the surface.

Day	**Reference**	**WID**	**Conventional plough**	**Conditioning plough**	Unit
t_0	18.39	281	251	197	(NTU)
$t_0 + 1$	9.93	25.64	23.10	22.45	(NTU)
$t_0 + 3$	8.42	8.66	13.64	15.78	(NTU)
$t_0 + 7$	6.67	5.88	5.50	4.94	(NTU)
$t_0 + 14$	2.0	2.46	2.70	2.90	(NTU)

Table 16: Turbidity for each dredging method on the measuring days

The most important value is the one measured shortly after dredging activity, so on t_0 and $t_0 + 1$. Since refilling of the basins caused resuspension of silt particles, the turbidity never fully decreased. Therefore the turbidity continues to decrease after $t_0 + 3$ and $t_0 + 7$ however this is due to the fact that the amount of time in between the measuring moments kept increasing as well. Furthermore, due to coagulation and flocculation in the static water of the basin, the turbidity decreases rapidly. In the field, this would be different due to flowing water. From Table 16, the following observations can be made:

- WID has the greatest effect on turbidity, as expected. The water jets suspend many fines into the water column.
- The conventional plough has a smaller effect on turbidity however, the conditioning plough has the smallest of all three. This is as expected as well since the flow of water is directed horizontally instead of vertically.
- After 24 hours, the effect of the different dredging methods seems to have flattened out and the values are similar. This is due to the fact that the basin consists of static water, as stated earlier.
- After $t_0 + 1$ the differences between the different dredging methods can be explained by the refilling of the tank.

Regarding the effectiveness of conditioning, it can be concluded that the WID is the most effective, followed by the conditioning plough and then the conventional plough. However, for the latter, the difference between the effectiveness appears to be minor. For the top layer of the mud, the conditioning plough seems to have a bigger impact on density and yield stress, however, for the bottom layer, this is roughly similar and close to zero. The WID does have the ability to penetrate deep into the mud, causing a reduction in density and strength for the bottom layer. In terms of impact on turbidity, the conditioning plough has the smallest impact, followed by the conventional plough and then the WID. The hypothesis that stated that the bed leveller can successfully condition pre-consolidated mud and the conditioning plough minimises impact on turbidity, however, the conditioning effectiveness of the WID is higher, appears to be true.

3.5 Field tests

An overview of this experiment is shown in Table 17. The WID had a longer dredging activity then the bed leveller but the area that was dredged was larger as well.

Details of test		
Vessel type	WID	Bed leveller
Vessel	AquaDelta	Husky
Date of test	7-2-2024	26-3-2024
Start of dredging	10:50	11:06
End of dredging	11:50	11:53
Time dredging activity	60 min	47 min
Total area dredged	4550 m^2	1400 m^2

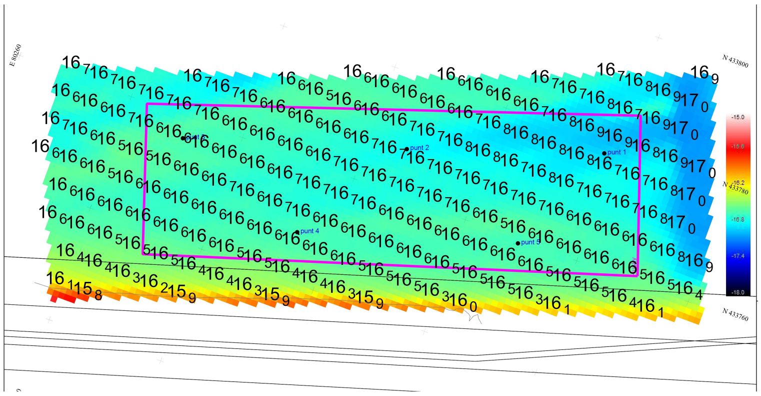
Table 17: Overview of the field tests

3.5.1 Depth

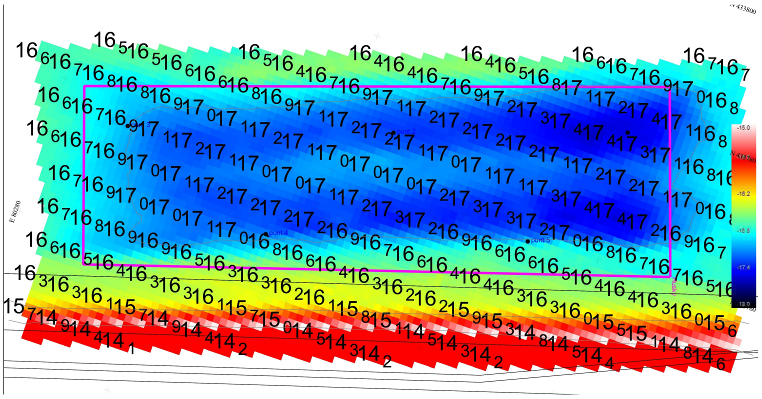
Using multibeam analysis, the depth of the testing areas is mapped before and a week after dredging activities. The multibeam shows the water-mud interface.

Bed leveller

In Figure 30a the initial bed profile of the testing area for the bed leveller is given. It shows a fairly even bed, with the lutocline layer depth being around 16.7 m. Figure 30b shows the bed of the testing area a week after the dredging activities. There are some oddities throughout the area, like in the middle. If a proper layer of fluid mud was produced, these oddities would not be present. This is because the Husky did not condition the whole area properly, which is likely due to the high frequency of the conditioning activity. If the conditioning actions are not executed accurately, parts of the area are not conditioned properly. There can be noticed that the depth increased in depth with roughly 0.4 m on average. The bed leveller thus deepens the area effectively, which is expected.



(a) Prior to conditioning

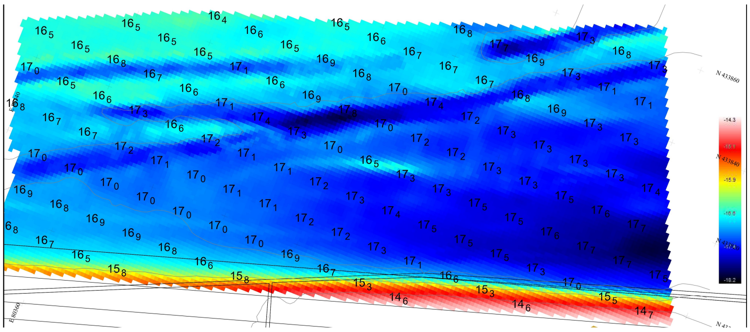


(b) Week after conditioning

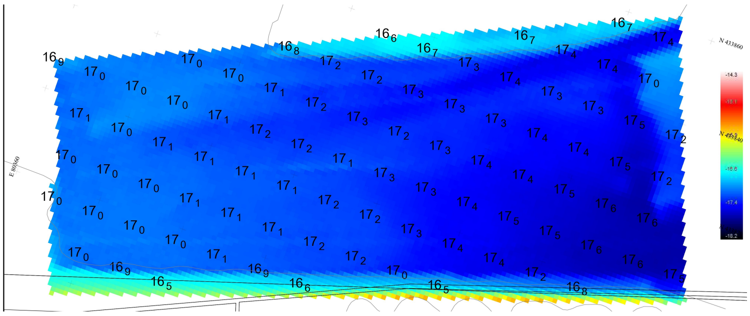
Figure 30: Bed leveller testing area depth analysis

WID

Figures 31a and 31b show the bed level of the AquaDelta's testing area prior to and a week after conditioning. In these figures can be seen that the WID smoothened the bed. The shallower parts of the testing area before dredging are removed and spread out. The depth increased for these shallow parts, however, the deeper parts of the testing area prior to dredging became a little more shallow. Throughout the whole area, the WID performed accurate conditioning. Besides the shallow parts, the WID did not deepen the area further.



(a) Prior to conditioning



(b) Week after conditioning

Figure 31: WID testing area depth analysis

These multibeam analyses point out that the accuracy of conditioning of the WID is higher than the bed leveller. This is dependent on the frequency of the conditioning activity. However, the bed leveller does increase the depth of the water-mud interface, whereas the WID does not.

3.5.2 Density and yield stress

The density and yield stress, measured with the Rheotune, give information about the ratio of water to solids and the strength of the mud. Combined, these can indicate the thickness of the fluid mud layer.

Bed leveller

In Appendix D.1, the density profiles and yield stress profiles prior to and directly after conditioning activities are given for each of the five measuring points. Table 18 shows the production of fluid mud at each measuring point, expressed in thickness of the layer. It is determined by subtracting the final fluid mud layer thickness by the initial fluid mud layer thickness (h_{fm}). Using Equation 2 the average layer of fluid mud produced ($\Delta h_{fm,av}$) can be determined. There should be noted that for simplicity, an even distribution of fluid mud throughout the area was assumed for the average value of fluid mud layer thickness layer thickness. This average value thus represents the produced fluid mud layer thickness throughout the whole testing area.

Measuring point	**Initial** h_{fm}	**Final** h_{fm}	Δh_{fm}
1	0.3 m	0.6 m	0.3 m
2	0.5 m	0.6 m	0.1 m
3	0.3 m	0.6 m	0.3 m
4	0.2 m	0.2 m	0 m
5	0.1 m	0.3 m	0.2 m
$\Delta h_{fm,av}$			0.2 m

Table 18: Production of fluid mud after bed leveller activities

WID test

In Appendix D.2, the density and yield stress profiles prior to and directly after dredging activities are given for each of the nine measuring points in the testing area of the WID. Table 19 shows the production of fluid mud layer at each measuring point, expressed in thickness of the layer. These values and the average fluid mud layer thickness is determined in the same way as in Table 18.

Measuring point	**Initial** h_{fm}	**Final** h_{fm}	Δh_{fm}
1	0.5 m	1.3 m	0.8 m
2	0.5 m	1.3 m	0.8 m
3	0.4 m	0.7 m	0.3 m
4	0.4 m	1.4 m	1.0 m
5	0.4 m	1.3 m	0.9 m
6	0.4 m	1.0 m	0.6 m
7	0.4 m	1.3 m	0.9 m
8	0.3 m	1.5	1.2 m
9	0.2	1.4	1.2 m
$\Delta h_{fm,av}$			0.85 m

Table 19: Production of fluid mud after WID activities

3.5.3 Turbidity

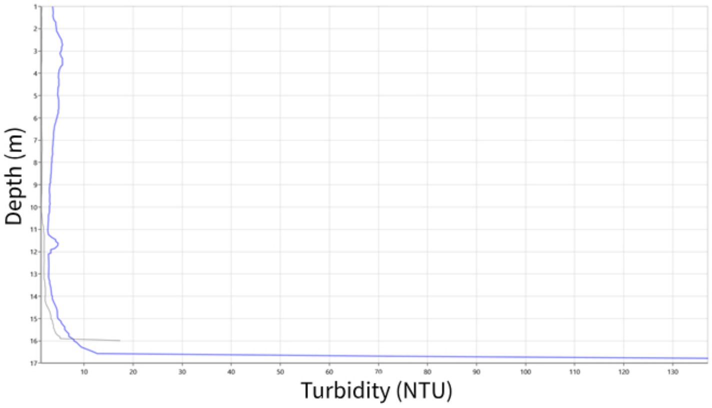
Using the Swift probe, the acoustical characteristics were measured, including the turbidity profile throughout the water column. The same measuring points were used as the ones used for the Rheotune, as shown in Figures 22a and 22b. In Appendix D.2 and D.1 the turbidity profiles are given for both field tests. In each figure, the grey line represents the initial turbidity profile and the blue line the profile directly after conditioning.

Bed leveller test

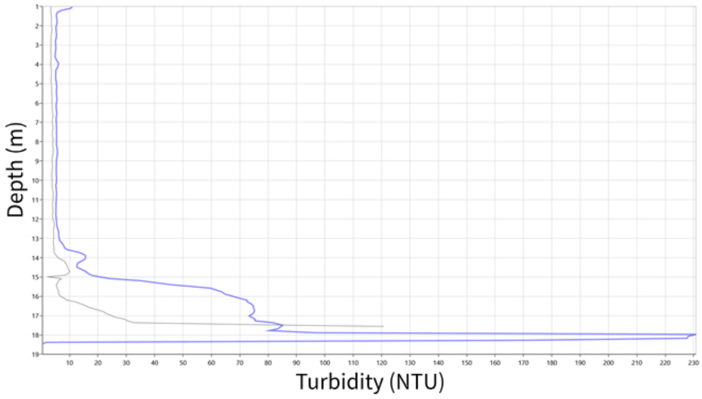
The profiles for turbidity of the bed leveller test are all quite similar. There is a minor change in turbidity as a result of conditioning activities, as expected. As an example, in Figure 32a the turbidity profile at measuring point 4 is given. The trajectory of the profile minorly changes due to the activities of the bed leveller. Near-bed there is a minor increase.

WID test

As can be seen in the figures of the turbidity profiles for the WID test in Appendix D.2, post-conditioning profiles differ per location. One thing all profiles do have in common is that the turbidity starts increasing from a depth of 14-15 m for the measurements conducted directly after dredging activities. As an example, Figure 32b shows the turbidity profile of measuring point 3. A large increase can be detected in a layer of 3-4 m near the bed.



(a) Bed leveller (Measuring point 4)



(b) WID (Measuring point 3)

Figure 32: Turbidity (prior to dredging: grey, directly after: blue)

3.5.4 Efficiency analysis

The produced layer of fluid mud at each measuring point was given in Tables 18 and 19. The average layer of fluid mud produced by the bed leveller is $\Delta h_{fm} = 0.2\ m$ and by the WID $\Delta h_{fm} = 0.85\ m$. With these values, the production rate can be determined by filling Equation 3. This results in a production rate of 358 m^3/h for the bed leveller and 3783 m^3/h for the WID, which is about a factor 10 higher for the WID.

Contracting costs

The contracting costs of the Husky and the AquaDelta are expressed in a fictional currency, called DredgeCoin (DC). The hourly rate of the Husky is set at 1904 DC/h and the AquaDelta has a rate of 6460 DC/h. To accurately compare the costs of the Husky and the AquaDelta, the costs per m^3 of effectively conditioned pre-consolidated mud should be determined. With the known production rate and hourly rates, equation 4 can be filled in and the Husky's costs become 5.32 DC/m^3 and the AquaDelta's costs become 1.71 DC/m^3. This means that currently, the AquaDelta is cheaper for the deployment of conditioning.

Fuel consumption

The fuel consumption of the Husky the dredging activity was 20 L. This means that the Husky has an hourly consumption rate of 24 L/h. The AquaDelta consumed 170 L, which means that the hourly consumption rate of this vessel is 170 L/h. If these values are incorporated into the production rate, the fuel consumption per m^3 of fluid mud can be calculated. For the Husky this results in a fuel consumption of 0.067 L/m^3 and for the AquaDelta in 0.045 L/m^3, so the fuel consumption of the WID is lower.

Table 20 shows an overview of the WID and bed leveller tests regarding their efficiency, based on production rate, costs and fuel consumption.

Production rate		
Vessel type	Bed leveller	WID
Vessel	Husky	AquaDelta
Time dredging activity t	47 min	60 min
Total area dredged (A_t)	1400 m^2	4550 m^2
Average layer produced fluid mud ($\Delta h_{fm,av}$)	0.2 m	0.85 m
Total volume of produced fluid mud (V_{fm})	280 m^3	3783 m^3
Production rate	358 m^3/h	3783 m^3/h
Costs	5.31 DC/m^3	1.71 DC/m^3
Fuel consumption	0.067 L/m^3	0.045 L/m^3

Table 20: Production rate of fluid mud for both conditioning methods

The hypothesis of this experiment stated that the bed leveller can effectively condition mud while having a smaller impact on turbidity than the WID, however, the WID is more effective. The efficiency analysis in Table 20 shows that this is true, as the WID has a production rate that is a factor 8 higher than the bed leveller. The impact on turbidity by the WID, however, is higher as well.

4 Discussion

4.1 The design phase

The design of the plough was dependent on certain assumptions. Since there was a limited time for this phase, some of the details could not be worked out and for these details, assumptions were made. If more time and effort could be invested into the design phase, the design could have been different. To include this in the decision for choosing the design's components, one of the MCA criteria was 'feasibility'. The traditional plough was chosen from the MCA as the component which would be included for breaking down the consolidated mud. If the criterion 'feasibility' was not included in the MCA, however, the rotary plough would have come out as the best possible option. This also complies with the literature on ploughing in agriculture.

Also, the cutters shown in Figure 34a were initially designed for breaking down the consolidated mud. Their shape was based on the shape of the cutting mechanism of the traditional/harrowing plough. However, the parabolic curve in the cutter's shape was not 3D-printable, so the design needed to be edited. This could have had an impact on the results of the comparative tests.

The funnel-like shape of the conditioning plough was designed with the upper and lower caps having a 20°angle to the horizontal bed. This can be seen in the technical drawings in Appendix B. The value is based on the assumption that the acceleration of the seawater through the funnel needs to be high to create energy by having a large angle, but on which the larger clods could still slide up and through the funnel.

The three vertical reinforcement components inside the funnel-shaped plough were added after consultation with the 3D printing manufacturer Xometry. Since the 2 mm thick plates were made from Nylon PA12, these could be quite flexible and the structure could fail when dragged through water and mud. Therefore, vertical reinforcements were added, however, these do have an impact on the flowing lines of the water and mud. Furthermore, the additional weights added to the ploughs also have an impact on the design. These also disturb the flowing trajectories of water and mud for both ploughs. Also, the ploughs' centre of gravity was disturbed due to the additional weights taped to the plough prototypes. Although there should be noted that this was prevented as much as possible when equipping the ploughs with extra weights.

4.2 Surveying equipment

For both the laboratory and the field tests, surveying equipment was used. The different pieces of measuring equipment used in this research were elaborated in Section 2.3.1. One should assume that for conducted measurements, errors can never be eliminated. However, it is safe to assume that the results obtained in the tests are reliable. However, looking at the executed tests, some difficulties were faced with some of these equipment pieces. Since the Portable Density Meter DM35 was not applicable for the pre-consolidated mud, a small container from the lab was used to determine the density of each mud layer, as explained in Chapter 2.3. The error margin becomes larger for determining density with this method. For measuring density in the lab tests phase, for example, an error of 0.2-0.3% was taken into account. This could mean that densities have an error of $\Delta\rho = 4\ kg/m^3$, which could have an impact on the graphs in Figure 28.

4.3 Laboratory tests phase

A main topic of discussion for each experiment conducted in the laboratory tests phase, is the amount of replicates, which was 1. This leaves room for marginal errors in the results.

The Botlek's conditions were mimicked in the laboratory by using mud and water from it. Of course, this is merely an imitation of the real-life situation. The static state of the water in the tanks is not representative of the actual conditions in the Botlek. Tides, wind and vessels all influence the flow of the water in the area, transporting fines in and out. Also, the amount of organic matter, influencing the mud cycle of mud particles that was shown in figure 2, present in a certain area changes constantly. The PSDs also could have contributed to the conclusions of the research, as floc size influences the mud cycle as well. One can still assume that findings in the laboratory may be assumed representative to a certain degree and could invite further research to be conducted in the Botlek itself.

Executing the tests in the lab was difficult in several aspects. Preventing any unintentional influence on conditions in the testing tanks was a tough task. When refilling the tanks with water at the comparative tests after taking samples of the mud, it was unavoidable that little dilution of the mud and water occurred. As could be seen in Figure 28 and Table 16 the mud was minorly affected every time the tank was refilled. This can also be concluded from visual observations. Refilling the tank with water stirred the top layer of the mud, increasing the turbidity of the water.

Furthermore, determining the fluid mud layer was hard as well. Since no probe was available in the lab to measure the densities and yield stresses throughout the water columns, it was hard to determine the thickness of the fluid mud layer. It could roughly be done based on visual observations. Also, the size of the tanks and the volumes of the Botlek's mud and water in the tanks were small, making this task difficult.

The turbidity measurements were quite straightforward, however since samples were taken by hand, the consistency of the depth of the measurement was not perfectly accurate at all times.

The dredging activities of the laboratory tests were all executed by hand. Again, consistency was tried to remain as high as possible regarding handling the dredging prototypes, however, this can not be assured. The dredging velocity for example was set at 0.12-0.15 m/s for both the conventional and the conditioning plough. It was difficult to preserve the consistency of this speed. Furthermore, the ploughs needed to be picked up and turned around each time the end of the tank was reached. It is likely that this also had an impact on the results.

The use of the WID prototype was not comparable to a real WID either, as was explained in Section 3.3. Overall the conclusion is that the conditions and equipment present at the laboratory are simplified and it is difficult to mimic certain dredging activities. Still, almost all results are as expected or seem logical. This tells that the performed tests went well and can be considered representative.

4.4 Field tests phase

Again, a main topic of discussion for each experiment conducted in the field tests phase, is the amount of replicates, which was 1. This leaves room for marginal errors in the results of the field tests phase as well.

Some odd results were obtained with the Rheotune for the density and yield stress profiles. As can be seen from figures in the Appendix D.1, the density increases at a certain depth, but at a further depth, the density decreases again. This is unlikely since density and yield stress increase for an increasing depth, as was explained in Section 1.1. Other studies show that the density decreases for increasing depth at the start of the water-mud interface as well (IMDC, 2009). It is a consistent problem faced with the Rheotune, which has to do with the calibration of the device (Poerbandano et al., 2022). The important part of the profiles obtained from the Rheotune, however, is where the limits of 1200 kg/m^3 and 100 Pa are exceeded and these values are still visible in the profiles.

Furthermore, for simplicity was assumed that the average value of the layers of produced fluid mud thickness represented the produced fluid mud layer thickness throughout the whole area, which is not correct.

For the deployment of the bed leveller in the field, it is difficult to compare it to the WID regarding conditioning, as the WID has an advantage. Since the vessel is specifically designed for fluidisation, the knowledge for applying the vessel is far more improved than the bed leveller.

5 Conclusions

Research question 1*: How can the conventional plough design be improved to minimise impact on the environment, while maintaining effective conditioning efficiency for port maintenance with the bed leveller?*

From findings in literature on ploughing in agricultural engineering, a technique called puddling was found that provides examples of the application of different ploughing equipment for conditioning soil, submerged in water. Systematical research that has been conducted in this field, suggests that a new ploughing techniques could contribute to an improvement in conditioning.

Exploring different puddling techniques, and comparing these through an MCA, gave the components for a new plough design which could effectively condition mud, while keeping the suspension of sediment particles higher in the water column at a minimum.

Designing, manufacturing and testing a new plough, specifically created for conditioning, in a laboratory, yields some intriguing results. In comparison to equal tests with a conventional plough used for bed levelling purposes, the conditioning plough effectively reduces the mud's strength. On the short term, the conditioning plough reduces the yield stress and density of the top layer of mud less than the conventional plough, however, on the long term, this is the opposite. Therefore the conditioning plough more effectively produced a fluid mud layer with its dredging activities and it can be concluded that effective conditioning efficiency was maintained. The new breaking and suspension mechanisms ensured improvement in creating fluid mud with a plough.

It was also found that the conditioning plough has less negative impact on the turbidity in the water column. This can be concluded from the results of turbidity measurements in the upper part of the basins at the comparative tests in the laboratory. Ensuring flow of water and particles in horizontal direction instead of vertical, contributed to this.

Research question 2*: In what way can a bed leveller effectively achieve comparable results to a WID regarding conditioning of pre-consolidated mud?*

The pre-tests at the laboratory indicate that solely shearing mud does not reduce the density and yield stress considerably. The dilution test, however, recreates similar results as a WID has. Dilution by adding water and stirring the mud can create fluid mud layers.

In case of applying the bed leveller, this means that the water above the muddy bed should be mixed as much as possible. In this manner, the process of stirring and mixing is initiated, and comparable results of the WID can be achieved by the bed leveller.

The comparative tests results suggest that both the conventional and the conditioning plough have the ability to reduce density and strength of the top layer of the mud, however, water injection is more effective. This can partly be concluded from the values for density for the top layer of the bed. The mud conditioned by the WID method, consistently has a lower density than the bed levellers over time, with a difference of about 15 kg/m^3 on average. The fluidic yield stress of the top layer of the mud indicates that the WID and the ploughs have a similar impact conditioning the mud, having values varying between 130 Pa and 200 Pa. The WID also has the capability to penetrate deep into the bed and modify the mud, which is a quality the ploughs do not possess. So although the bed leveller can condition top layers of mud accurately, it means that the WID has a better ability to condition large quantities of mud.

This is confirmed by the findings in the field tests. Results from these tests indicate that an average fluid mud layer of 0.2 m is created by the bed leveller and 0.85 m by the WID over a period of 45-60 min. This results in production rates of the bed leveller being 358 m^3/h and WID 3783 m^3/h. So although the production rate is about 10 times lower than the WID, the bed leveller can attain comparable results. The eddies created in and around the structure of the moving plough provide mixing while the plough itself provides the stirring. If this action is carried out often, comparable results to the WID can be reached. In the field tests, this meant that the bed leveller dredged the mud a total amount of 10 times and the WID 3 times to create the previously mentioned fluid mud layer thicknesses. It is therefore safe to conclude that the time required for conditioning with the bed leveller is higher than with the WID, before comparable results are achieved.

In terms of fuel consumption, the WID is more economical than the bed leveller, consuming 0.045 L/m^3 and 0.067 L/m^3 of produced fluid mud, respectively. Furthermore, from a financial perspective, the bed leveller is expensive to deploy for conditioning in comparison to the WID. The cost per volume of fluid mud produced is 5.31 DC/m^3 for the bed leveller and 1.71 DC/m^3 for the WID.

In general, the bed leveller could effectively achieve comparable results to the WID and it has some considerable advantages. It has a relatively small impact on the turbidity, it is a small, manoeuvrable vessel and therefore accurate. The Port of Rotterdam's accessibility to a bed leveller is larger than a WID, so it is attractive for the company to implement the bed leveller for conditioning purposes. However, consideration should be given to the higher frequency and time consumption of such a conditioning activity.

Research question 3*: Does the frequency in a dredging activity with the bed leveller at a certain area influence the effectiveness of conditioning for pre-consolidated mud?*

The frequency tests executed in the laboratory confirm that increasing frequency in a conditioning activity leads to increasing volumes of fluid mud. The density and yield stress values of the top layer of the mud do not decrease majorly with increasing frequency. However, the visual observations indicate a thicker layer of fluid mud for increasing frequency. The actions of either plough, caused a dark fluid mud layer to keep thickening. It can be reasonably concluded that an increase in frequency leads to enhanced efficiency in the conditioning of pre-consolidated mud. However, the extent of this influence appears to stagnate, looking at the flattening values for fluid mud layer thickness.

Research question 4*: How does the bed leveller perform compared to the WID in terms of the environmental impact regarding conditioning dredging?*

The results of both the comparative tests at the laboratory and the field tests, point out that the bed leveller has a less negative environmental impact in terms of turbidity in comparison with the WID. In the comparative tests, the turbidity by activities of the bed leveller is 10-30% lower than the WID. The conditioning plough even has a smaller impact than the conventional plough, with a difference of over 20%.

In a small closed basin with hydrostatic conditions, such as the tanks used in the laboratory tests, the effect of this is the largest. At a height of 2 cm below the surface of a 10 cm high water column, the difference in turbidity is still significant between the WID and the ploughs.

In the field, the difference in turbidity is mainly noticeable near-bed, in the lowest few meters of the water column. Here the turbidity at 1-2 m above the bed increases with a factor 15-20 as a result of WID activities. For the bed leveller this factor is just 1.5-2.

6 Recommendations

To further investigate the implementation of the bed leveller for conditioning pre-consolidated mud, research on the design of a new conditioning plough can be conducted. To start, the conditioning plough designed in this research can be manufactured and tested on a larger scale. Using the proper equipment such as a Rheotune in a lab on such a larger scale, will give better insights into the ability of the conditioning plough to produce fluid mud. The results from this research do not imply that the conditioning plough has much more potential than the conventional plough, however, the equipment used to perform the tests and conduct measurements obstructed a proper insight. The working principle did come out as expected and based on the literature, still can be concluded that this design could have a better ability to condition pre-consolidated mud. The design of the conditioning plough can be improved by investigating the ability of the teeth to cut the mud and the angle of the funnel shape. The latter can be executed by using 3D modelling software like Delft3D. The design of the teeth can be enhanced by researching different types of cutting mechanisms and their ability to cut through pre-consolidated mud.

Furthermore, the several explored possibilities for potential components for such a design in this study can be developed. The following suggestions for a new design can be investigated further:

- A rotary plough should be manufactured and tested. From the literature on ploughing in agriculture, and puddling in particular, was found that a rotary plough is widely implemented for cultivating rice fields submerged in water. In this field, research has been performed systematically for decades. Implementing an existing plough could be an initial step in investigating the deployment of a rotational plough for conditioning purposes.
- Another system that should be considered in follow-up research is the combination of a bed leveller and WID. Designing a plough with a water injection system or solely installing a water injection system to an existing plough could be options for this. The plough is suitable for cutting through preconsolidated mud, functioning as the breaking component and the water injection system mixes the mud, effectively producing a fluid mud layer.

To further research if the bed leveller can effectively achieve comparable results to a water injection dredger regarding conditioning of pre-consolidated mud, some follow-up tests should be executed. Varying the frequency of conditioning activities with the bed leveller in the field, would contribute to a more fundamental support of the findings in the laboratory. Using the Rheotune, the influence of this frequency can be properly determined. The WID frequencies can be varied as well, to further study this influence.

Furthermore, experiments should be conducted, investigating the manner of conditioning with the bed leveller. In this study, an assumption was made for lowering the plough after each time dredging the testing area. Varying this value can contribute to the working method of conditioning with the bed leveller.

Measurements conducted over a longer period for these field tests can contribute to knowledge on the effectivity of the bed leveller, compared to the WID. If these measurements are conducted for the field tests in the manner that was done for the comparative laboratory tests, for example, more knowledge can be obtained about the recovery of the mud.

This is something that can be tested in the laboratory as well. Two factors that were not included in this research are structural recovery and flocculation. Both play a role in the concept of creating fluid mud, settling and consolidation. The size of flocs inside a fluid mud layer causes the amount of settling over time (Dronkers, 2024a), which can be analysed by conducting measurements for PSD for example. The smaller the flocs are, the less settling will take place and the longer a fluid mud layer will remain. Flocculation is the process of flocs binding on to other flocs. Structural recovery is a factor which is strongly associated with flocculation (Shakeel et al., 2020a). The structural recovery gives insight into the amount of time it takes for a fluid mud layer to settle and consolidate. These parameters should be taken into account to further study the effectiveness of the bed leveller in comparison with the WID.

To further investigate the performance of the bed leveller compared to the WID in terms of environmental impact, the oxygen distribution through the water column should be taken into account besides the turbidity. This value has an impact on the aquatic environment and dredging activities disturb this distribution (Zhang et al., 2010). The change in pH values of the water column could also be included for determining environmental impact Zhang et al. (2010).

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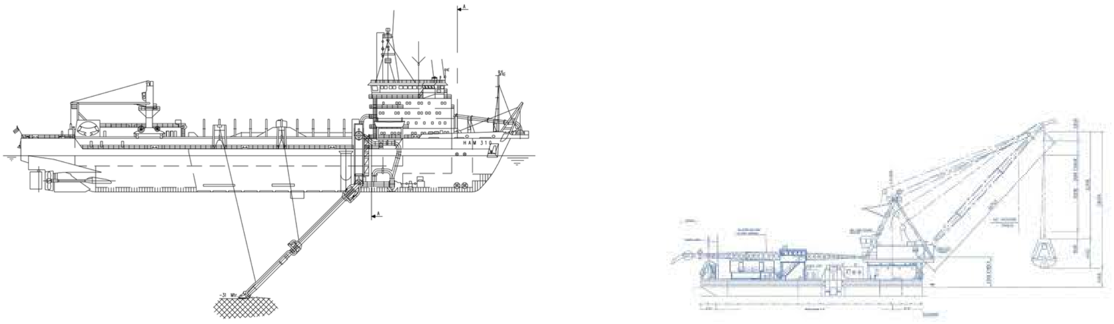
Appendix

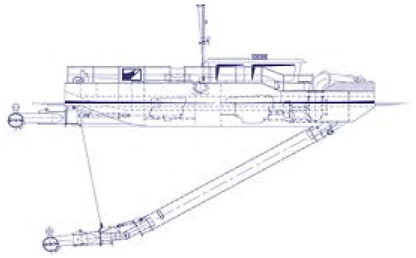
A Additional info

A.1 Maintenance dredging vessels in the Port of Rotterdam



(a) Trailing Suction Hopper Dredger (Bai et al., 2021)

(b) Grab dredger (Van Loon, nd)



(c) WID (Van Loon, nd)

Figure 33: Different types of dredgers

A.2 Mud properties

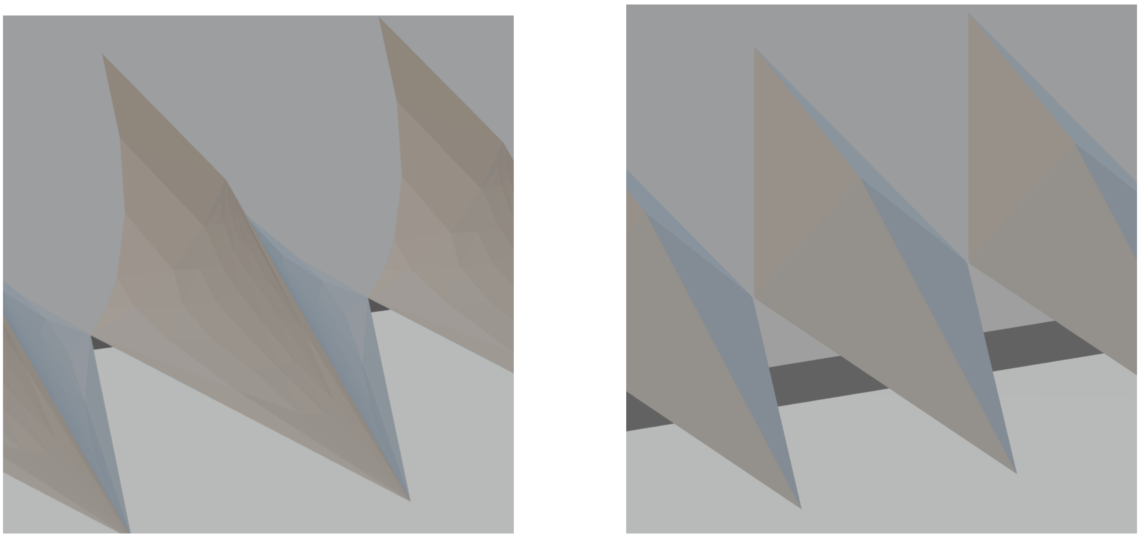
The behaviour of fluid mud

As mentioned, fluid mud layers naturally exist in estuarine environments. Fluid mud is composed mainly of water and clay- and silt-sized particles. The solid content is dominated by clay minerals with a smaller proportion of silt size minerals such as micas (see Coastal and marine sediments). The mineral composition is location dependent. Cohesiveness is due to electrochemical interparticle bonds and EPS, extracellular polymeric substances exuded by organisms. The fraction of organic matter in marine mud is generally very small, especially in comparison with fresh water environments. The water fraction is very high, more than 90% up to 99.5%. At densities above $1150 - 1200 kg/m3$ (gelling point) the fluidity disappears. (Dronkers, 2024b), however, this varies per location. In nature, fluid mud is created by erosion of pre-consolidated mud deposits due to wave forces combined with currents, in combination with the convergence of fine sediment transport. These fines flocculate due to organic matter present in the water column. This is a complicated process involving chemistry and hydrodynamics, where organic matter forms bridges between fine particles. Briefly explained, the particles carry a certain surface charge, attracting the organic matter to stabilize this charge (Burban et al., 1989), (Deng et al., 2022). When the flocs grow in size, the velocity of settling increases too, causing suspended fines to sink to the bed. Flocculation will not be treated further in this result, but to understand the settling-consolidation mechanism, it is important to address this theory. A fluid mud layer can be formed under quiet hydrodynamic conditions when a high concentration of flocs is created near the sea bed. This high concentration contributes to hindered settling, an obstruction in the settling process due to the presence of many particles. Therefore the flocs float above the bed, creating the fluid mud layer (Gregory, 1992). Another contribution to the fluid mud layer is the stirring of unconsolidated mud deposits. However, if the mud is too consolidated, it tends to erode or suspend rather than fluidise. Eventually, in periods of low intensity, flocs do settle, form the new top layer of the bed and consolidate (Toorman and Berlamont, 2023). Water injection dredging is particularly effective for creating fluid mud since the technique aims to fluidise the partially consolidated mud and keep fluid mud layers in suspension by adding extra water to the mixture. The energy of the injected water causes interfloccular bonds to break again and a lot of particles to be resuspended higher into the water column again. As stated before water injection dredging can be used for reallocation purposes and conditioning purposes. So long as the fluid mud layer layer is subjected to forces by currents, gravity or waves, it will be on the move.

Consolidation of mud

Below the fluid mud layer, the pre-consolidated and consolidated layers of mud are reached in the port's bed as visualised in 1. Consolidation is the process of sediment bodies getting denser and therefore stronger. Another word for consolidation is compaction, meaning the volume of the sediment entity decreases. The saturated voids in the mud are constantly under pressure by the body of mixtures above it. The consolidation process is essentially a vertical process with downward movement of sediments and upward movement of expelled pore water, just like settling (**?**). For these reasons the degree of consolidation increases when decreasing in the water and bed columns. Shakeel et al. consider pre-consolidated and consolidated mud in several of their studies (Shakeel et al., 2020c), (Shakeel et al., 2020b).

B Technical drawings of the designs



(a) Initial design

(b) Final design

Figure 34: Design of the cutting teeth

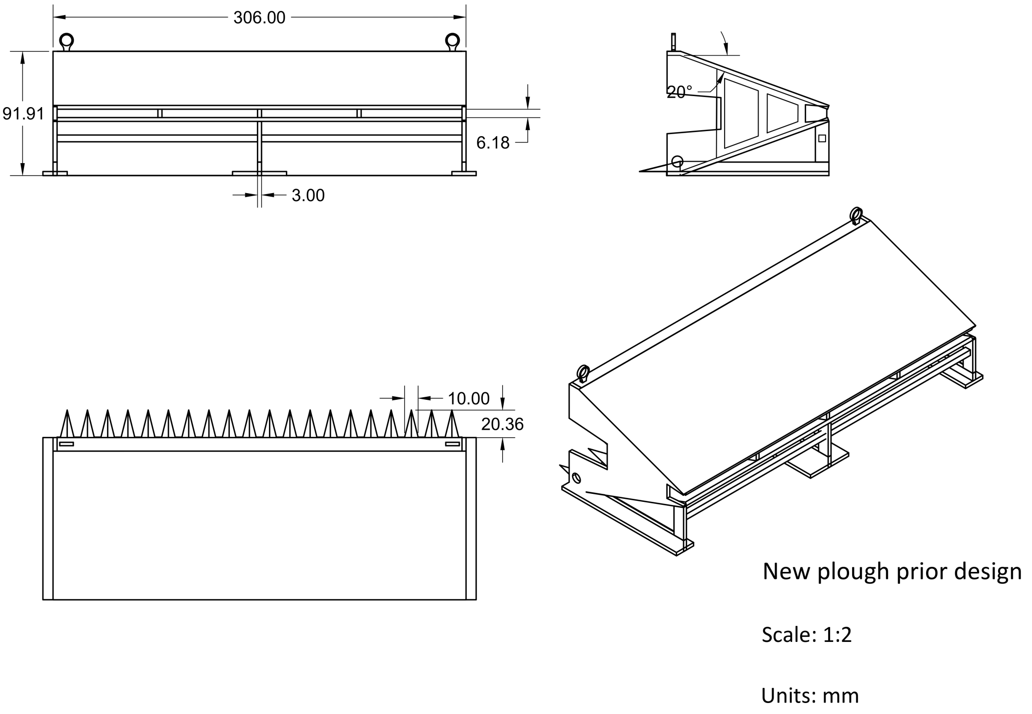
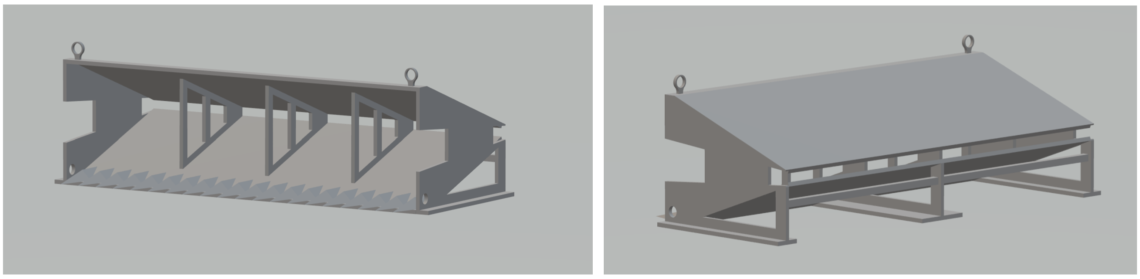


Figure 35: Technical drawing of the initial conditioning plough design

Name prototype	**Initial design new plough**
Process	3D Printing SLS - Selective Laser Sintering
Material	Nylon PA12 Gray / White (SLS)
Density material	1010 kg/m^3
Thickness plates	3 mm

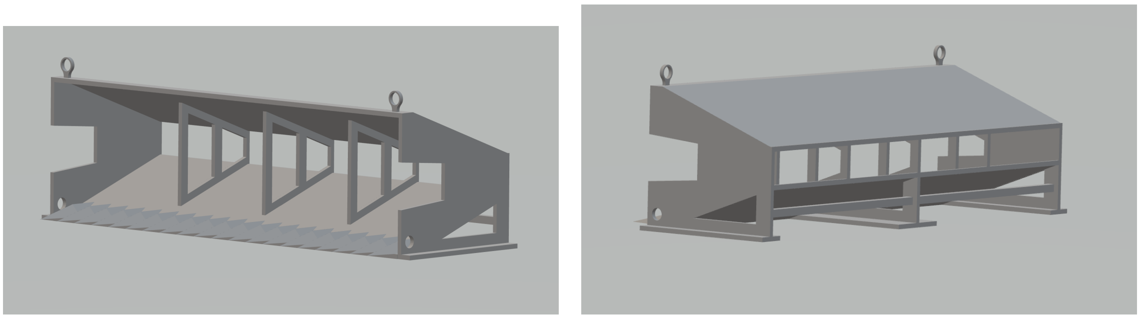
Table 21: Details of initial prototype conditioning plough



(a) Front side (b) Back side

Figure 36: Initial design new plough specifically for conditioning

For testing this initial prototype to check its working principle, similar actions were performed as in Figure 12. The plough seemed to cut through the mud as expected. As can be seen in Figure 35, the gap at the backside of the plough is 6 mm from the prior design. In these initial tests was observed that the mud did not always pass through the gap due to large clods of the pre-consolidated mud. As a result, the plough clogged up.
Furthermore, the initial plough did just nearly have enough space in the tanks, so it was chosen to scale the design a factor $\frac{2}{3}$ of the initial design.



(a) Front side (b) Back side

Figure 37: Final design conditioning plough

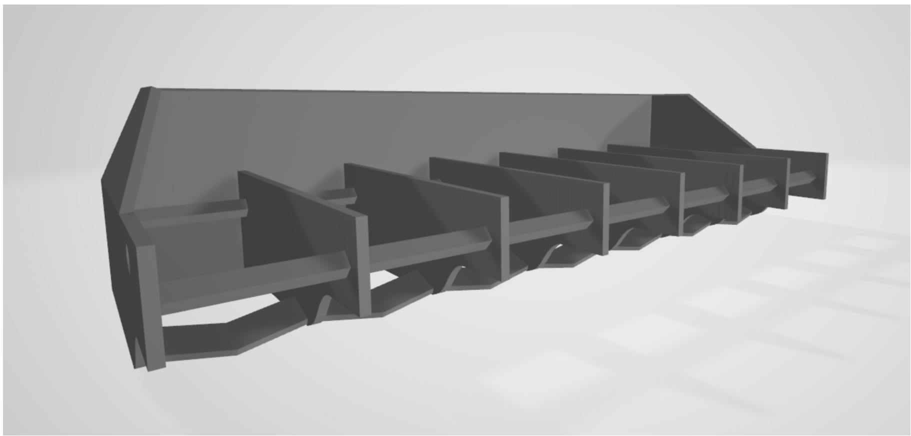


Figure 38: 3D view of the conventional plough prototype model

Name prototype	Initial design new plough
Process	3D Printing SLS - Selective Laser Sintering
Material	Nylon PA12 Gray / White (SLS)
Density material	1010 kg/m^3
Thickness plates	2 mm

Table 22: Details of final prototypes of both ploughs

B.1 Prototypes

A picture of the two 3D printed prototypes is shown in Figure 39. Since both designs have a different volume of 3D printed material, the weight of the prototypes were different. These needed to be equal to find accurate results for comparison of the two. In Table 14, the specifications of the final design of the new prototype are given. The material density value ρ_m of the plough is close to the water density value ρ_w and well below the mud density ρ_{mud} value. For these reasons the ploughs needed additional weights.
In Figure 39 a picture is shown of the final 3D printed prototypes. The specifications and weights of these are found in 14 and 23, respectively.

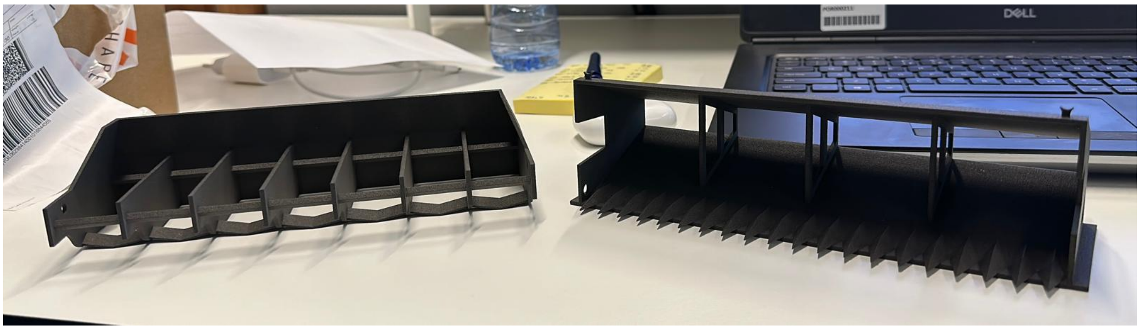
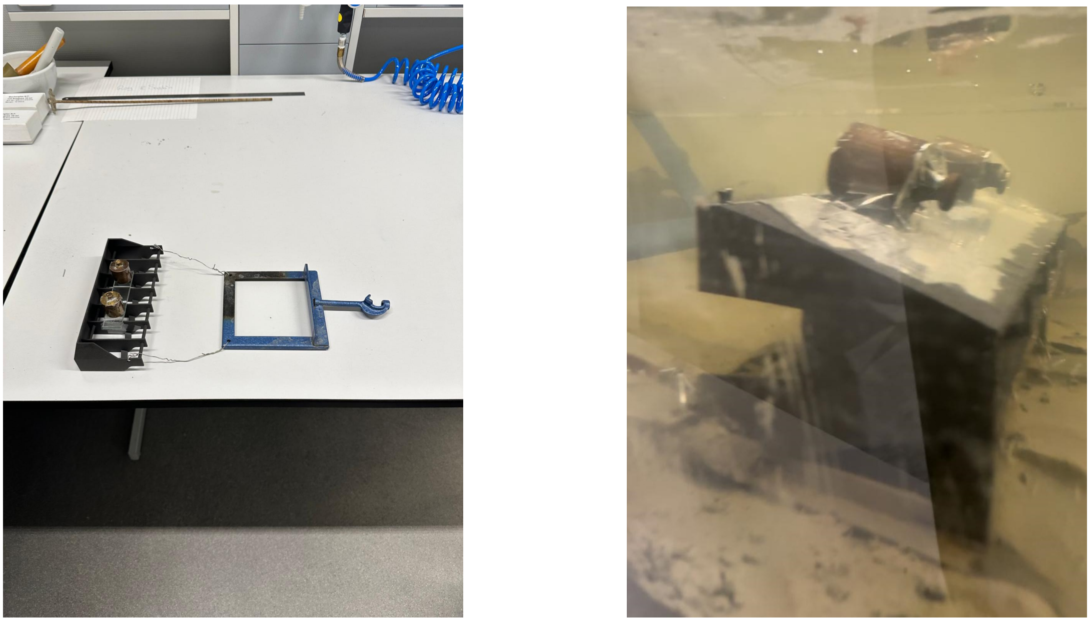


Figure 39: Final prototypes for the conventional plough (left) and new plough (right)

In Figures 40a and 40b two pictures are shown of the prototypes with additional weights to secure and equalize the downward force of both prototypes. For the conventional plough, a bridge (26 gr)was connected on top of the plough where two weights of 50 gr could rest on. For the new plough two weights of 50 gr were connected to the top of the funnel-shaped plough. Unfortunately, a clear picture of this new plough with the added weights was lost, but Figure 40a still shows both weights clearly connected to the plough.



(a) Conventional plough with additional weights

(b) New plough with additional weights

Figure 40: Comparison of conventional and new plough with additional weights

In Table 23 an overview is given of the weights of the prototypes before and after adding weights.

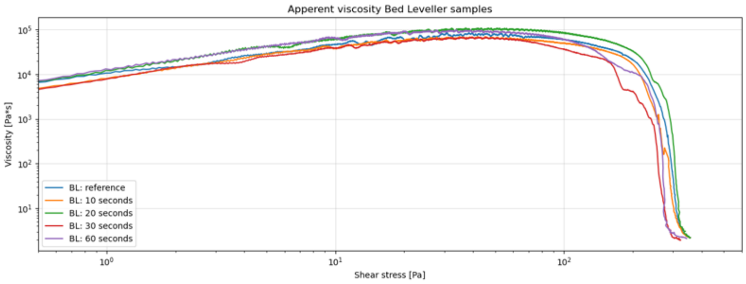
Prototype	**Initial weight**	**Final weight**
Conventional plough	147 *gr*	273 *gr*
New plough	172 *gr*	272 *gr*

Table 23: Weight of the prototypes

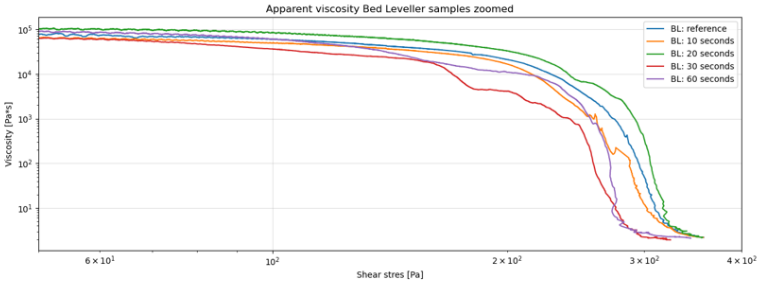
C Lab tests phase

C.1 Technique transition tests

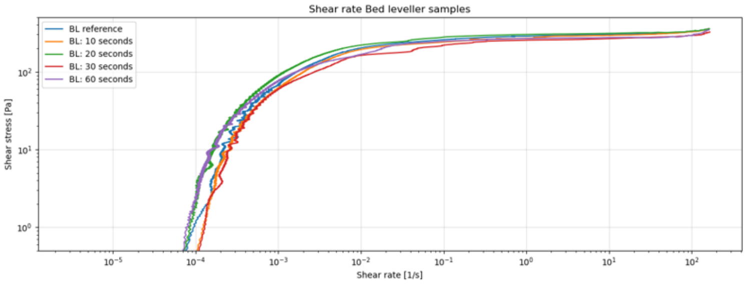
Rheometer results of the **shear-thinning** tests:



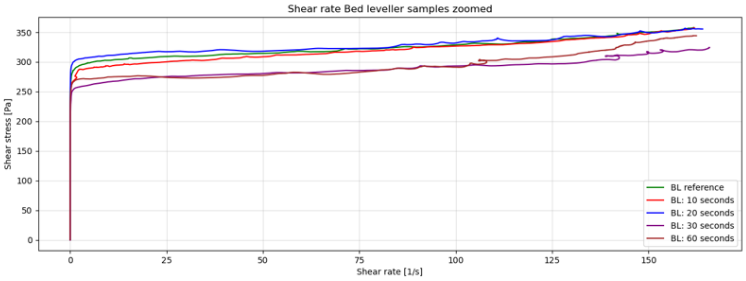
(a) Viscosity to shear stress



(b) Viscosity to shear stress (zoomed in)



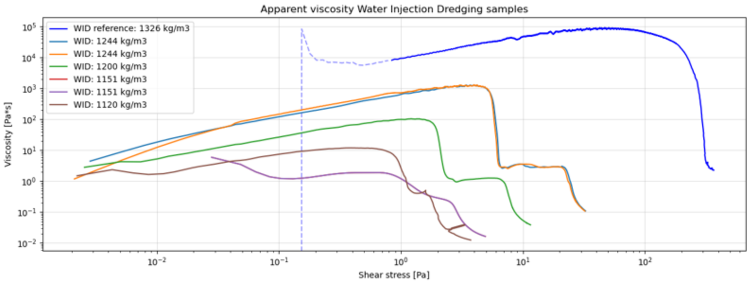
(c) Shear stress to shear rate



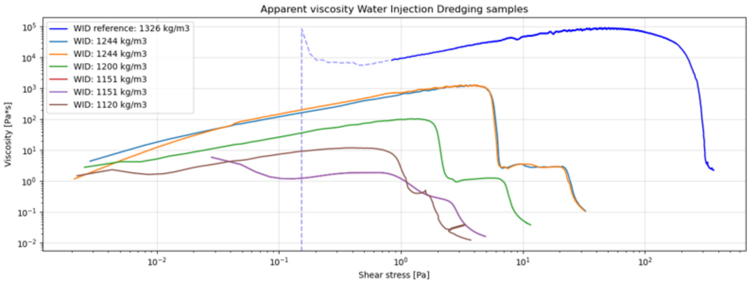
(d) Shear stress to shear rate linear (zoomed in)

Figure 41: Graphs for the shear-thinning test

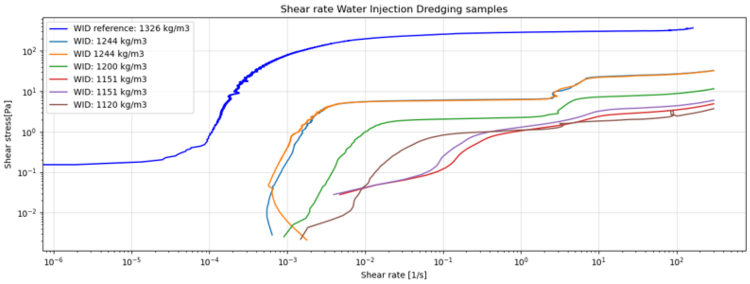
Rheometer results of the **dilution** test:



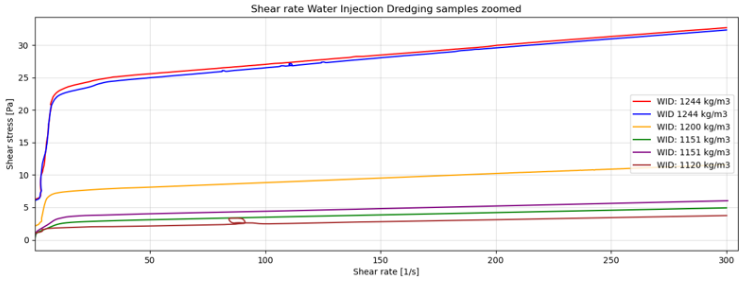
(a) Viscosity to shear stress



(b) Viscosity to shear stress



(c) Shear stress to shear rate



(d) Shear stress to shear rate linear (zoomed in)

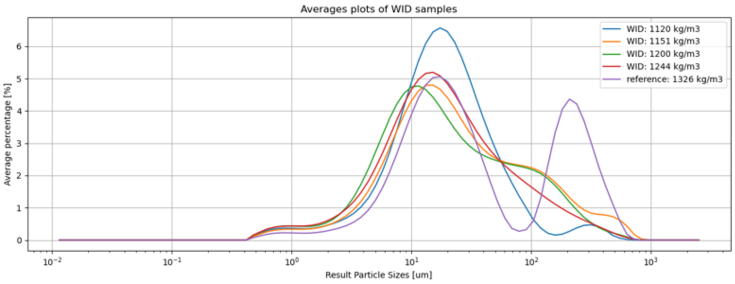
Figure 42: Rheological graphs for the dilution test

Particle Size Distributions (PSDs) were included in some of the tests as well, but do not add value to this research. The reason for this is that throughout some of the tests, there was a lack of consistency in measuring PSDs. They are included in this part of the Appendix. The measuring device for obtained PSD data:

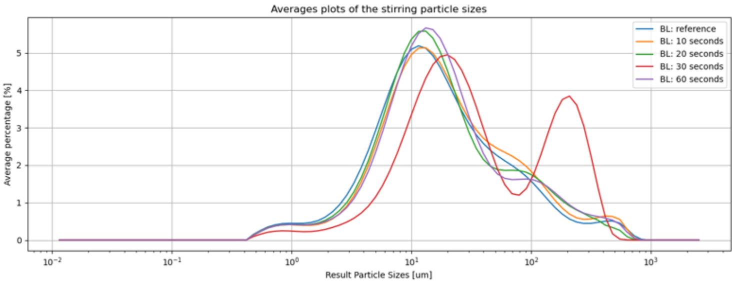
Malvern Instruments Mastersizer 2000 MU & Mastersizer 3000

The Mastersizer 2000 MU and 3000 from Malvern Instruments is a particle size analyzer. This type of equipment can be used to develop particle size distributions (PSD) before and after conditioning activities to analyze the change in particle characteristics in the sediment. The device uses laser diffraction as a method to measure particle size (Richmondscientific, nd). This is achieved by measuring the intensity of light scattered when a laser beam passes through a sample containing dispersed particles. The device captures this angular intensity by a series of photosensitive detectors This information is then analysed to determine the size of the particles responsible for the scattering. Data retrieved by either of the Mastersizers can be developed into PSD's. Furthermore, the device can determine other parameters like concentration and particle shape as well.

PSDs of the transition technique tests:



(a) Dilution



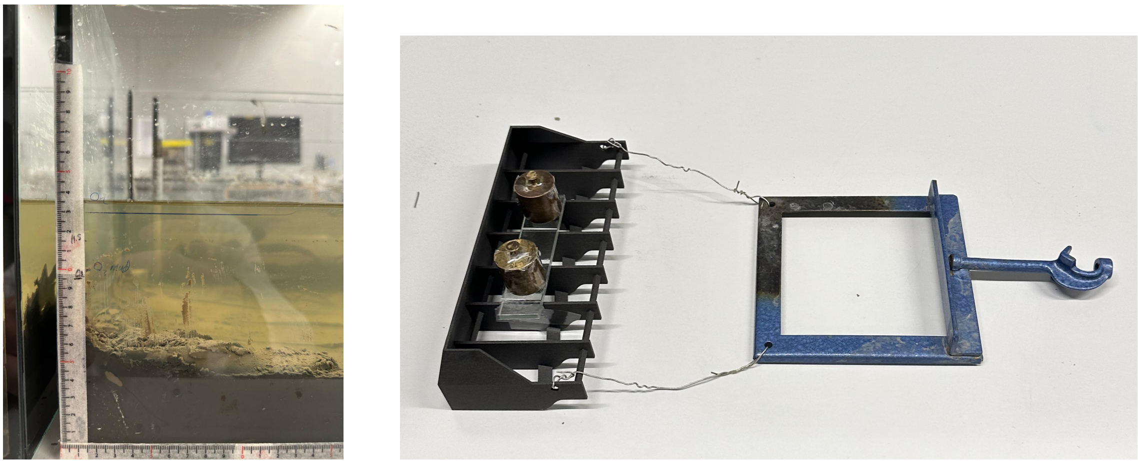
(b) Shear-thinning

Figure 43: PSD's of the mud sample from the silt trap in the Botlek before and after treatment

The dent in the reference PSD of the WID sample in figure 43a can be explained as a faulty measurement from the Malvern Mastersizer. A reason for this anomaly could be a hindrance in the light scattering, affecting the intensity measured. For PSDs, no major differences are detected.

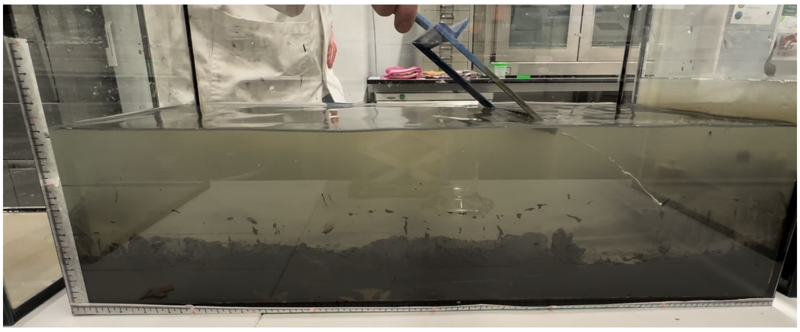
C.2 Frequency tests

Pictures of the tank/plough set-up:



(a) Set-up of the tanks

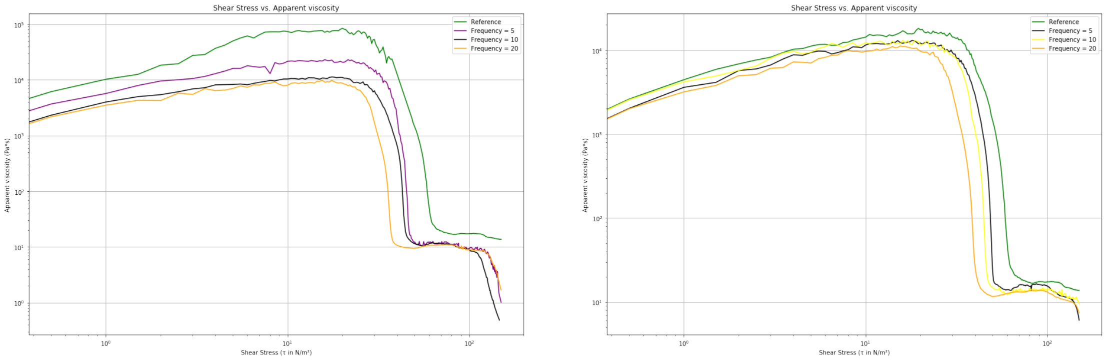
(b) Outside the tank



(c) Inside the tank

Figure 44: Pictures of set-up

Results:

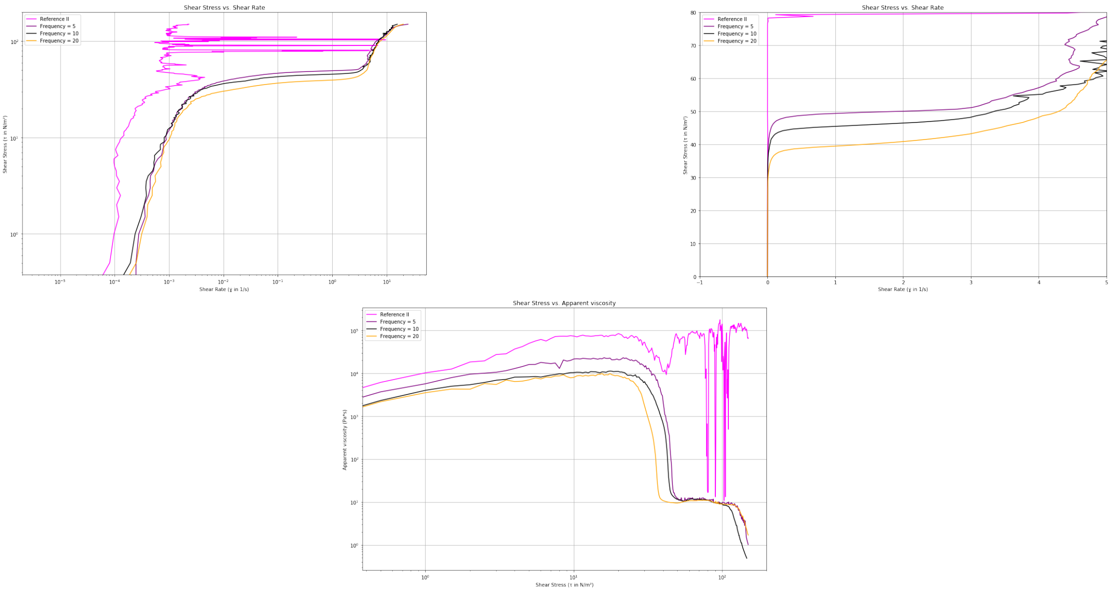


(a) Conventional plough

(b) Conditioning plough

Figure 45: Frequency tests - Apparent viscosity vs shear stress

For the **conventional plough** the results of the rheological parameters in the frequency tests are given in figures 47 and 47b. Some faulty measurements were conducted with the tests. As a result, for the reference situation the values for shear stress ranging from about $40 Pa$ until $150 Pa$ are not reliable.


Shear Stress vs. Shear Rate

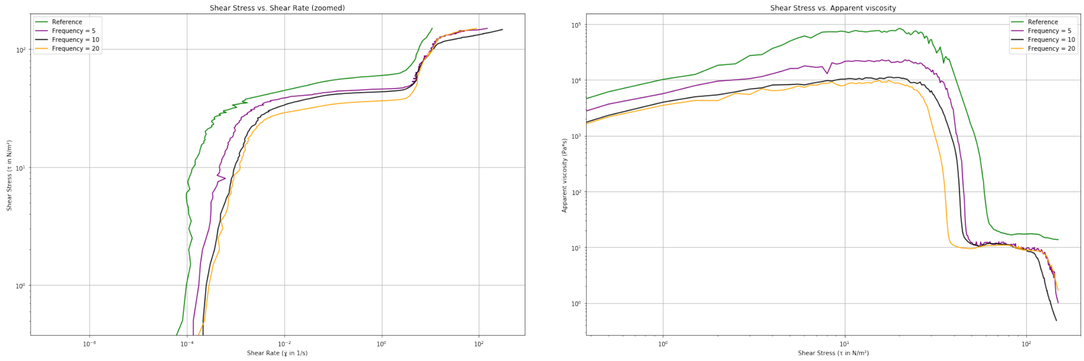
Shear Stress vs. Shear Rate

Shear Stress vs. Apparent viscosity

Figure 46: Freq tests with faulty reference measurements for the conventional bed leveller

Therefore in figure 47 and 47b the faulty graph is replaced for an interpolated figure for the reference measurement. Still, an increasing frequency of conditioning activities results in a decreasing static yield strength. And also the dynamic yield strength decreases from the reference situation to the situation after conditioning, however the frequency of conditioning activities do not affect this dynamic yield strength further for the top layer.

The Rheometer results with the interpolated reference graph for the conventional plough:


Shear Stress vs. Shear Rate (zoomed)

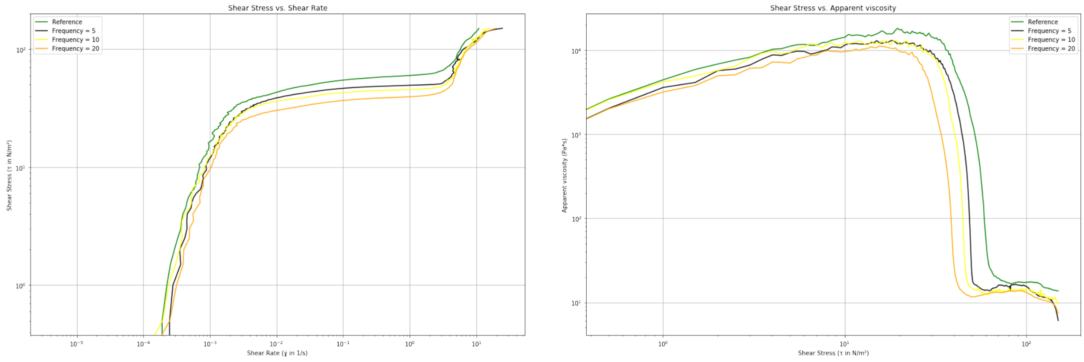
Shear Stress vs. Apparent viscosity

(a) Shear rate to shear stress

(b) Viscosity to shear stress

Figure 47: Rheological graphs for the conventional plough - frequency tests

Rheometer results for the conditioning plough:

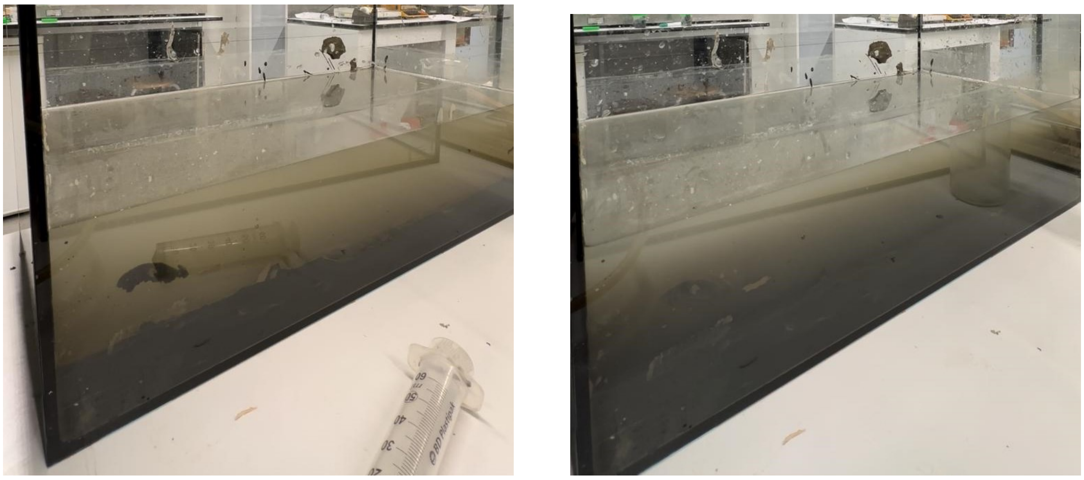


(a) Shear rate to shear stress

(b) Viscosity to shear stress

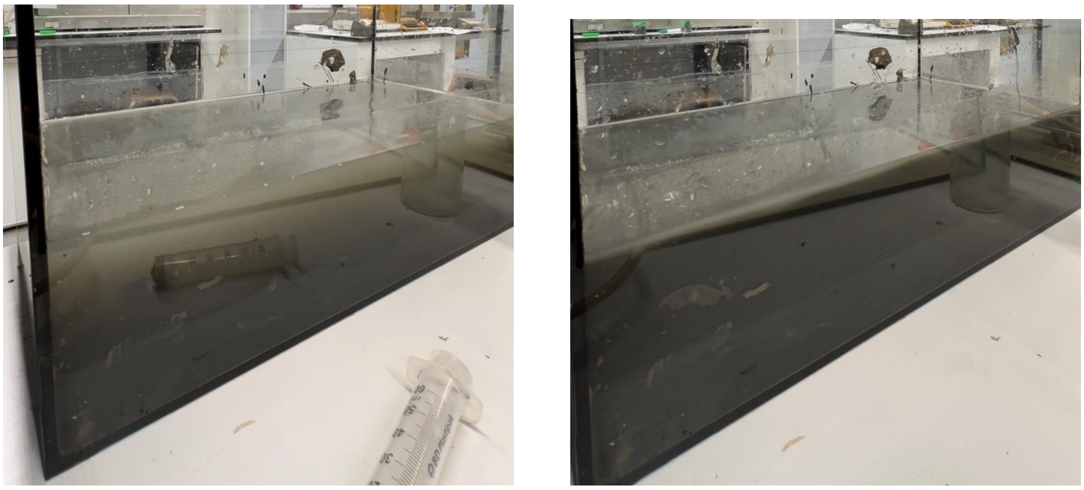
Figure 48: Rheological graphs for the conditioning plough - frequency tests

Visual observations



(a) $N = 0$ of the tank for the new plough.

(b) $N = 5$ of the tank for the new plough.

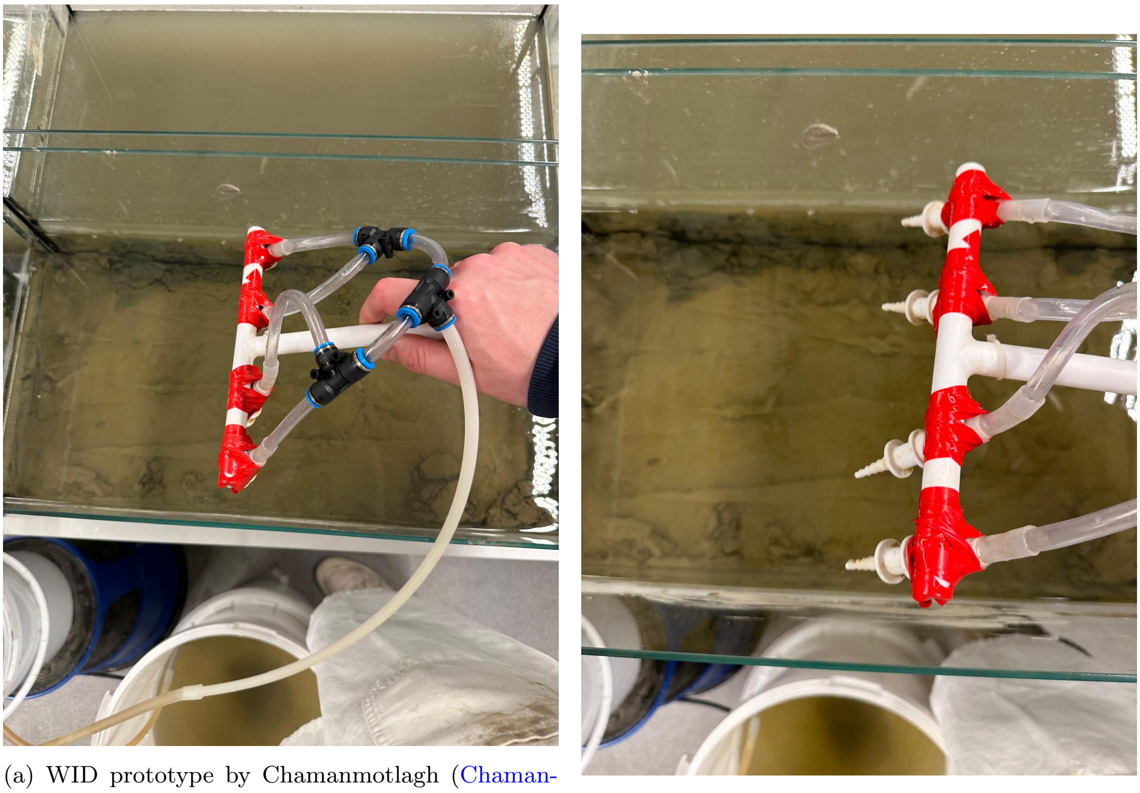


(c) $N = 10$ of the tank for the new plough.

(d) $N = 20$ of the tank for the new plough.

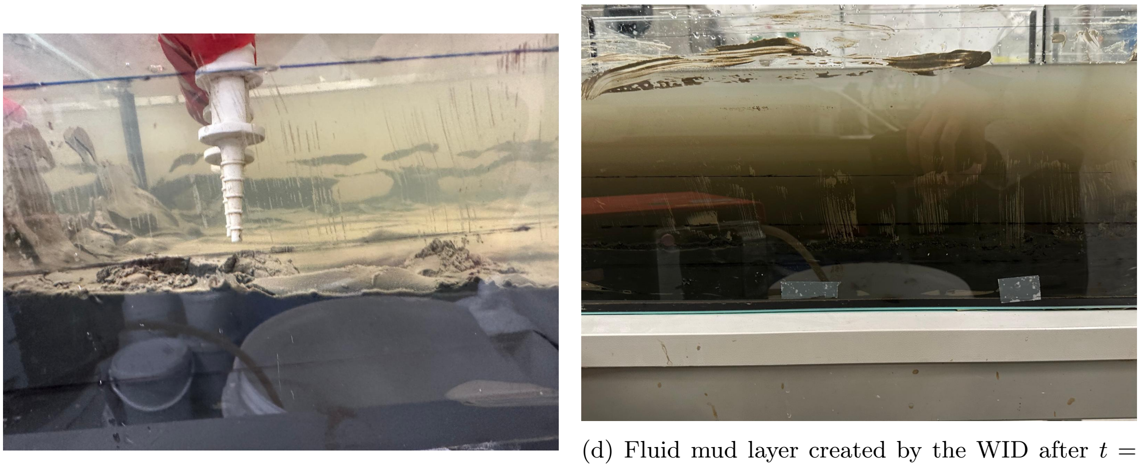
C.3 Comparative tests

Pictures of experiment:



(a) WID prototype by Chamanmotlagh (Chamanmotlagh et al., 2023)

(b) Second angle



(c) Test setup of submerged WID prototype

(d) Fluid mud layer created by the WID after $t = 350\ s$.

Figure 50: Pictures of test setup WID prototype

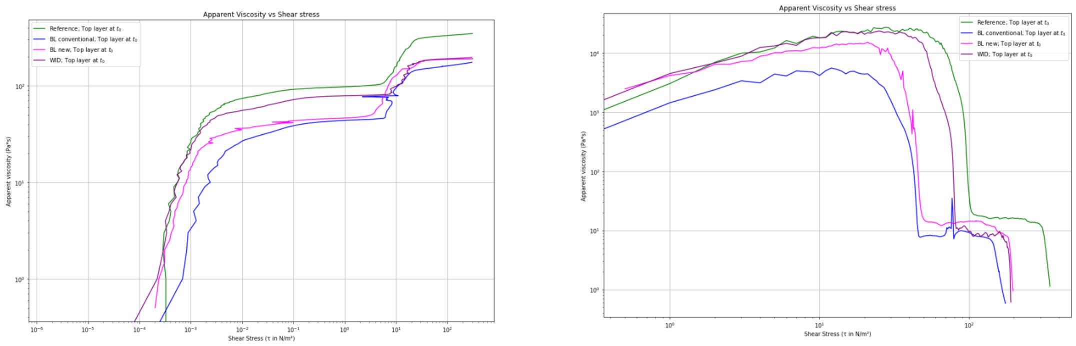
Density

Density	*Reference*	*WID*	*BL conv*	*BL new*
t_0	64.78	62.97	64.14	63.60
$t_0 + 1$	64.55	63.42	63.50	63.88
$t_0 + 3$	64.44	63.30	63.95	63.84
$t_0 + 7$	63.81	63.16	63.86	63.35
$t_0 + 14$	64.38	63.08	64.06	63.60

Table 24: Weight over time top layer mud

Yield stress top mud layers

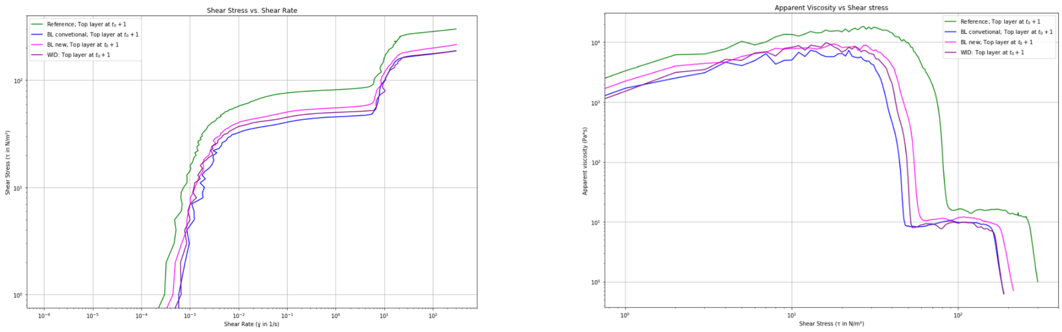
The figures for the Rheometer results for the top layer of each conditioning method is given at a measuring moment in time:



(a) Shear stress vs. shear rate

(b) Viscosity vs. shear stress

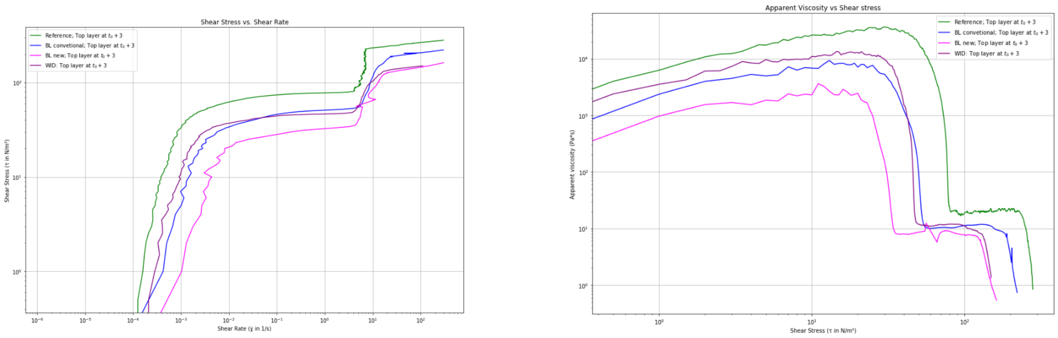
Figure 51: Rheological comparison for the top layer at t_0



(a) Shear stress vs. shear rate

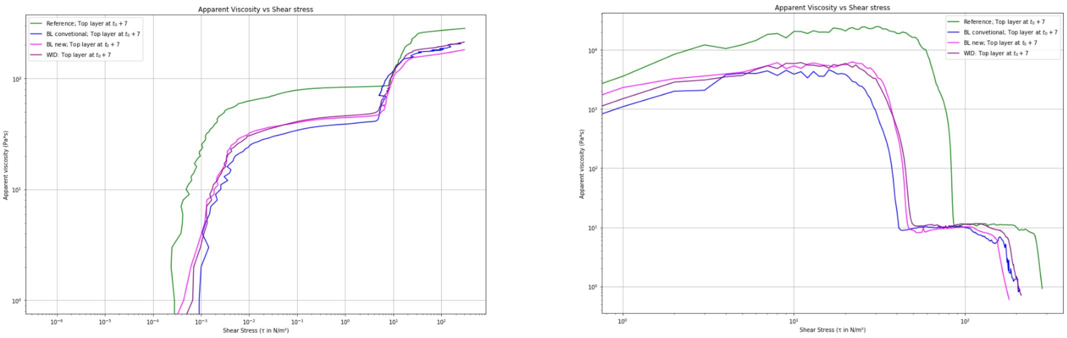
(b) Viscosity vs. shear stress

Figure 52: Rheological comparison for the top layer at $t_0 + 1$



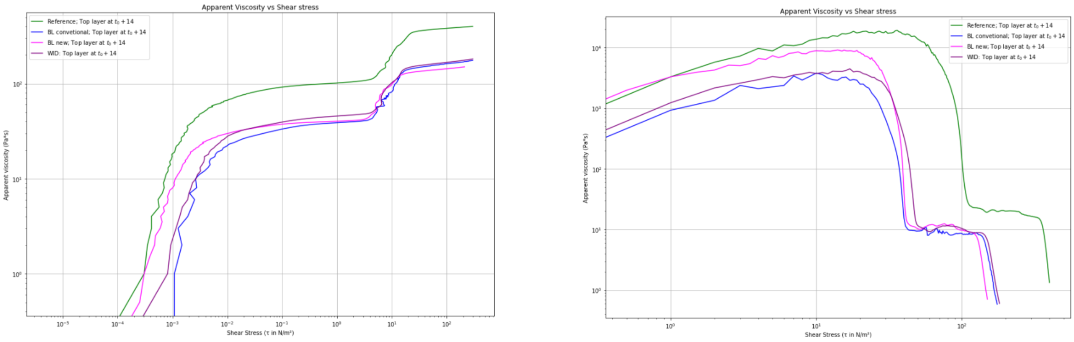
(a) Shear stress vs. shear rate (b) Viscosity vs. shear stress

Figure 53: Rheological comparison for the top layer at $t_0 + 3$



(a) Shear stress vs. shear rate (b) Viscosity vs. shear stress

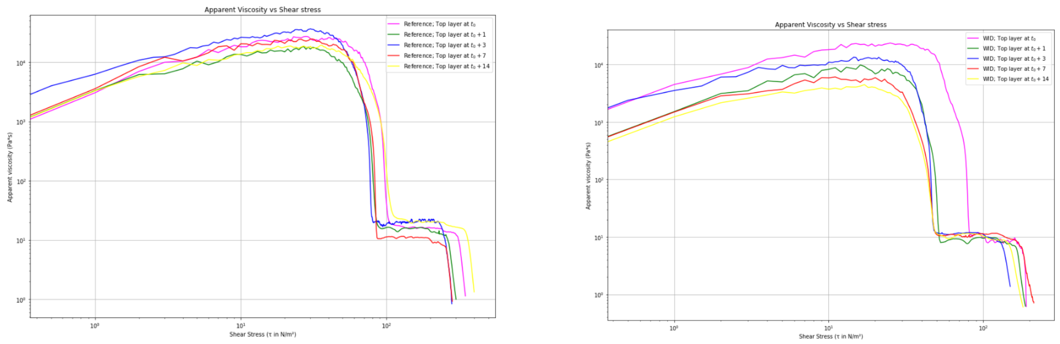
Figure 54: Rheological comparison for the top layer at $t_0 + 7$



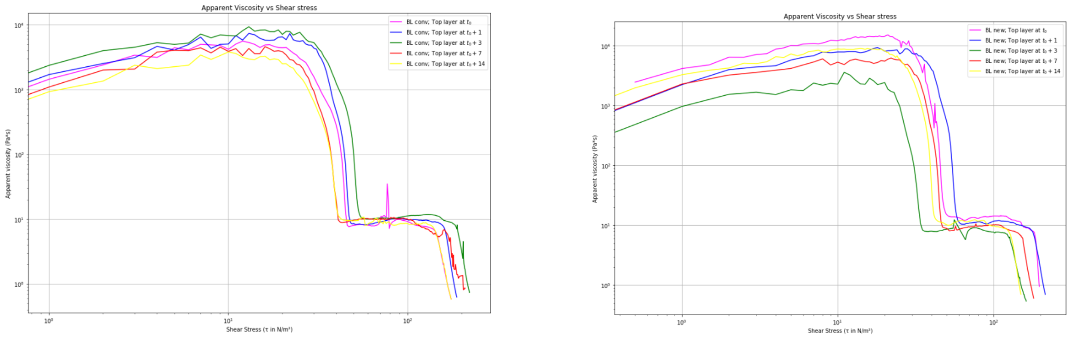
(a) Shear stress vs. shear rate (b) Viscosity vs. shear stress

Figure 55: Rheological comparison for the top layer at $t_0 + 14$

The same graphs can also be plotted to observe the progress in time of the yield stresses for each conditioning method.



(a) Reference (b) WID

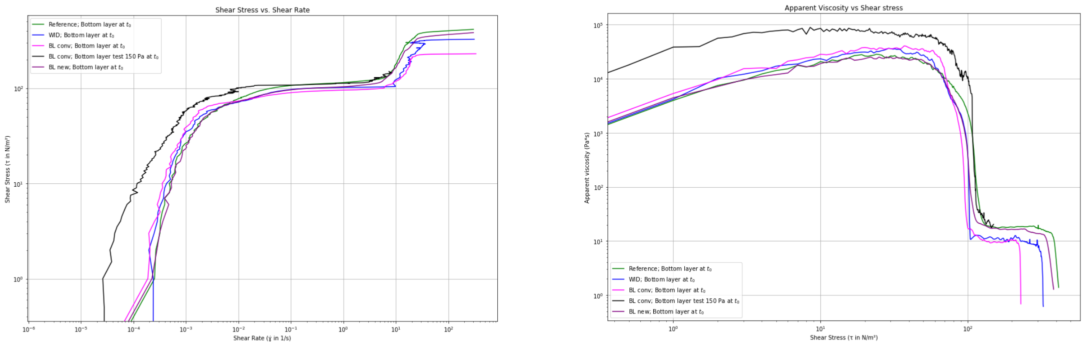


(c) Conventional plough (d) Conditioning plough

Figure 56: Progress of rheological parameters for different treatments in the top layer over time

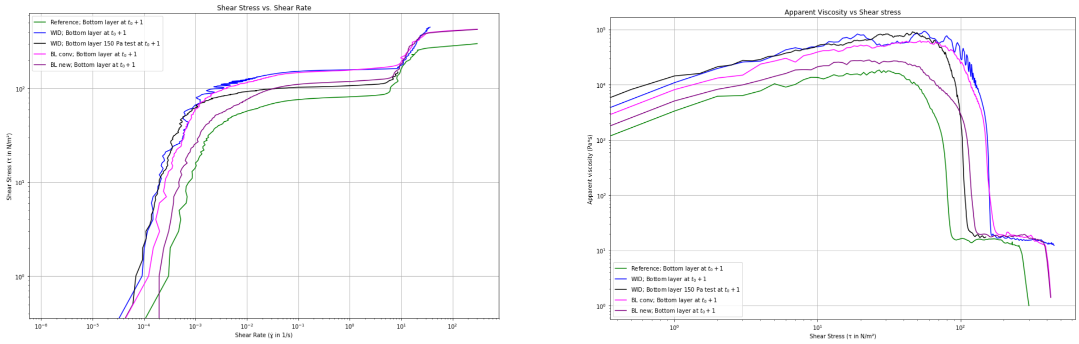
Yield stress bottom mud layers

The figures for the Rheometer results for the bottom layer of each conditioning method is given at a measuring moment in time:



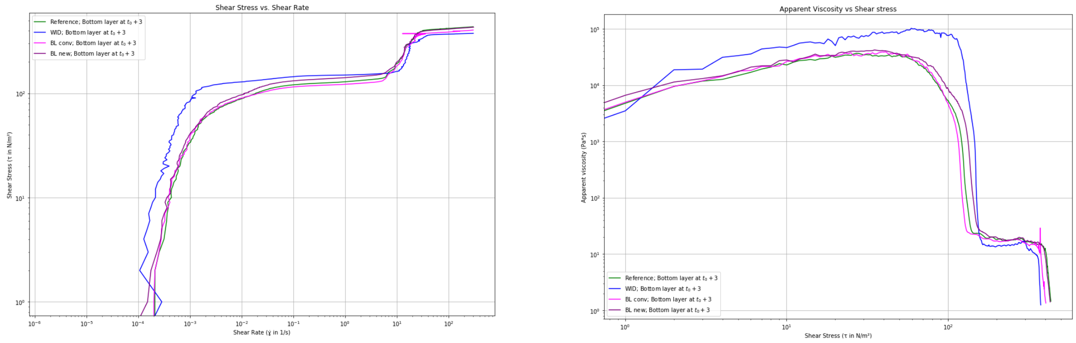
(a) Shear stress vs. shear rate (b) Viscosity vs. shear stress

Figure 57: Rheological comparison for the bottom layer at t_0



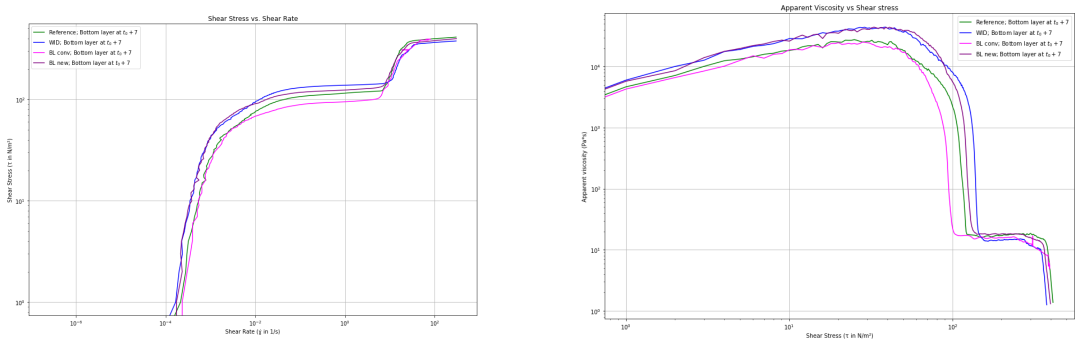
(a) Shear stress vs. shear rate (b) Viscosity vs. shear stress

Figure 58: Rheological comparison for the bottom layer at $t_0 + 1$



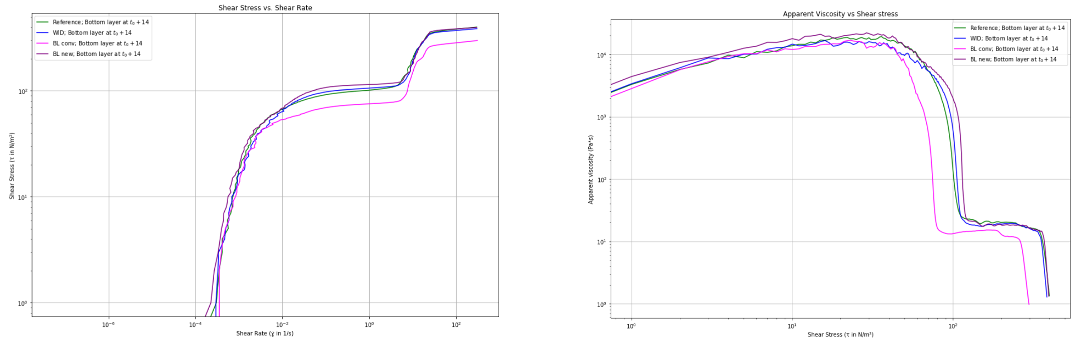
(a) Shear stress vs. shear rate (b) Viscosity vs. shear stress

Figure 59: Rheological comparison for the bottom layer at $t_0 + 3$



(a) Shear stress vs. shear rate (b) Viscosity vs. shear stress

Figure 60: Rheological comparison for the bottom layer at $t_0 + 7$

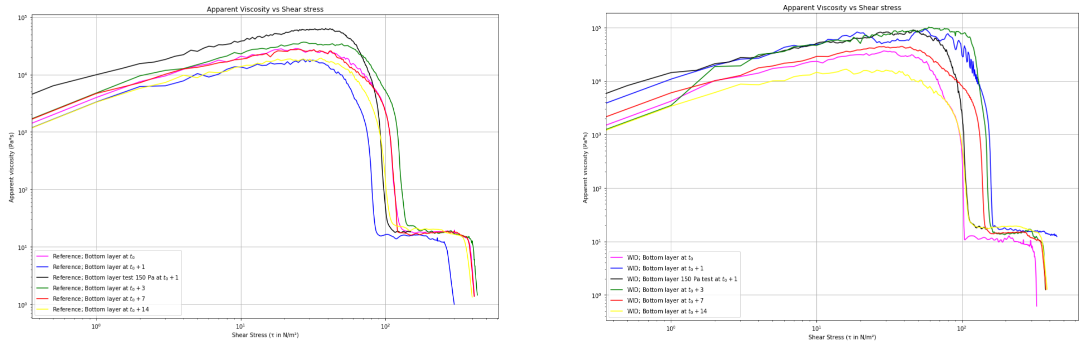


(a) Shear stress vs. shear rate

(b) Viscosity vs. shear stress

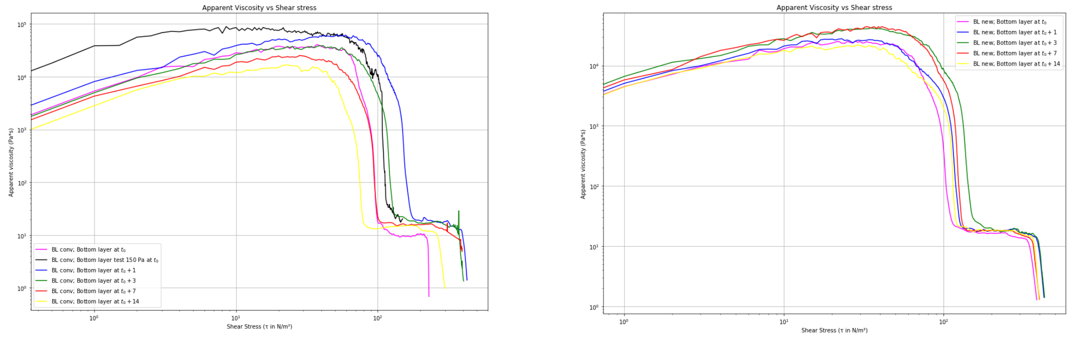
Figure 61: Rheological comparison for the bottom layer at $t_0 + 14$

The same graphs can also be plotted to observe the progress in time of the yield stresses for each conditioning method.



(a) Reference

(b) WID



(c) Conventional plough

(d) Conditioning plough

Figure 62: Progress of rheological parameters for different treatments in the bottom layer over time

Particle size distribrution

The PSDs of each sample were taken as well. All samples were tested, however, for simplicity just part of the samples are visualized for each conditioning method as can be seen in figure 63. The samples show a mode of around 10 μm. The consolidated samples show some anomalies at a particle size diameter of $D = 1000$ μm. It is most likely that these have ruined the data, as those are due to bubbles that got mixed into the Matersizer. The trajectories of the PSDs are disturbed by these high values and end in mode diameter values that can not be relied upon. Furthermore, consolidated mud has clumped together in the two weeks after retrieving the samples. It would have been helpful to analyse the floc sizes but this is unfortunately not possible anymore. Still, the figures of the retrieved PSD data can be found below.

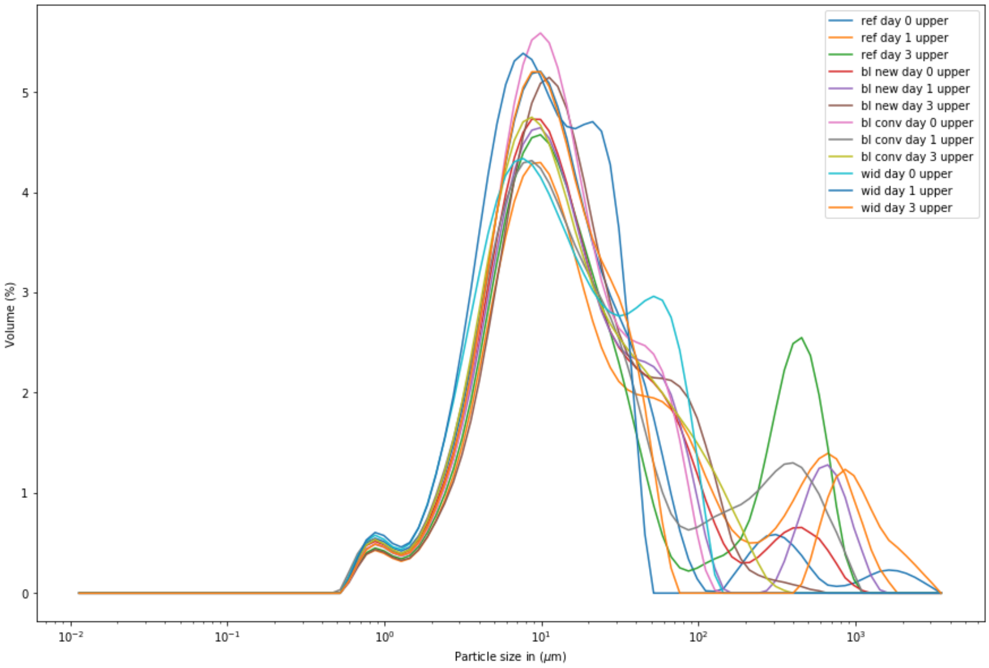
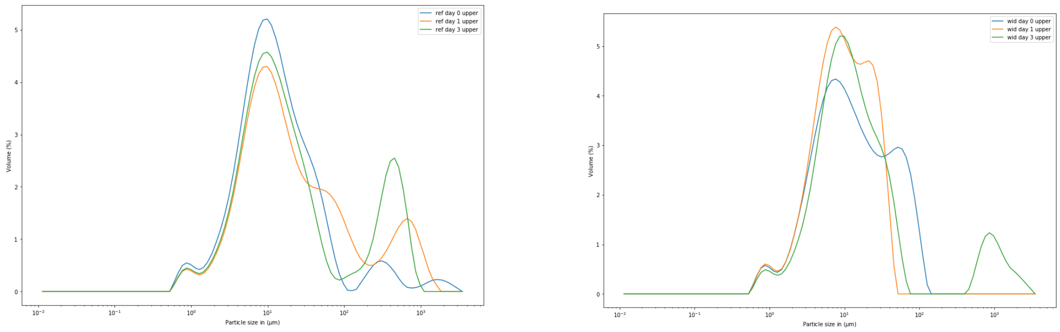
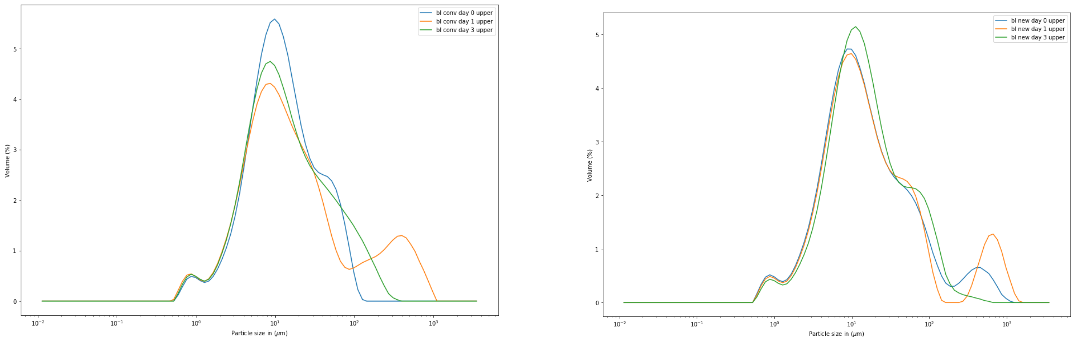


Figure 63: PSD of the upper layer of all conditioning methods from $t = t_0$ *to* $t_0 + 3$ *days*

In figure 64a-64d the PSD's for the different samples are given for the upper layer of each tank representing a conditioning method.



(a) Reference (b) WID



(c) Conventional plough (d) Conditioning plough

Figure 64: PSDs for the upper layers

Again, no major differences are detected in the graphs apart from the bubbles at $D = 1000\ \mu m$.

Sample	D_x**(10)**	D_x **(50)**	D_x **(90)**
Reference $\{t_0\}$	3.5020	12.180	114.22
Reference $\{t_0\}$ + 1 day	4.0740	16.660	390.00
Reference $\{t_0\}$ + 3 days	3.9560	15.380	401.00
New BL $\{t_0\}$	3.6200	13.400	92.10
New BL $\{t_0\}$ + 1 day	3.8360	15.080	371.42
New BL $\{t_0\}$ + 3 days	4.2000	14.760	87.66
Conv BL $\{t_0\}$	3.7780	12.220	51.88
Conv BL $\{t_0\}$ + 1 day	3.4900	14.400	332.75
Conv BL $\{t_0\}$ + 3 days	3.5425	12.975	82.80
WID $\{t_0\}$	3.1740	12.460	65.56
WID $\{t_0\}$ + 1 day	3.1540	10.160	30.04
WID $\{t_0\}$ + 3 days	3.7360	12.800	433.88

Table 25: Your table caption here.

D Field tests phase

Vessel type	Vessel	Date of test
WID	AquaDelta	7-2-2024
Bed leveller	Husky (van den Bosch Marine)	26-3-2024
Surveying vessel	Surveyor 2 (PoR)	Both testing dates

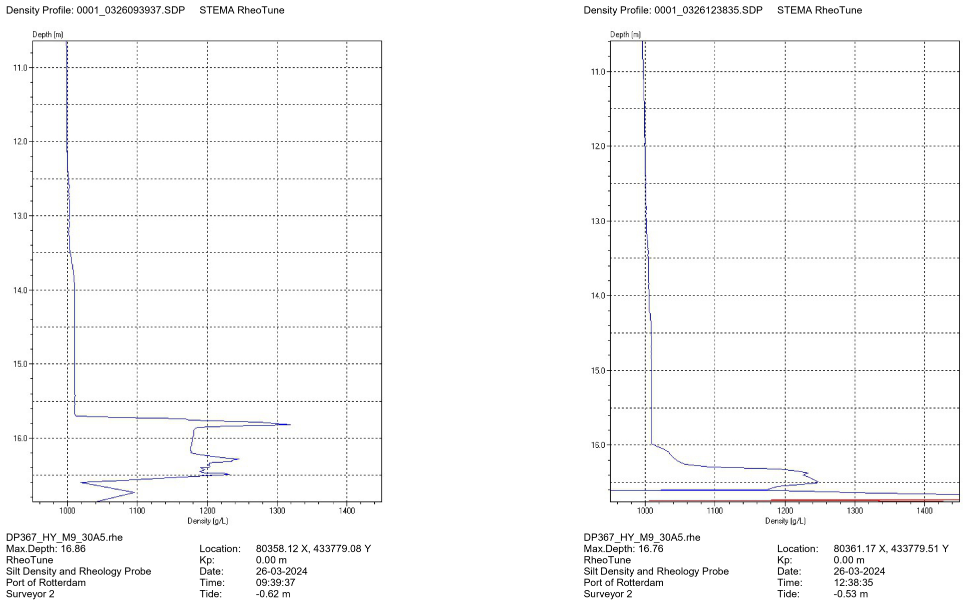
Table 26: Details for field tests

D.1 Bed leveller field tests

In this appendix section the graphs of the bed leveller test results are shown. There should be noted that MP stands for Measuring Point.

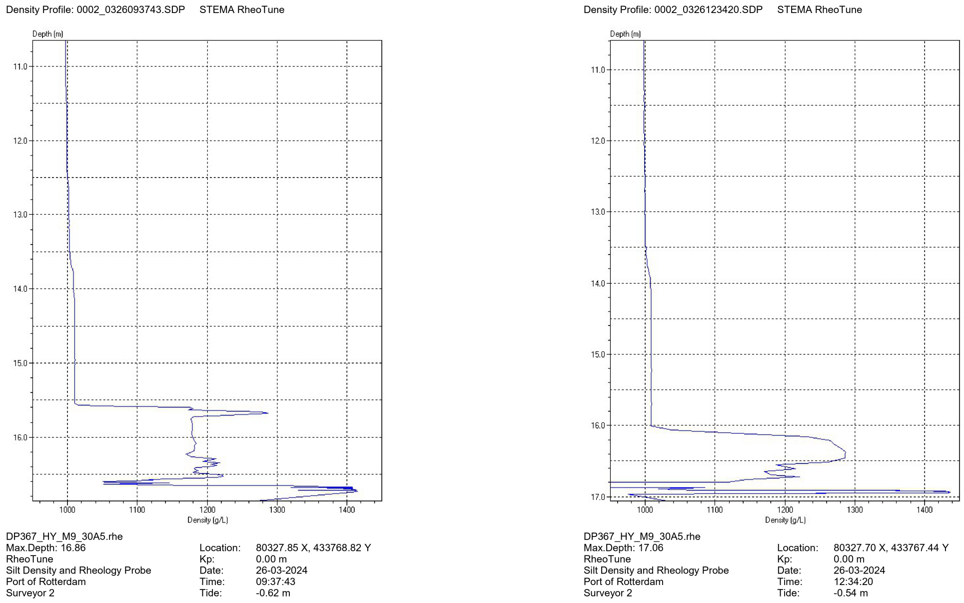
Density

There should be noted for these density profiles that the horizontal axis shows density in g/L, which is equal to kg/m^3. The latter is the value that has been used in this whole research however, the profiles were compiled with a program that has g/L as standard unit for density.



(a) Before (b) After

Figure 65: Density measurements at MP 1 before and after conditioning



Density Profile: 0002_0326093743.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.86
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80327.85 X, 433768.82 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 09:37:43
Tide: -0.62 m

Density Profile: 0002_0326123420.SDP STEMA RheoTune

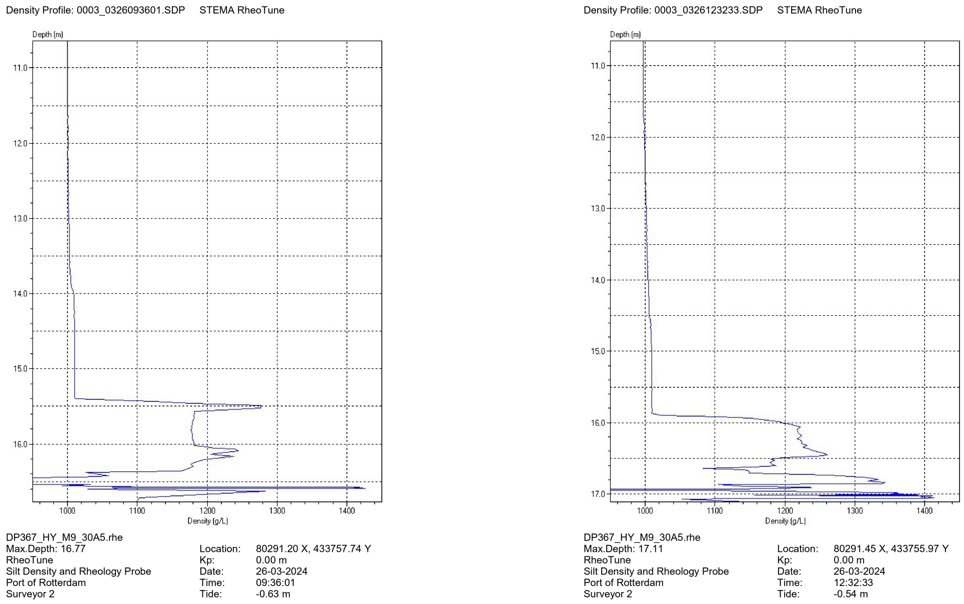
DP367_HY_M9_30A5.rhe
Max.Depth: 17.06
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80327.70 X, 433767.44 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 12:34:20
Tide: -0.54 m

(a) Before

(b) After

Figure 66: Density measurements at MP 2 before and after conditioning



Density Profile: 0003_0326093601.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.77
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80291.20 X, 433757.74 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 09:36:01
Tide: -0.63 m

Density Profile: 0003_0326123233.SDP STEMA RheoTune

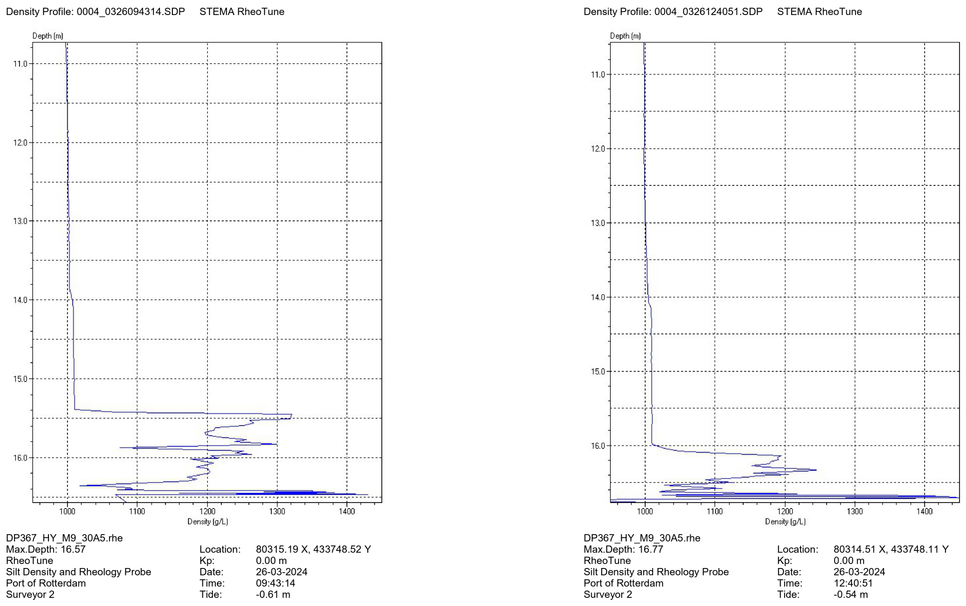
DP367_HY_M9_30A5.rhe
Max.Depth: 17.11
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80291.45 X, 433755.97 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 12:32:33
Tide: -0.54 m

(a) Before

(b) After

Figure 67: Density measurements at MP 3 before and after conditioning



DP367_HY_M9_30A5.rhe
Max.Depth: 16.57
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

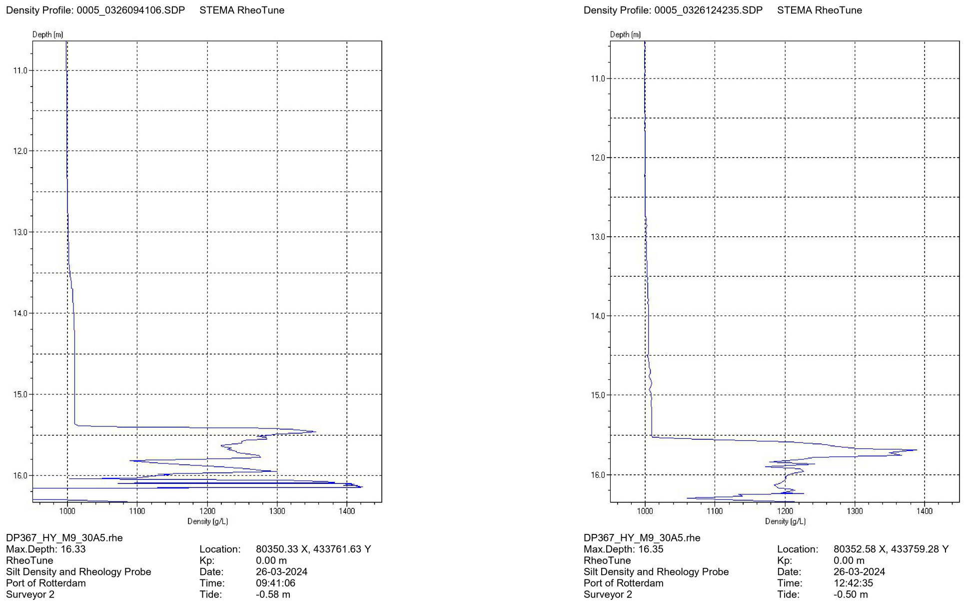
Location: 80315.19 X, 433748.52 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 09:43:14
Tide: -0.61 m

DP367_HY_M9_30A5.rhe
Max.Depth: 16.77
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80314.51 X, 433748.11 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 12:40:51
Tide: -0.54 m

(a) Before (b) After

Figure 68: Density measurements at MP 4 before and after conditioning



DP367_HY_M9_30A5.rhe
Max.Depth: 16.33
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80350.33 X, 433761.63 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 09:41:06
Tide: -0.58 m

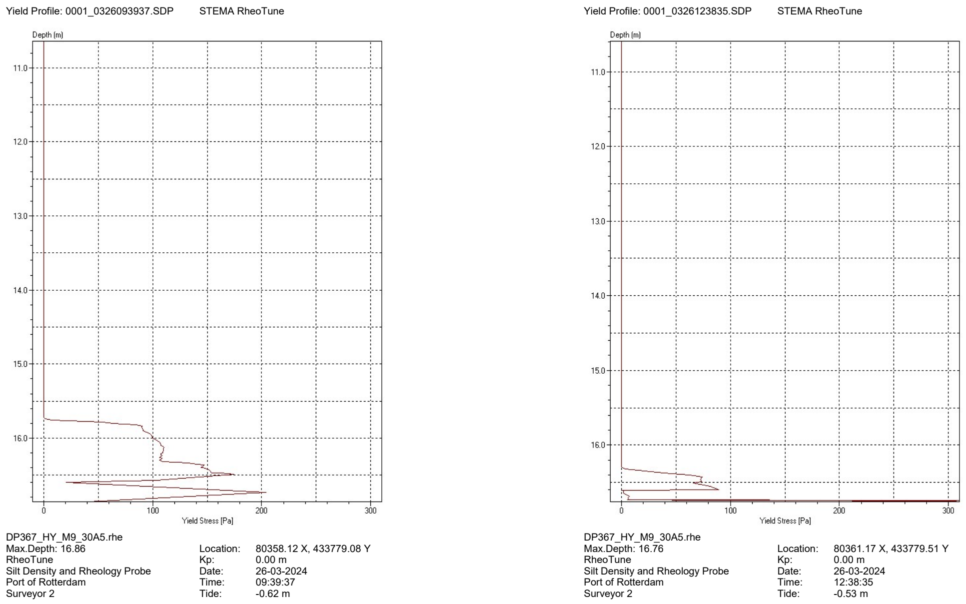
DP367_HY_M9_30A5.rhe
Max.Depth: 16.35
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80352.58 X, 433759.28 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 12:42:35
Tide: -0.50 m

(a) Before (b) After

Figure 69: Density measurements at MP 5 before and after conditioning

Stress distribution



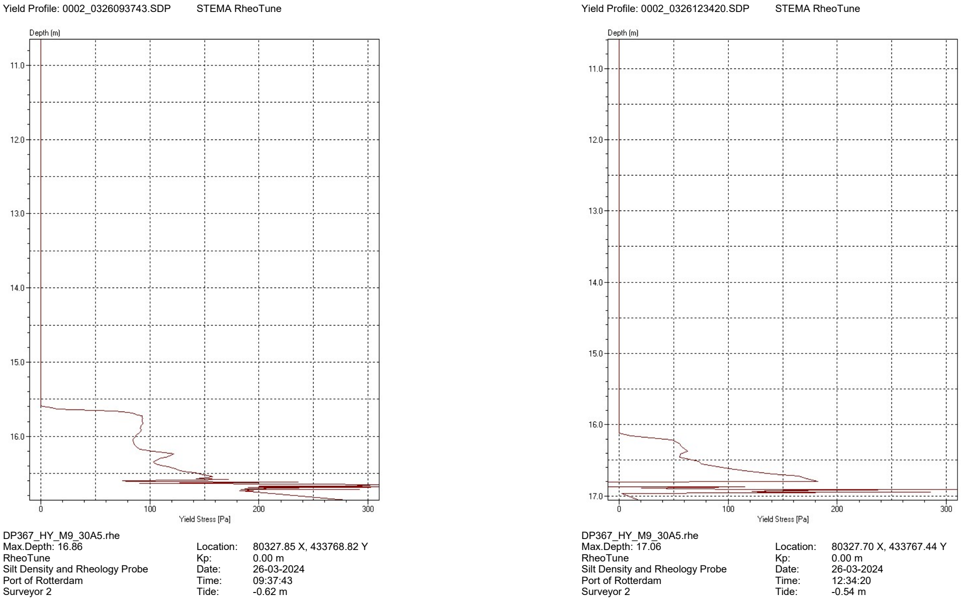
DP367_HY_M9_30A5.rhe
Max.Depth: 16.86
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2
Location: 80358.12 X, 433779.08 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 09:39:37
Tide: -0.62 m

DP367_HY_M9_30A5.rhe
Max.Depth: 16.76
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2
Location: 80361.17 X, 433779.51 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 12:38:35
Tide: -0.53 m

(a) Before conditioning

(b) After conditioning

Figure 70: Stress measurements at MP 1 before and after conditioning



Yield Profile: 0002_0326093743.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.86
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80327.85 X, 433768.82 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 09:37:43
Tide: -0.62 m

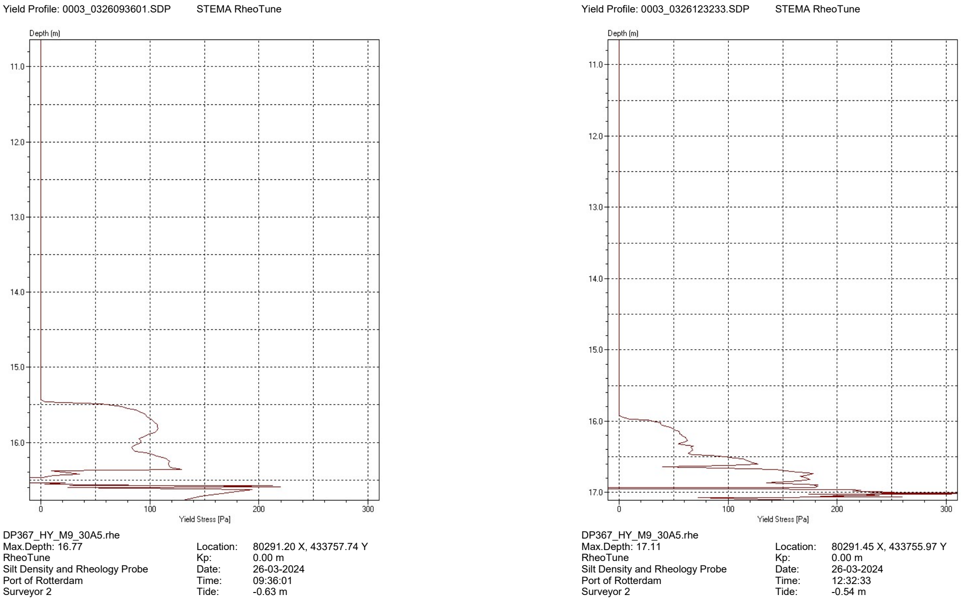
Yield Profile: 0002_0326123420.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 17.06
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80327.70 X, 433767.44 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 12:34:20
Tide: -0.54 m

(a) Before conditioning (b) After conditioning

Figure 71: Stress measurements at MP 2 before and after conditioning



Yield Profile: 0003_0326093601.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.77
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80291.20 X, 433757.74 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 09:36:01
Tide: -0.63 m

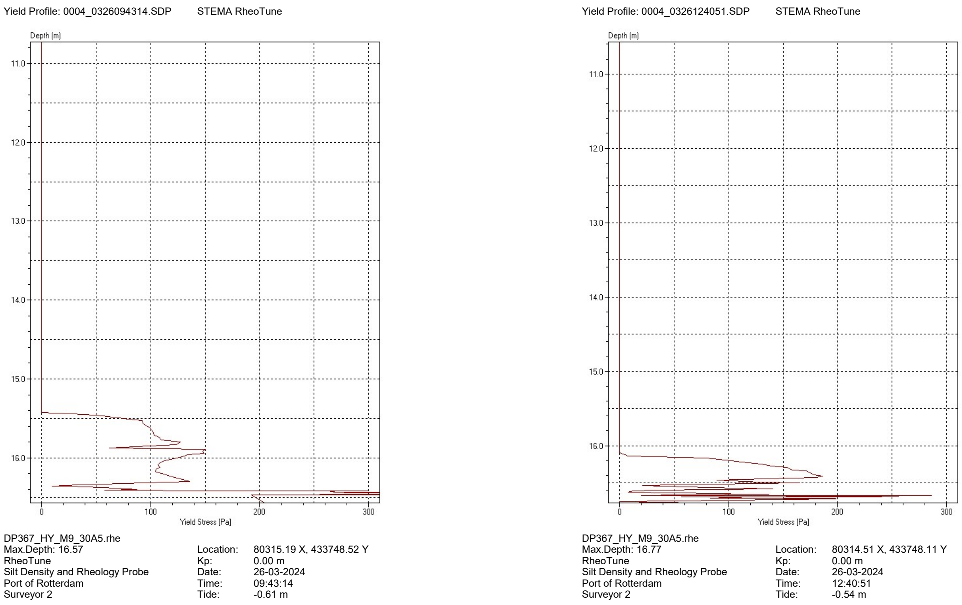
Yield Profile: 0003_0326123233.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 17.11
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80291.45 X, 433755.97 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 12:32:33
Tide: -0.54 m

(a) Before conditioning (b) After conditioning

Figure 72: Stress measurements at MP 3 before and after conditioning



Yield Profile: 0004_0326094314.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.57
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80315.19 X, 433748.52 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 09:43:14
Tide: -0.61 m

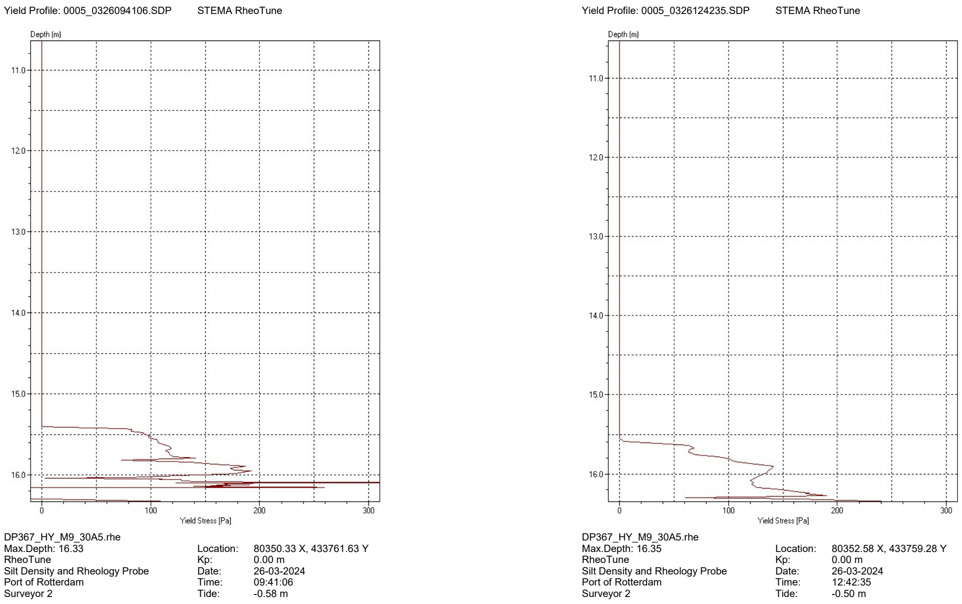
Yield Profile: 0004_0326124051.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.77
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80314.51 X, 433748.11 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 12:40:51
Tide: -0.54 m

(a) Before conditioning (b) After conditioning

Figure 73: Stress measurements at MP 4 before and after conditioning



Yield Profile: 0005_0326094106.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.33
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80350.33 X, 433761.63 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 09:41:06
Tide: -0.58 m

Yield Profile: 0005_0326124235.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.35
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

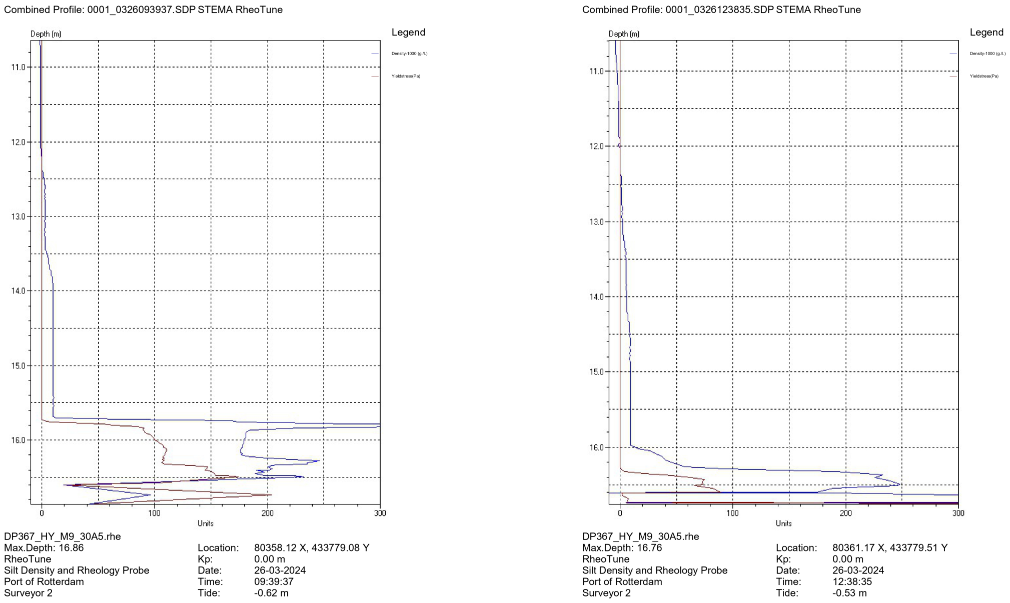
Location: 80352.58 X, 433759.28 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 12:42:35
Tide: -0.50 m

(a) Before conditioning (b) After conditioning

Figure 74: Stress measurements at MP 5 before and after conditioning

Combined profiles

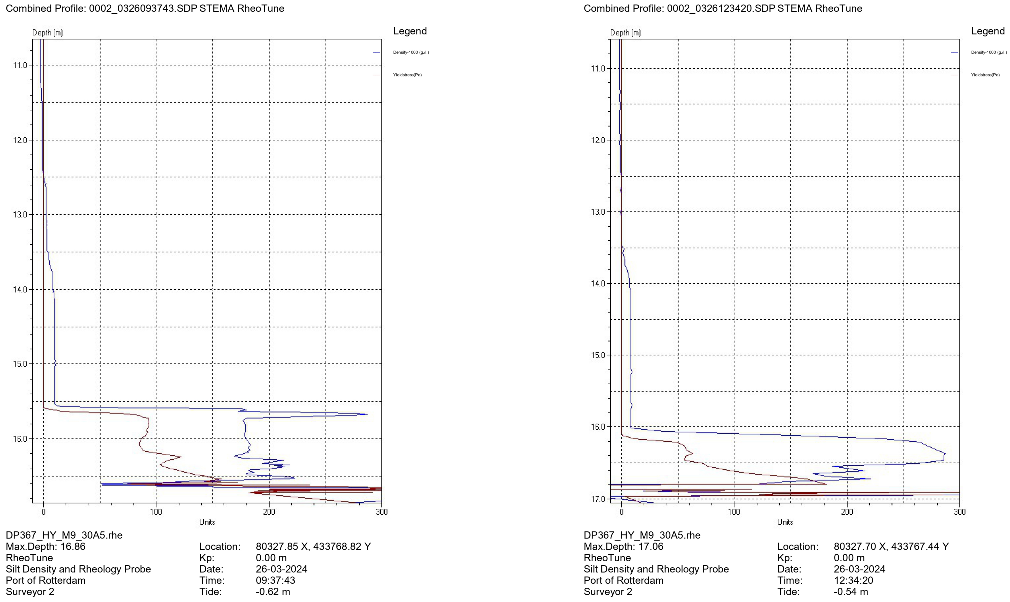
There should be noted for the combined density and yield stress profiles that the blue line represents the density and the red line yield stress. The vertical axis shows depth and horizontal axis a unit that represents both stress in Pa and density in kg/m^3. For the latter, a value of 1000 kg/m^3 should be added to obtain the real density values.



(a) Before conditioning

(b) After conditioning

Figure 75: Density/stress at MP 1 before and after conditioning



DP367_HY_M9_30A5.rhe
Max.Depth: 16.86
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

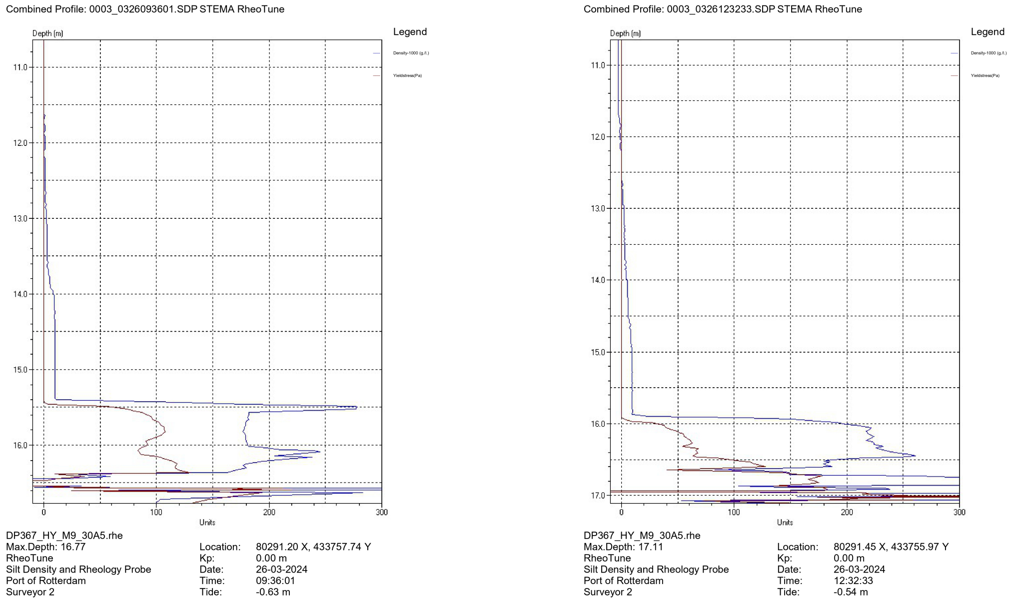
Location: 80327.85 X, 433768.82 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 09:37:43
Tide: -0.62 m

DP367_HY_M9_30A5.rhe
Max.Depth: 17.06
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80327.70 X, 433767.44 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 12:34:20
Tide: -0.54 m

(a) Before conditioning (b) After conditioning

Figure 76: Density/stress at MP 2 before and after conditioning



DP367_HY_M9_30A5.rhe
Max.Depth: 16.77
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

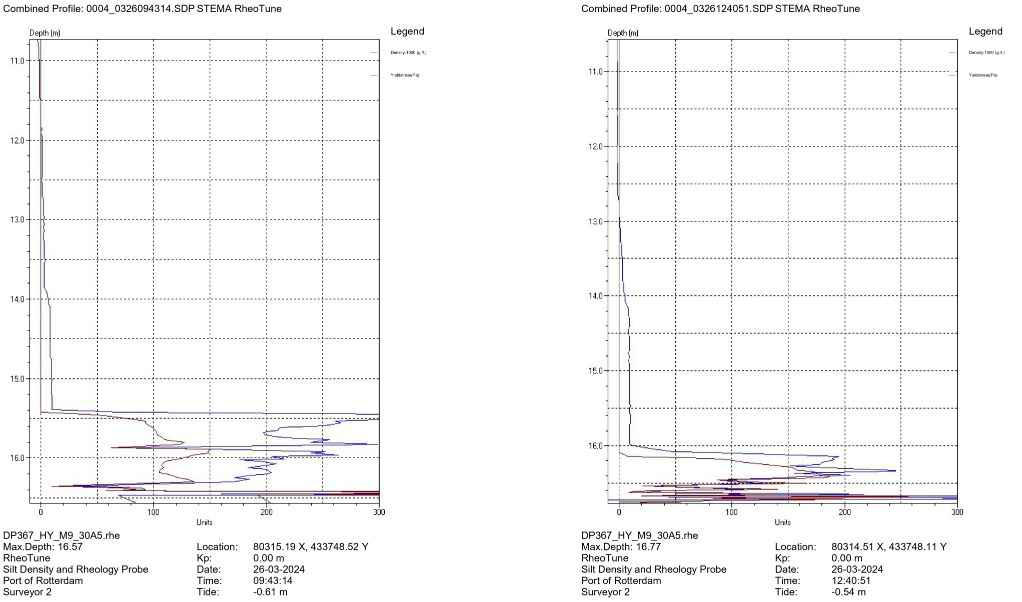
Location: 80291.20 X, 433757.74 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 09:36:01
Tide: -0.63 m

DP367_HY_M9_30A5.rhe
Max.Depth: 17.11
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80291.45 X, 433755.97 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 12:32:33
Tide: -0.54 m

(a) Before conditioning (b) After conditioning

Figure 77: Density/stress at MP 3 before and after conditioning



DP367_HY_M9_30A5.rhe
Max.Depth: 16.57
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

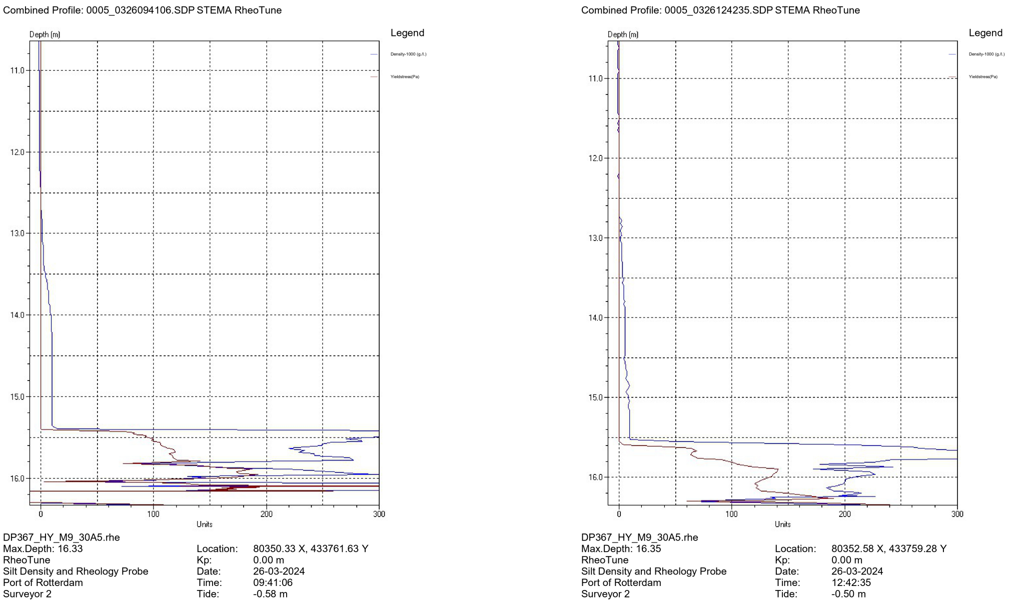
Location: 80315.19 X, 433748.52 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 09:43:14
Tide: -0.61 m

DP367_HY_M9_30A5.rhe
Max.Depth: 16.77
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80314.51 X, 433748.11 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 12:40:51
Tide: -0.54 m

(a) Before conditioning (b) After conditioning

Figure 78: Density/stress at MP 4 before and after conditioning



DP367_HY_M9_30A5.rhe
Max.Depth: 16.33
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80350.33 X, 433761.63 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 09:41:06
Tide: -0.58 m

DP367_HY_M9_30A5.rhe
Max.Depth: 16.35
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

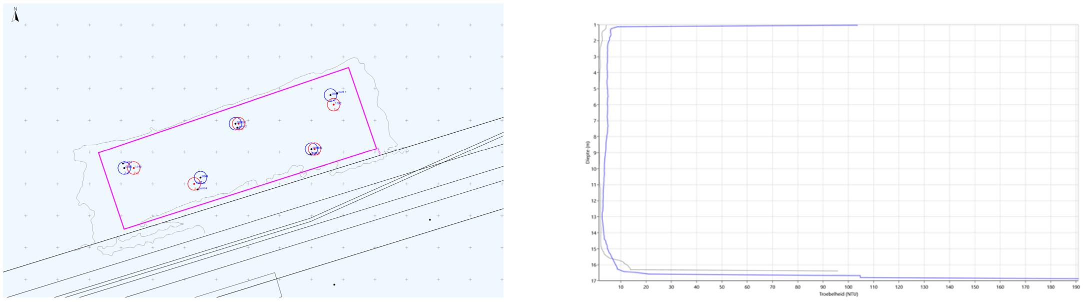
Location: 80352.58 X, 433759.28 Y
Kp: 0.00 m
Date: 26-03-2024
Time: 12:42:35
Tide: -0.50 m

(a) Before conditioning (b) After conditioning

Figure 79: Density/stress at MP 5 before and after conditioning

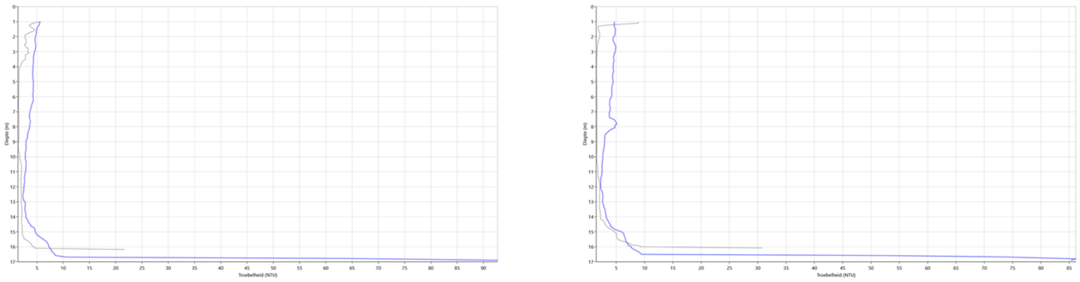
Turbidity

There should be noticed that for the following figures representing the turbidity profile at each measuring point, the horizontal axis is for turbidity (NTU) and the vertical axis is for depth (m). This is not perfectly readable from the figures.



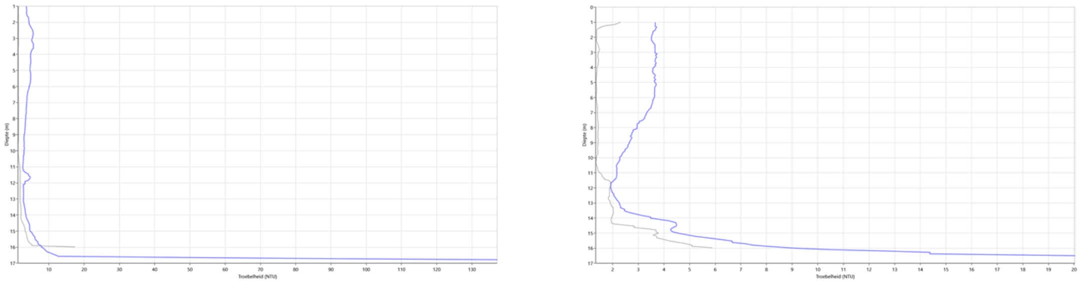
(a) Bed leveller testing area with MP locations

(b) Turbidity change MP 1



(c) Turbidity change MP 2

(d) Turbidity change MP 3



(e) Turbidity change MP 4

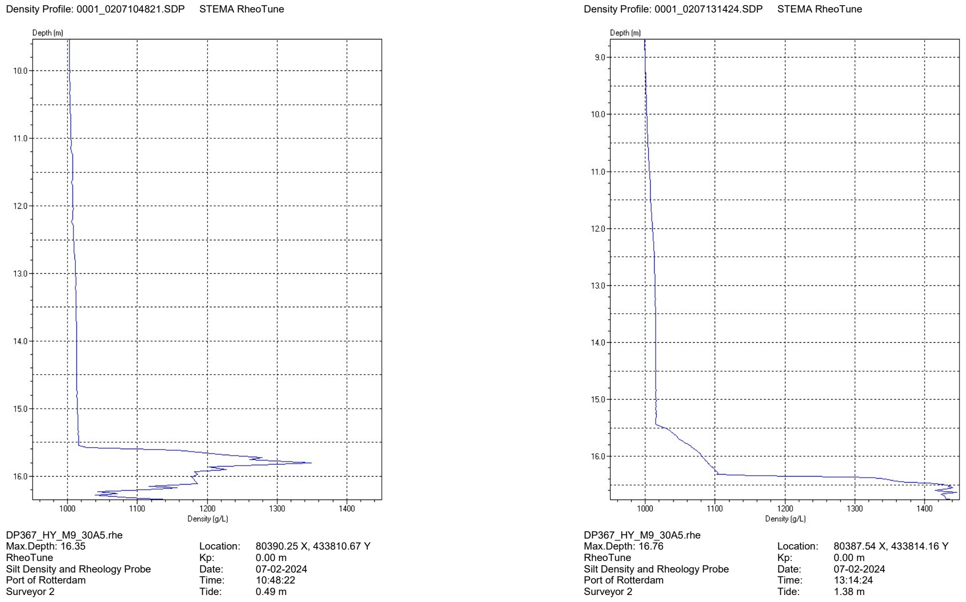
(f) Turbidity change MP 5

Figure 80: Turbidity changes at various MP locations

D.2 WID field tests

Density

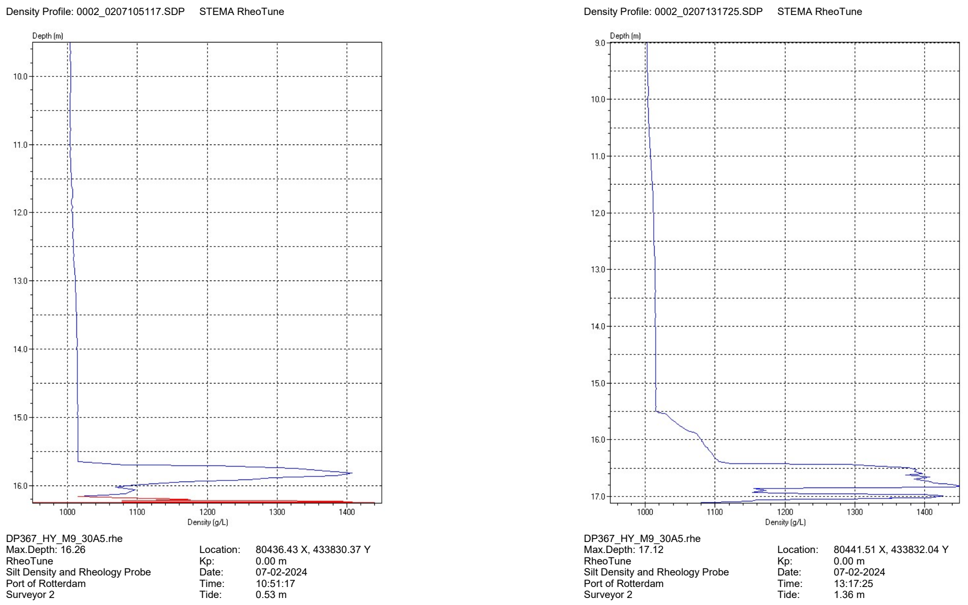
There should be noted for these density profiles that the horizontal axis shows density in g/L, which is equal to kg/m^3. The latter is the value that has been used in this whole research however, the profiles were compiled with a program that has g/L as standard unit for density.



(a) Before

(b) After

Figure 81: Density measurements at MP 1 before and after conditioning



Density Profile: 0002_0207105117.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.26
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80436.43 X, 433830.37 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 10:51:17
Tide: 0.53 m

Density Profile: 0002_0207131725.SDP STEMA RheoTune

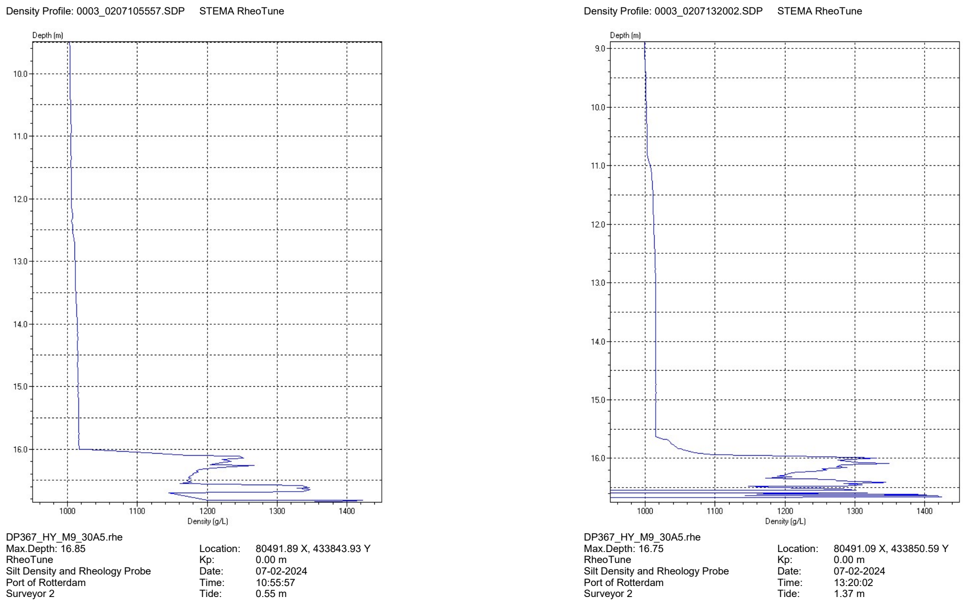
DP367_HY_M9_30A5.rhe
Max.Depth: 17.12
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80441.51 X, 433832.04 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 13:17:25
Tide: 1.36 m

(a) Before

(b) After

Figure 82: Density measurements at MP 2 before and after conditioning



Density Profile: 0003_0207105557.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.85
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80491.89 X, 433843.93 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 10:55:57
Tide: 0.55 m

Density Profile: 0003_0207132002.SDP STEMA RheoTune

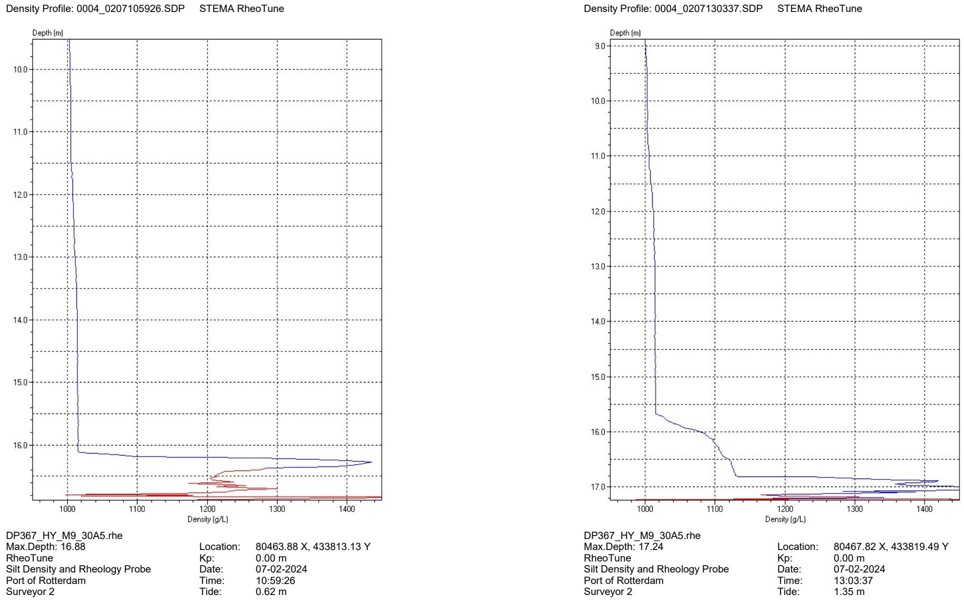
DP367_HY_M9_30A5.rhe
Max.Depth: 16.75
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80491.09 X, 433850.59 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 13:20:02
Tide: 1.37 m

(a) Before

(b) After

Figure 83: Density measurements at MP 3 before and after conditioning


Density Profile: 0004_0207105926.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.88
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80463.88 X, 433813.13 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 10:59:26
Tide: 0.62 m

Density Profile: 0004_0207130337.SDP STEMA RheoTune

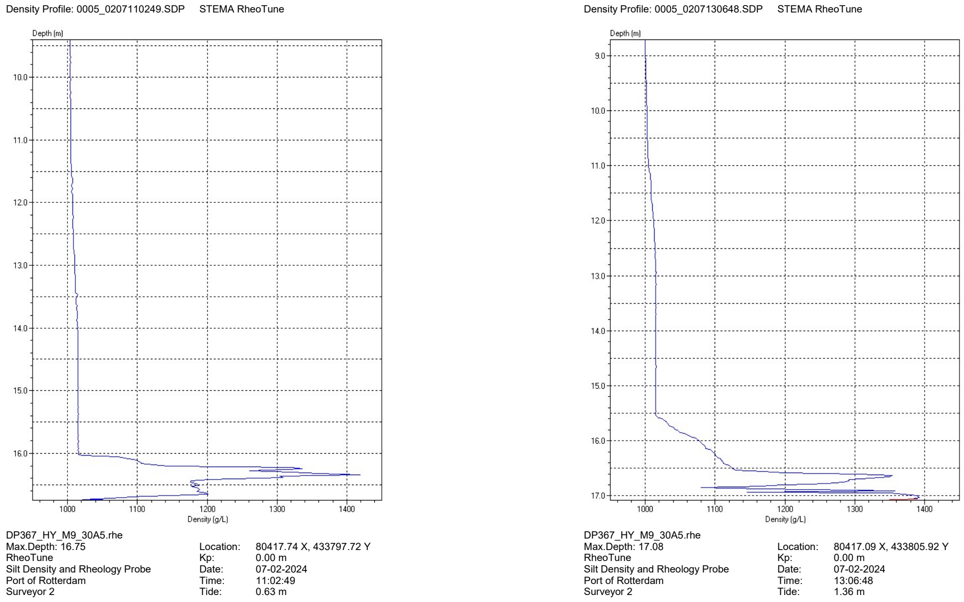
DP367_HY_M9_30A5.rhe
Max.Depth: 17.24
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80467.82 X, 433819.49 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 13:03:37
Tide: 1.35 m

(a) Before

(b) After

Figure 84: Density measurements at MP 4 before and after conditioning


Density Profile: 0005_0207110249.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.75
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80417.74 X, 433797.72 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 11:02:49
Tide: 0.63 m

Density Profile: 0005_0207130648.SDP STEMA RheoTune

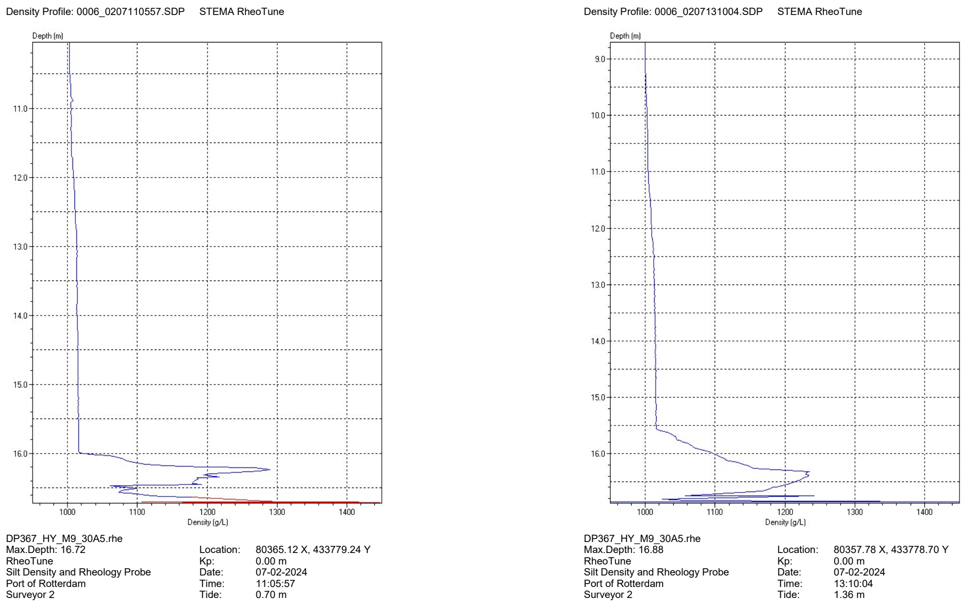
DP367_HY_M9_30A5.rhe
Max.Depth: 17.08
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80417.09 X, 433805.92 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 13:06:48
Tide: 1.36 m

(a) Before

(b) After

Figure 85: Density measurements at MP 5 before and after conditioning



Density Profile: 0006_0207110557.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.72
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80365.12 X, 433779.24 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 11:05:57
Tide: 0.70 m

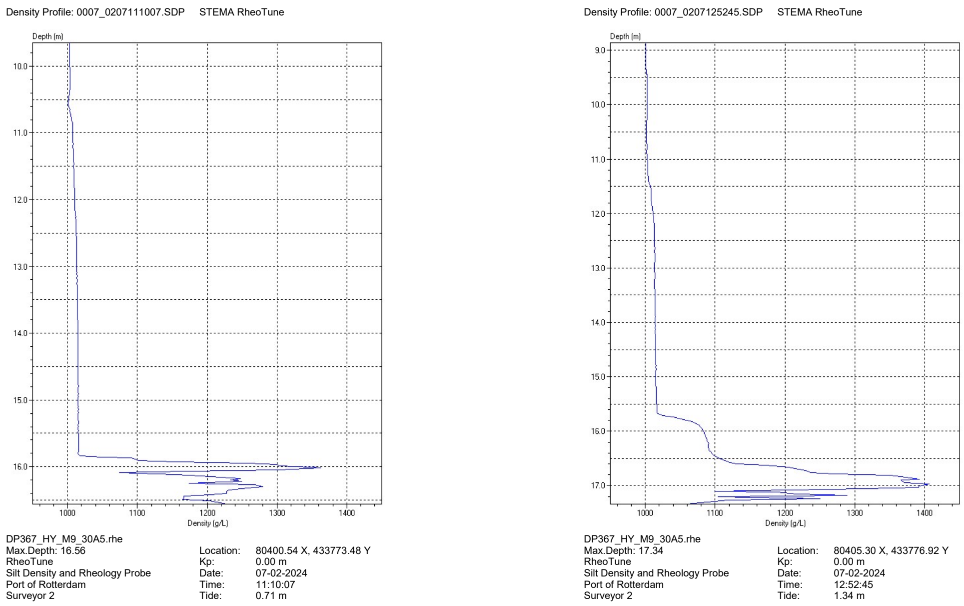
Density Profile: 0006_0207131004.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.88
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80357.78 X, 433778.70 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 13:10:04
Tide: 1.36 m

(a) Before (b) After

Figure 86: Density measurements at MP 6 before and after conditioning



Density Profile: 0007_0207111007.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.56
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80400.54 X, 433773.48 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 11:10:07
Tide: 0.71 m

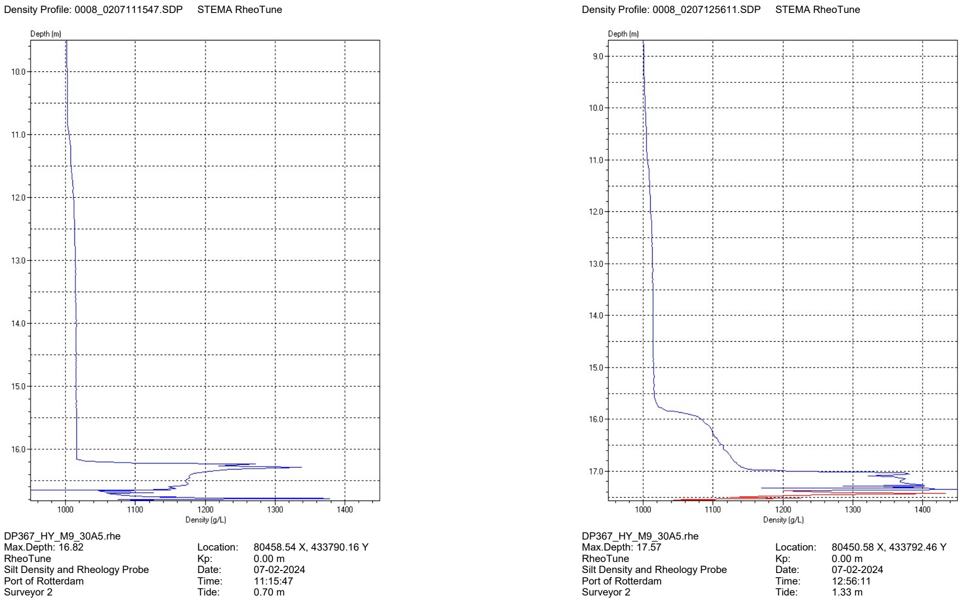
Density Profile: 0007_0207125245.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 17.34
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80405.30 X, 433776.92 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 12:52:45
Tide: 1.34 m

(a) Before (b) After

Figure 87: Density measurements at MP 7 before and after conditioning



DP367_HY_M9_30A5.rhe
Max.Depth: 16.82
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

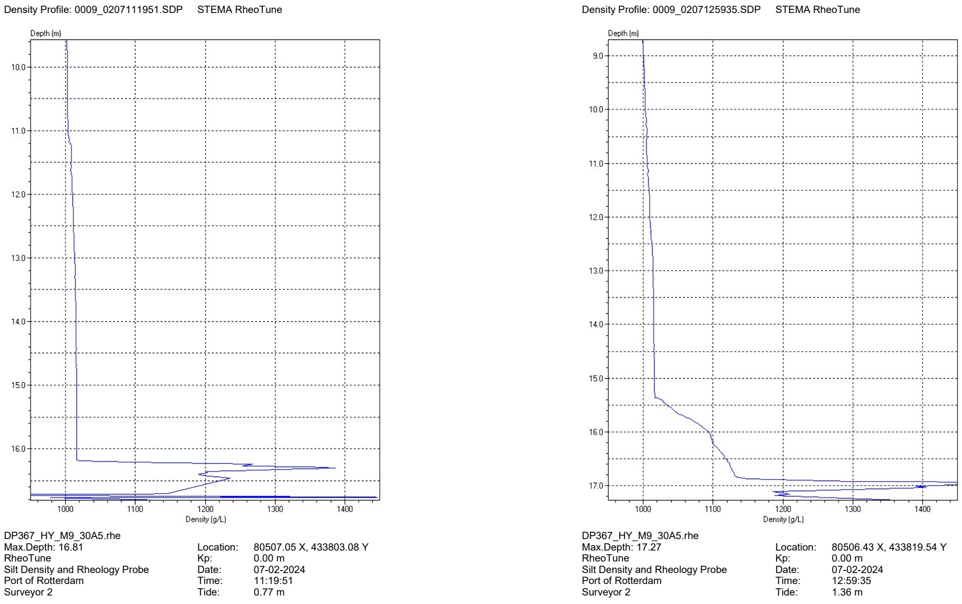
Location: 80458.54 X, 433790.16 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 11:15:47
Tide: 0.70 m

DP367_HY_M9_30A5.rhe
Max.Depth: 17.57
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80450.58 X, 433792.46 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 12:56:11
Tide: 1.33 m

(a) Before (b) After

Figure 88: Density measurements at MP 8 before and after conditioning



DP367_HY_M9_30A5.rhe
Max.Depth: 16.81
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80507.05 X, 433803.08 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 11:19:51
Tide: 0.77 m

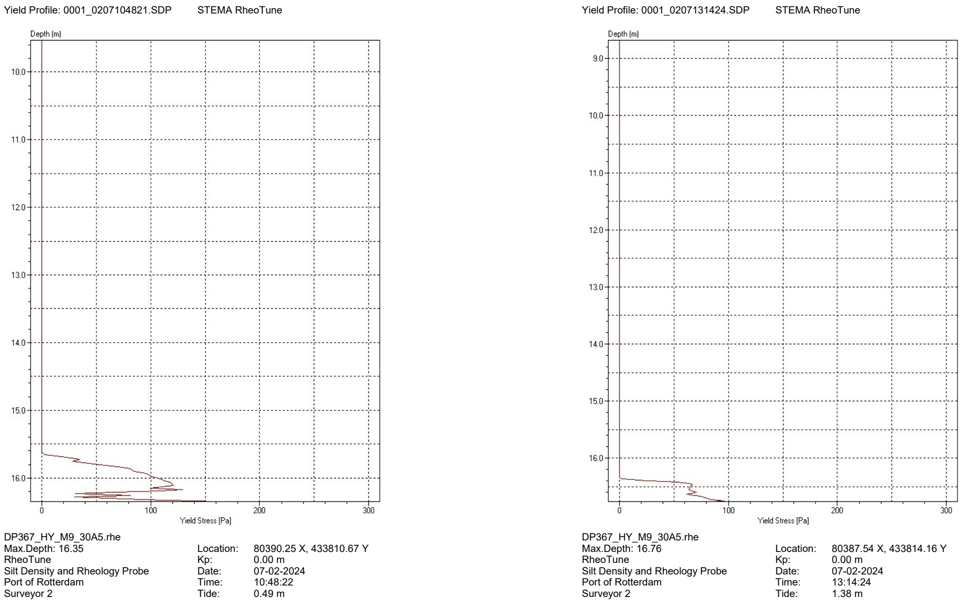
DP367_HY_M9_30A5.rhe
Max.Depth: 17.27
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80506.43 X, 433819.54 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 12:59:35
Tide: 1.36 m

(a) Before (b) After

Figure 89: Density measurements at MP 9 before and after conditioning

Stress distribution



Yield Profile: 0001_0207104821.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.35
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80390.25 X, 433810.67 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 10:48:22
Tide: 0.49 m

Yield Profile: 0001_0207131424.SDP STEMA RheoTune

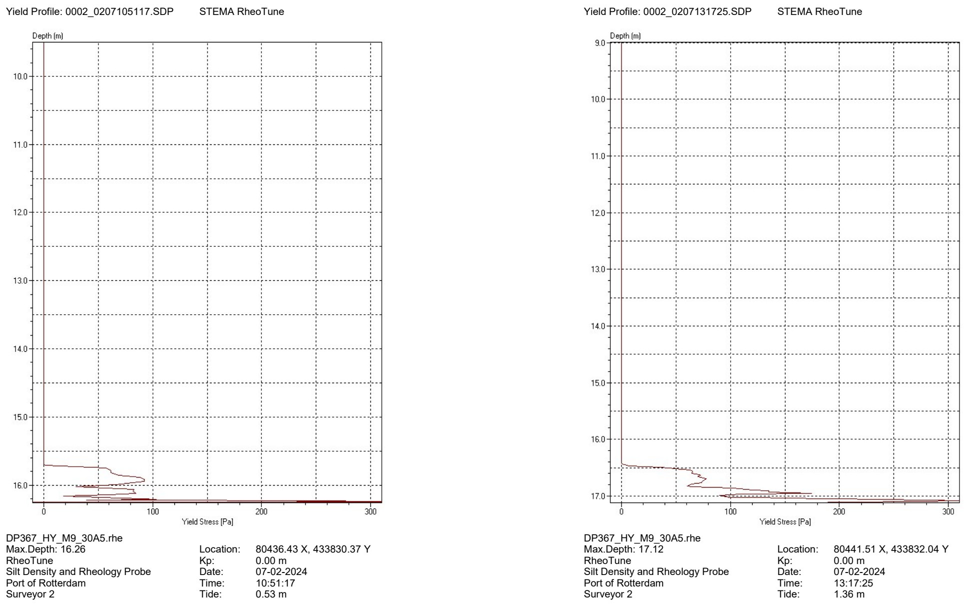
DP367_HY_M9_30A5.rhe
Max.Depth: 16.76
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80387.54 X, 433814.16 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 13:14:24
Tide: 1.38 m

(a) Before

(b) After

Figure 90: Stress measurements at MP 1 before and after conditioning


Yield Profile: 0002_0207105117.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.26
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80436.43 X, 433830.37 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 10:51:17
Tide: 0.53 m

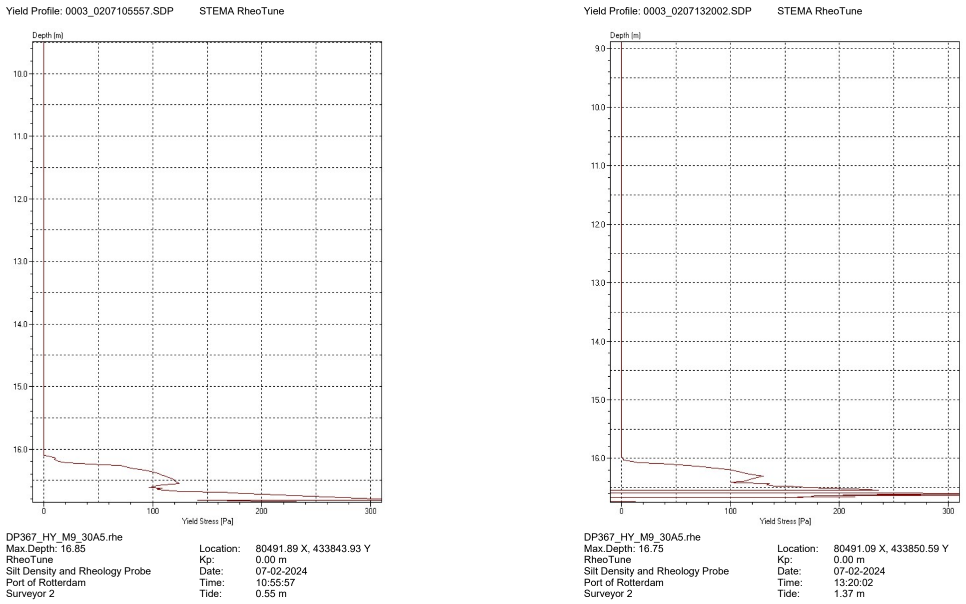
Yield Profile: 0002_0207131725.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 17.12
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80441.51 X, 433832.04 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 13:17:25
Tide: 1.36 m

(a) Before (b) After

Figure 91: Stress measurements at MP 2 before and after conditioning


Yield Profile: 0003_0207105557.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.85
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80491.89 X, 433843.93 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 10:55:57
Tide: 0.55 m

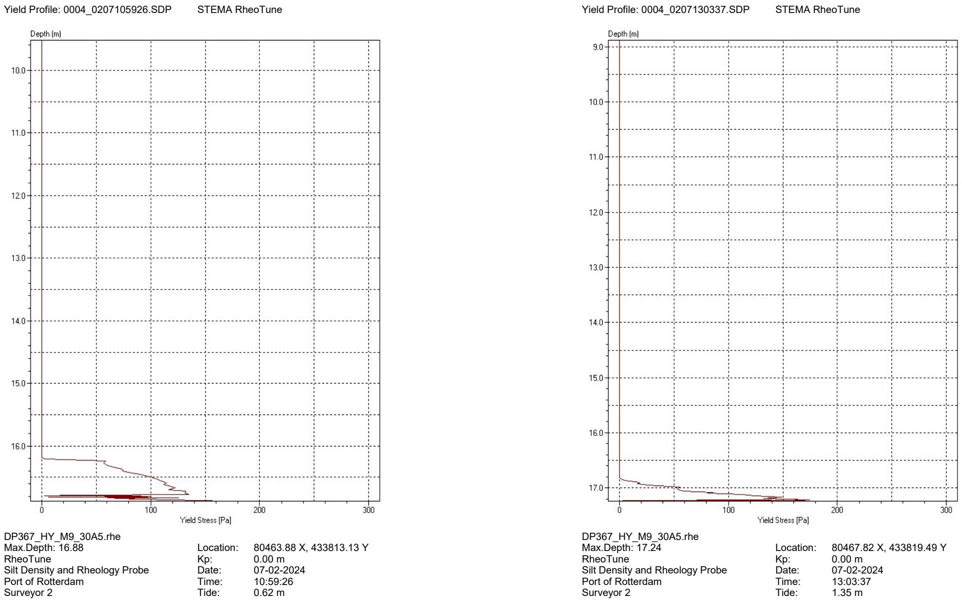
Yield Profile: 0003_0207132002.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.75
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80491.09 X, 433850.59 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 13:20:02
Tide: 1.37 m

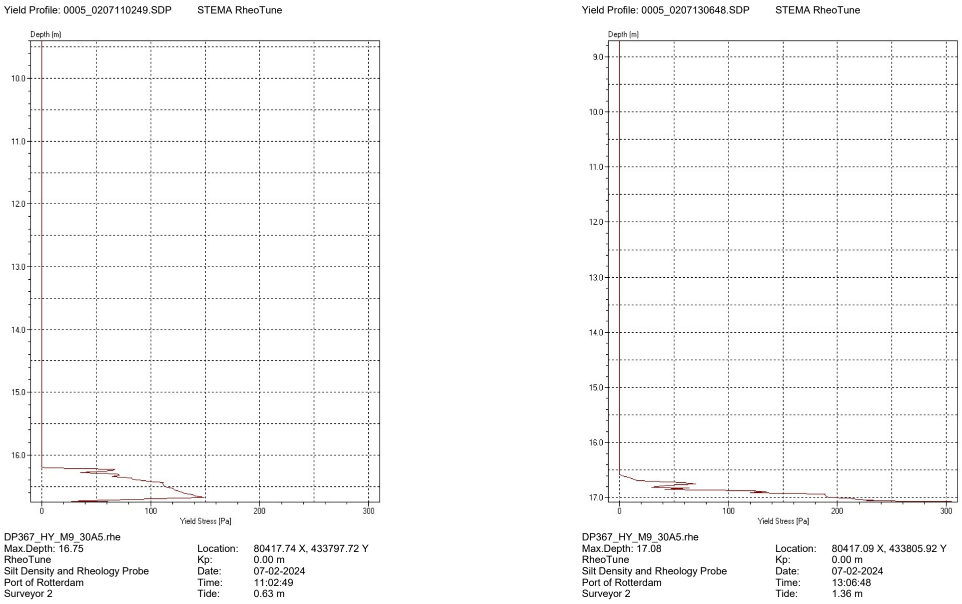
(a) Before (b) After

Figure 92: Stress measurements at MP 3 before and after conditioning



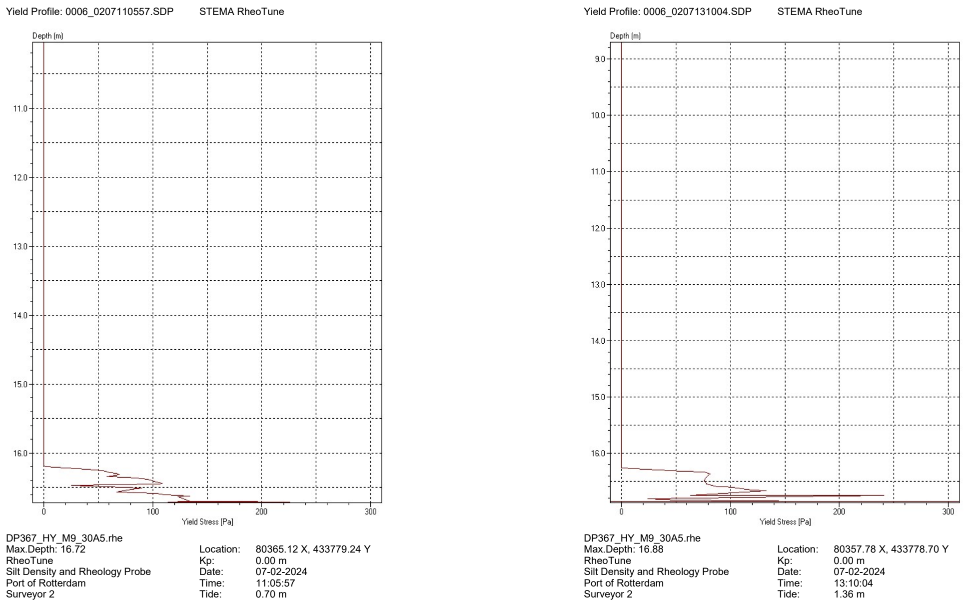
(a) Before (b) After

Figure 93: Stress measurements at MP 4 before and after conditioning



(a) Before (b) After

Figure 94: Stress measurements at MP 5 before and after conditioning



Yield Profile: 0006_0207110557.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.72
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80365.12 X, 433779.24 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 11:05:57
Tide: 0.70 m

Yield Profile: 0006_0207131004.SDP STEMA RheoTune

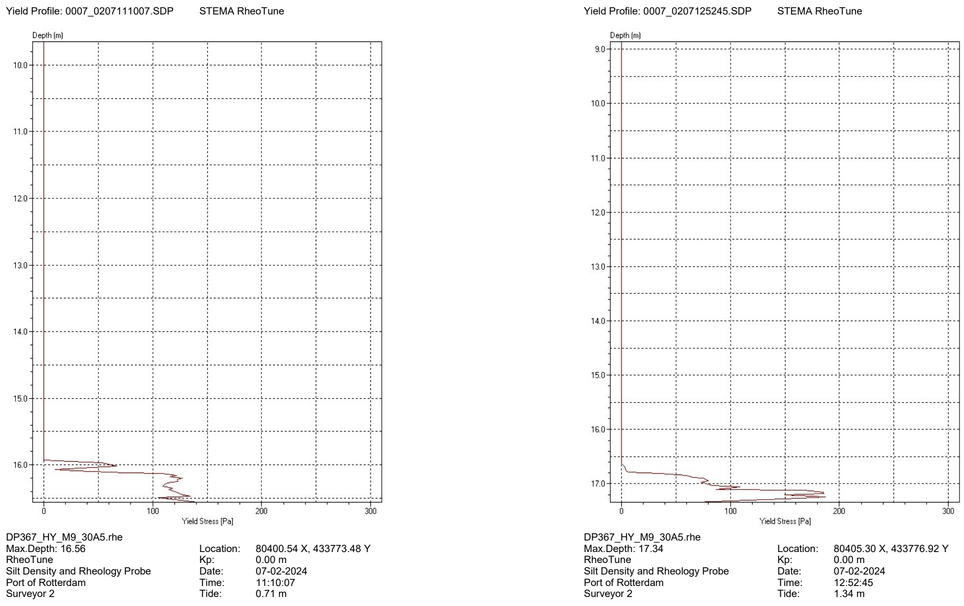
DP367_HY_M9_30A5.rhe
Max.Depth: 16.88
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80357.78 X, 433778.70 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 13:10:04
Tide: 1.36 m

(a) Before

(b) After

Figure 95: Stress measurements at MP 6 before and after conditioning



Yield Profile: 0007_0207111007.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.56
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80400.54 X, 433773.48 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 11:10:07
Tide: 0.71 m

Yield Profile: 0007_0207125245.SDP STEMA RheoTune

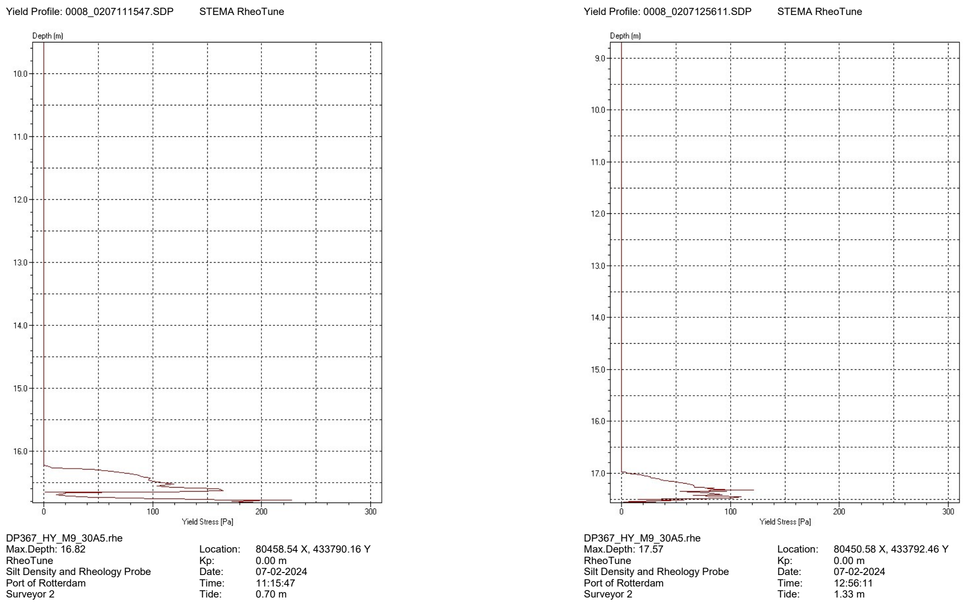
DP367_HY_M9_30A5.rhe
Max.Depth: 17.34
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80405.30 X, 433776.92 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 12:52:45
Tide: 1.34 m

(a) Before

(b) After

Figure 96: Stress measurements at MP 7 before and after conditioning



Yield Profile: 0008_0207111547.SDP STEMA RheoTune

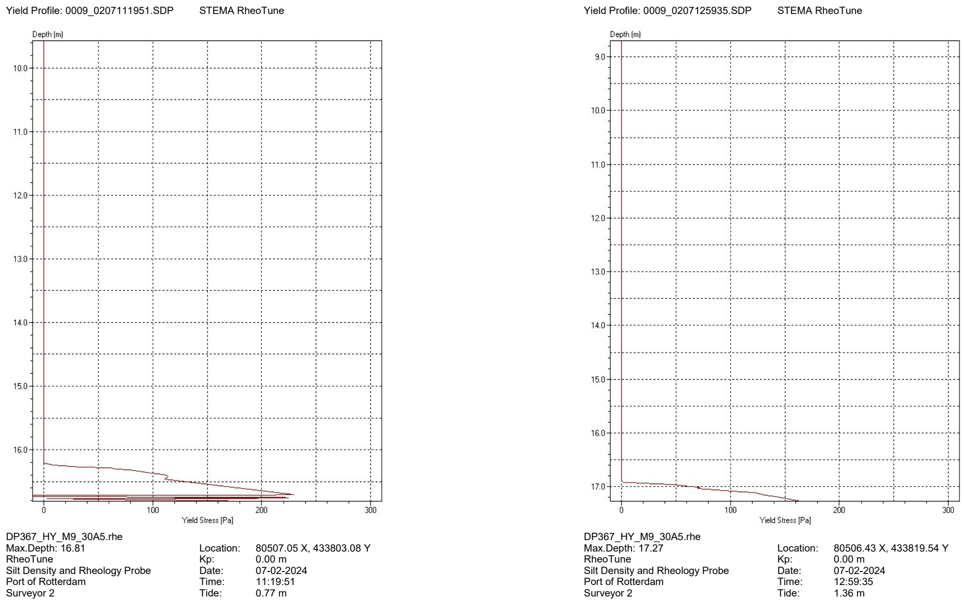
DP367_HY_M9_30A5.rhe
Max.Depth: 16.82
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2
Location: 80458.54 X, 433790.16 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 11:15:47
Tide: 0.70 m

Yield Profile: 0008_0207125611.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 17.57
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2
Location: 80450.58 X, 433792.46 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 12:56:11
Tide: 1.33 m

(a) Before (b) After

Figure 97: Stress measurements at MP 8 before and after conditioning



Yield Profile: 0009_0207111951.SDP STEMA RheoTune

DP367_HY_M9_30A5.rhe
Max.Depth: 16.81
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2
Location: 80507.05 X, 433803.08 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 11:19:51
Tide: 0.77 m

Yield Profile: 0009_0207125935.SDP STEMA RheoTune

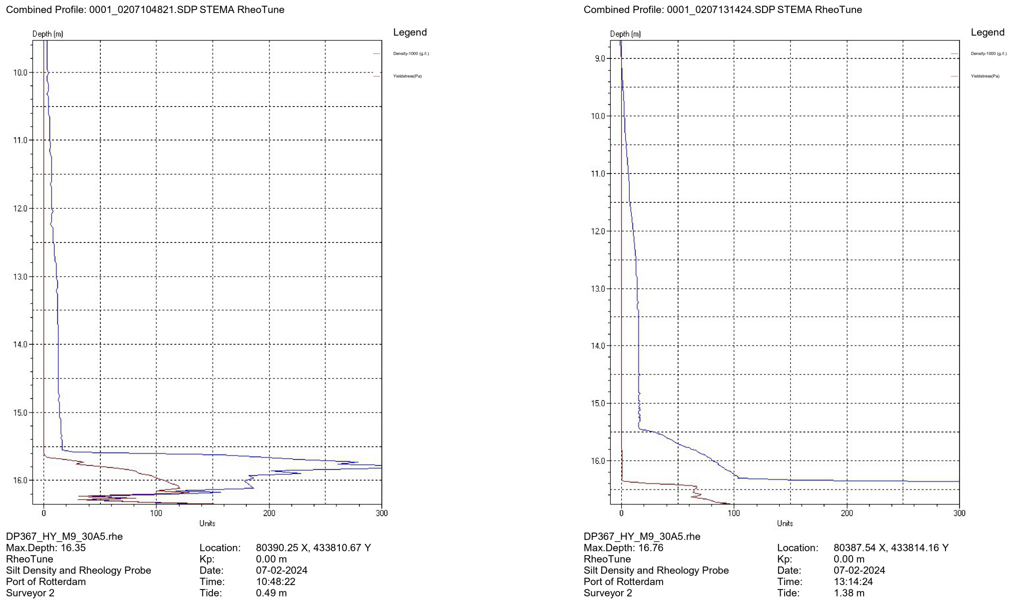
DP367_HY_M9_30A5.rhe
Max.Depth: 17.27
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2
Location: 80506.43 X, 433819.54 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 12:59:35
Tide: 1.36 m

(a) Before (b) After

Figure 98: Stress measurements at MP 9 before and after conditioning

Combined profiles

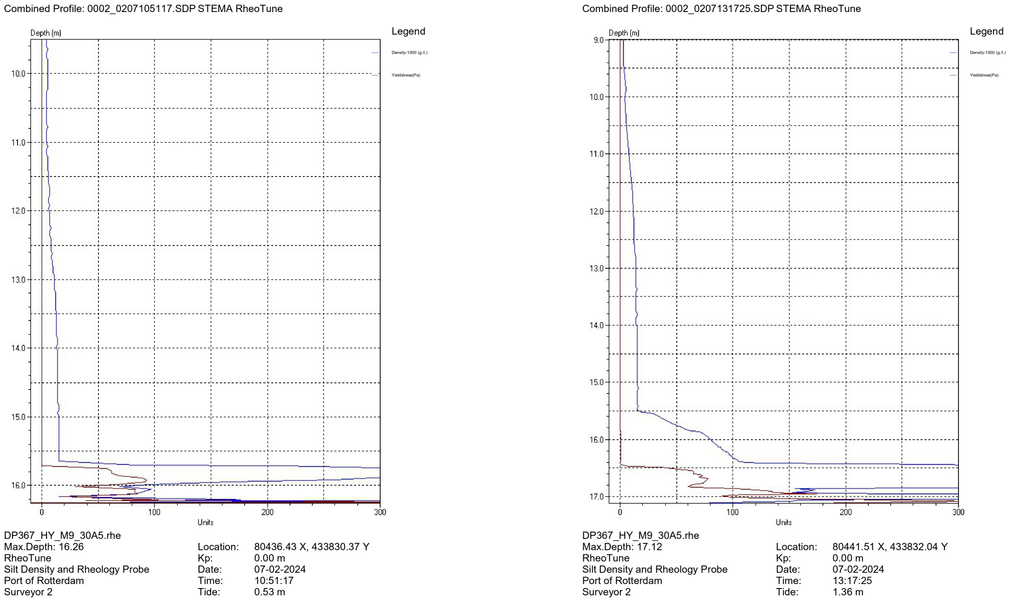
There should be noted for the combined density and yield stress profiles that the blue line represents the density and the red line yield stress. The vertical axis shows depth and horizontal axis a unit that represents both stress in Pa and density in kg/m^3. For the latter, a value of 1000 kg/m^3 should be added to obtain the real density values.



(a) Before

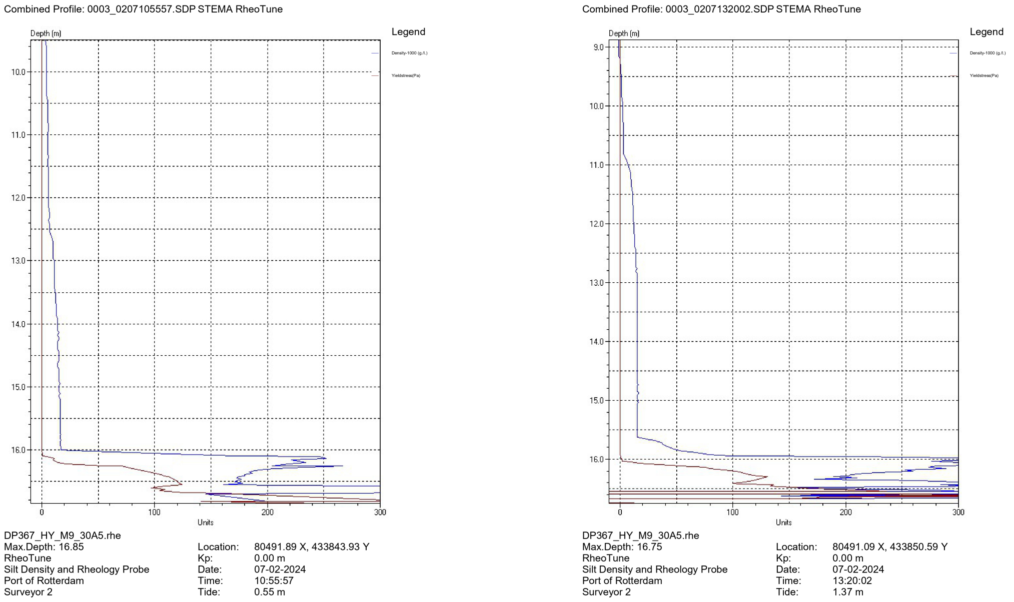
(b) After

Figure 99: Density/stress at MP 1 before and after conditioning



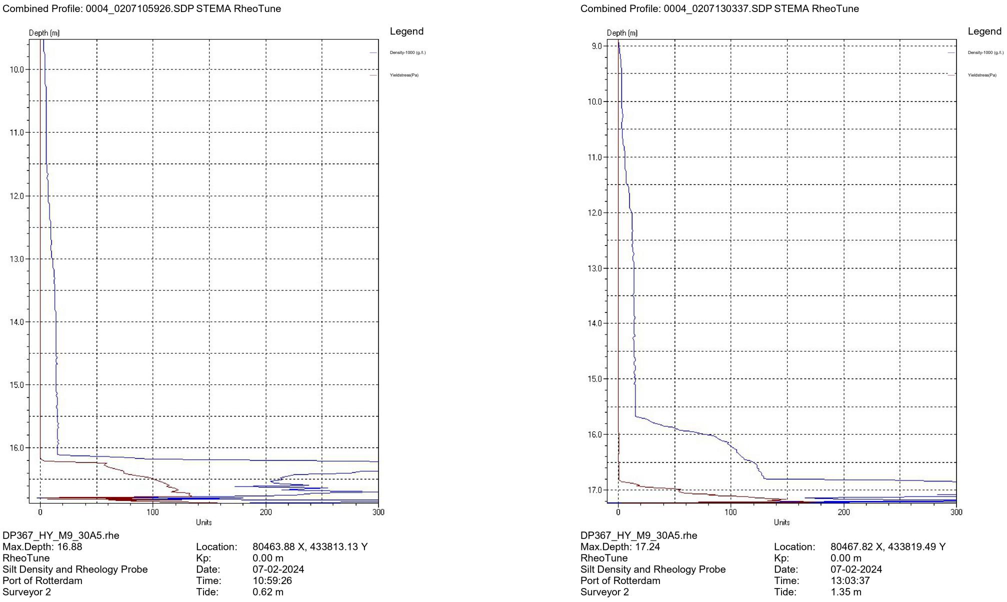
(a) Before (b) After

Figure 100: Density/stress at MP 2 before and after conditioning



(a) Before (b) After

Figure 101: Density/stress at MP 3 before and after conditioning



DP367_HY_M9_30A5.rhe
Max.Depth: 16.88
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80463.88 X, 433813.13 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 10:59:26
Tide: 0.62 m

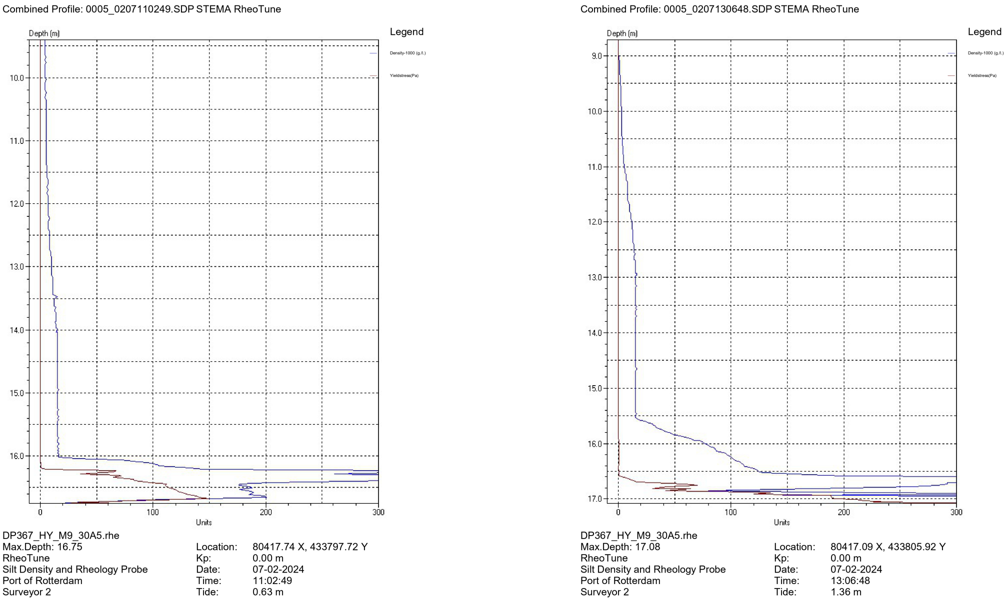
DP367_HY_M9_30A5.rhe
Max.Depth: 17.24
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80467.82 X, 433819.49 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 13:03:37
Tide: 1.35 m

(a) Before

(b) After

Figure 102: Density/stress at MP 4 before and after conditioning



DP367_HY_M9_30A5.rhe
Max.Depth: 16.75
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80417.74 X, 433797.72 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 11:02:49
Tide: 0.63 m

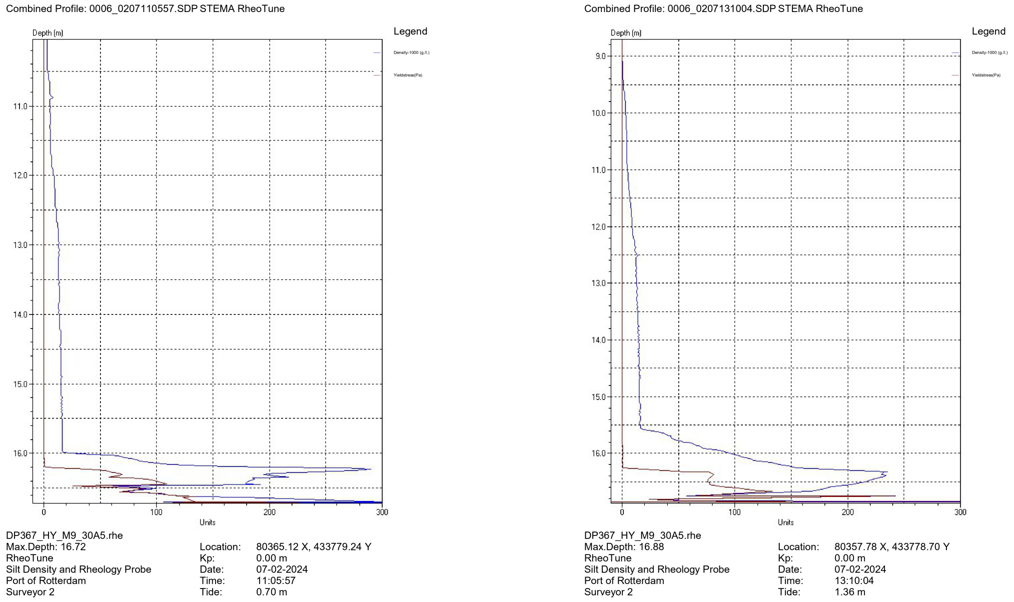
DP367_HY_M9_30A5.rhe
Max.Depth: 17.08
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80417.09 X, 433805.92 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 13:06:48
Tide: 1.36 m

(a) Before

(b) After

Figure 103: Density/stress at MP 5 before and after conditioning



DP367_HY_M9_30A5.rhe
Max.Depth: 16.72
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80365.12 X, 433779.24 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 11:05:57
Tide: 0.70 m

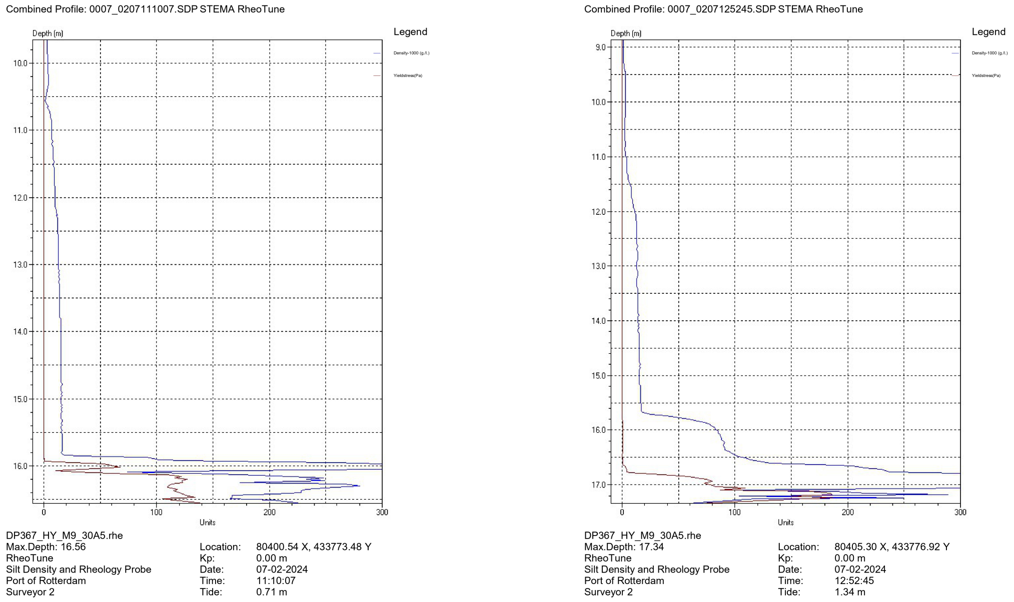
DP367_HY_M9_30A5.rhe
Max.Depth: 16.88
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80357.78 X, 433778.70 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 13:10:04
Tide: 1.36 m

(a) Before

(b) After

Figure 104: Density/stress at MP 6 before and after conditioning



DP367_HY_M9_30A5.rhe
Max.Depth: 16.56
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80400.54 X, 433773.48 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 11:10:07
Tide: 0.71 m

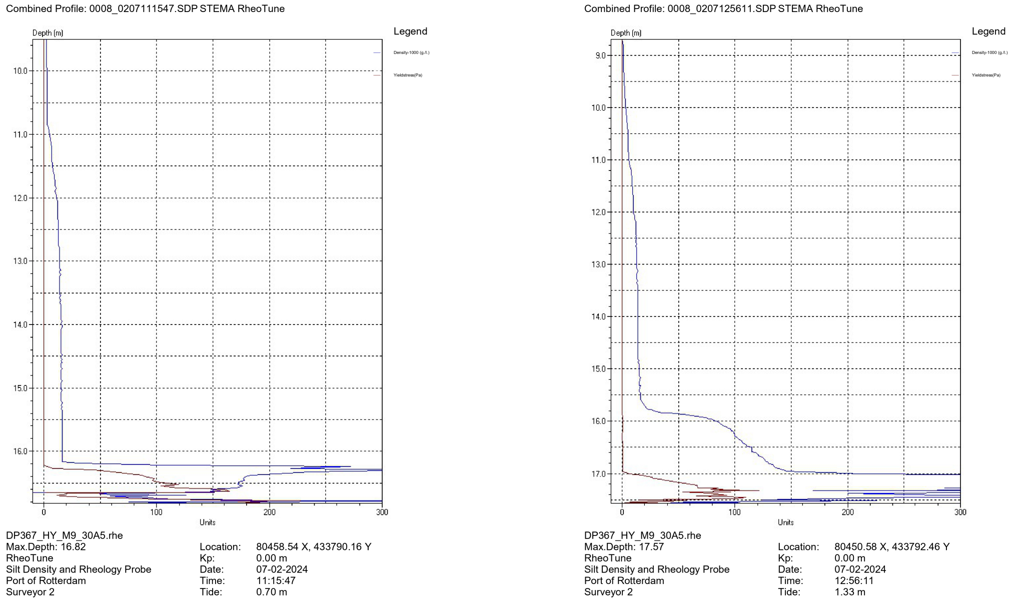
DP367_HY_M9_30A5.rhe
Max.Depth: 17.34
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80405.30 X, 433776.92 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 12:52:45
Tide: 1.34 m

(a) Before

(b) After

Figure 105: Density/stress at MP 7 before and after conditioning



DP367_HY_M9_30A5.rhe
Max.Depth: 16.82
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

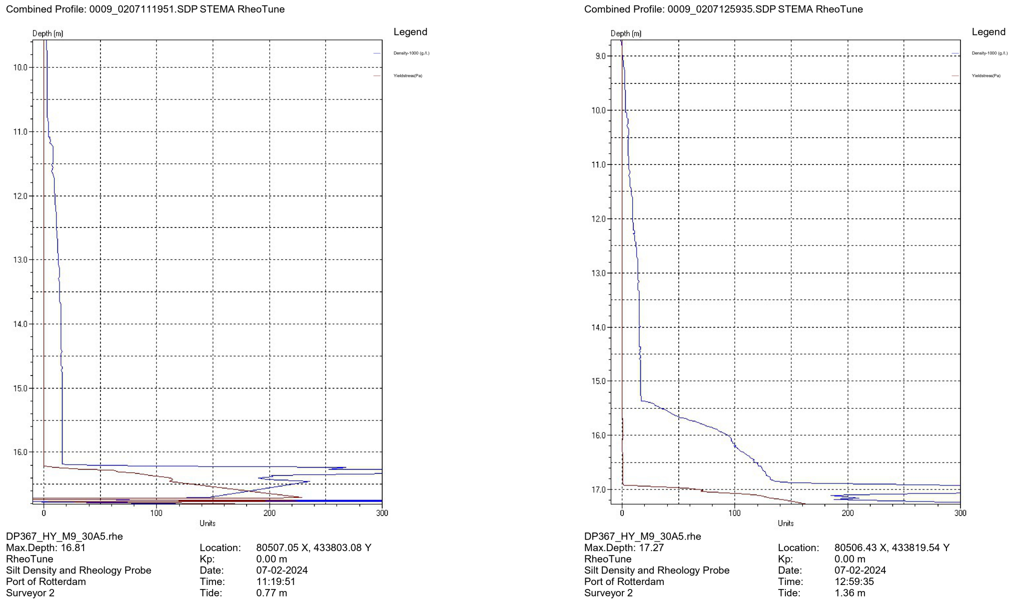
Location: 80458.54 X, 433790.16 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 11:15:47
Tide: 0.70 m

DP367_HY_M9_30A5.rhe
Max.Depth: 17.57
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80450.58 X, 433792.46 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 12:56:11
Tide: 1.33 m

(a) Before (b) After

Figure 106: Density/stress at MP 8 before and after conditioning



DP367_HY_M9_30A5.rhe
Max.Depth: 16.81
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

Location: 80507.05 X, 433803.08 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 11:19:51
Tide: 0.77 m

DP367_HY_M9_30A5.rhe
Max.Depth: 17.27
RheoTune
Silt Density and Rheology Probe
Port of Rotterdam
Surveyor 2

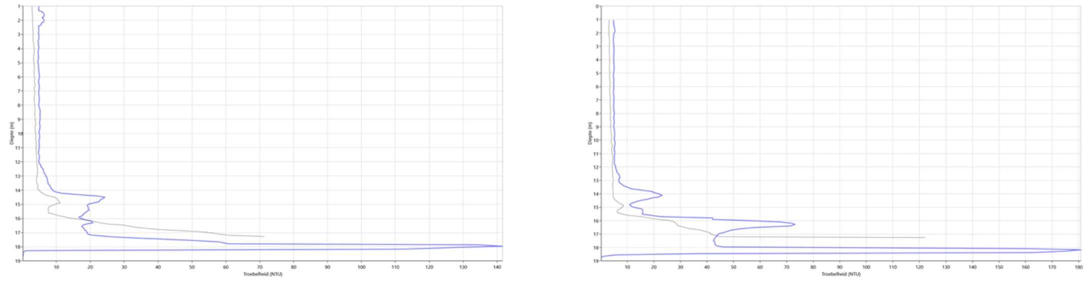
Location: 80506.43 X, 433819.54 Y
Kp: 0.00 m
Date: 07-02-2024
Time: 12:59:35
Tide: 1.36 m

(a) Before (b) After

Figure 107: Density/stress at MP 9 before and after conditioning

Turbidity

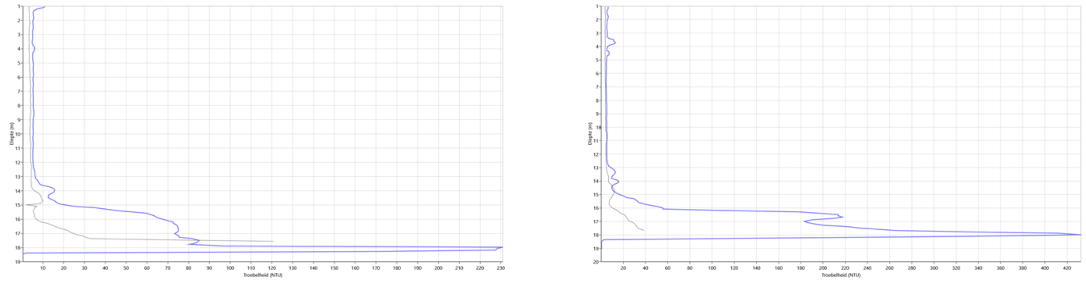
There should be noticed that for the following figures representing the turbidity profile at each measuring point, the horizontal axis is for turbidity (NTU) and the vertical axis is for depth (m). This is not perfectly readable from the figures.



(a) MP 1

(b) MP 2

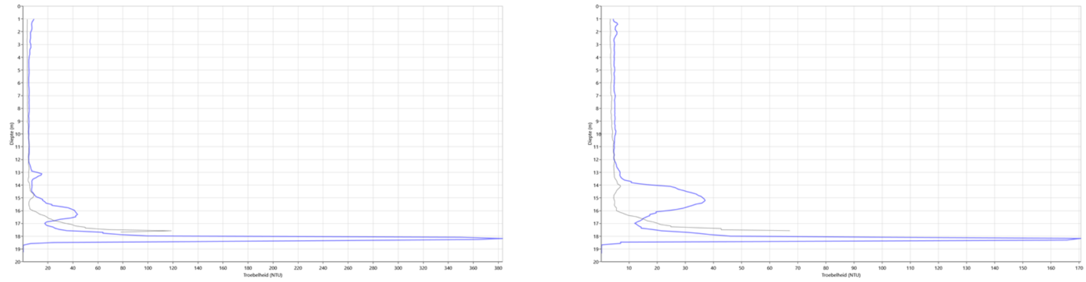
Figure 108: Turbidity change



(a) MP 3

(b) MP 4

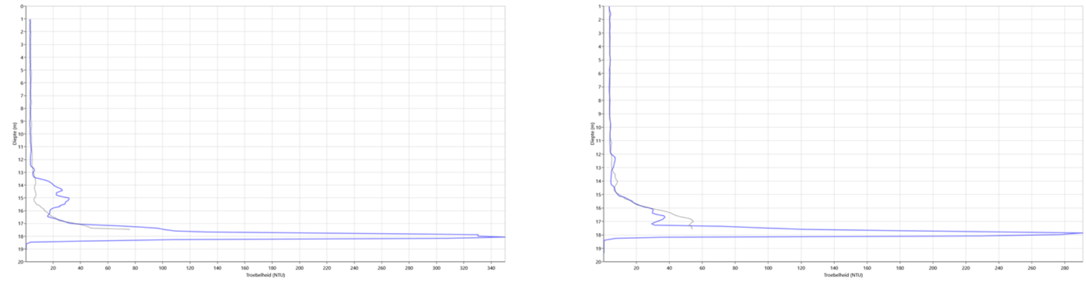
Figure 109: Turbidity change



(a) MP 5

(b) MP 6

Figure 110: Turbidity change



(a) MP 7

(b) MP 8

Figure 111: Turbidity change

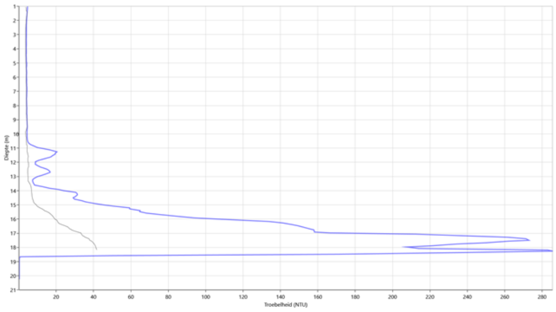


Figure 112: Turbidity change at MP 9