

MSc Thesis in Offshore and Dredging Engineering

Contained Dredging System as a solution for turbidity

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CONTAINED DREDGING SYSTEM

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ABSTRACT

This thesis aims to investigate the effectiveness of the contained dredging system (CDS) in avoiding turbidity during dredging activities. Turbidity is a common issue that arises during dredging activities and causes the sediment to be suspended in the water column, which can have negative impacts on the environment. The CDS is a novel way of dredging that focuses on avoiding turbidity, and it has been developed by Hydrex, an Antwerp-based firm. The research aims to determine whether the CDS provides a solution to the environmental problems associated with turbidity at contaminated sites. The research methodology involves conducting a literature study, theoretical analysis, and real-life testing of the CDS. The main research question is "To what extent does the CDS create turbidity?", and a set of sub-questions is formulated to answer the main research question.

Based on the analysis and findings presented in this thesis, it can be concluded that dredging activities can have a negative impact on the environment through the generation of turbidity. Traditional dredging techniques such as the clamshell, backhoe, trailing suction hopper dredger (TSHD), and cutter suction dredger (CSD) all create turbidity to varying degrees. However, methods such as silt curtains, sedimentation ponds, polymer flocculants, pH adjustment, vegetation buffers, and bio-engineering can be used to minimize the spread of sediment and reduce turbidity levels. Furthermore, new dredging techniques have been developed to minimize turbidity.

The contained dredging system (CDS) was developed to minimize the negative impact of dredging on the environment by focusing on avoiding turbidity by dredging within an air chamber. However, the theoretical analysis of the CDS showed that it creates turbidity when the critical height of the dredged wall is exceeded. The CDS was designed to create no turbidity, but the theory and calculations presented in this thesis suggest that it does create turbidity.

In conclusion, the CDS, although developed with good intentions, does not fulfill its requirement of not creating turbidity. The device creates turbidity due to the low critical height of the vertical wall, which will collapse after dredging. However, the CDS could still be used in non-sensitive areas or in very polluted areas where accurate dredging is necessary.

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1

INTRODUCTION

1.1 BACKGROUND

Turbidity is silt and sediment stirred up into the water column and is a common issue associated with dredging projects [Nechad et al., 2009]. Turbidity can have negative effects on the environment [Pennekamp and Quaak, 1990], including the potential loss of flora and fauna, impact on fish production, and long-term damage to coral [Henricson et al., 2006; Dodge and Vaisnys, 1977].

The increased pollution of waterways has necessitated the development of innovative types of dredging equipment that avoid turbidity, because at contaminated sites polluted sediment can spread uncontrollably when turbidity occurs [Bray, 2008a; Pennekamp, 1996; Pennekamp and Quaak, 1990; Bray et al., 1997]. Moreover, the need to avoid turbidity has been highlighted by increased public awareness of possible impact of dredging projects. Luckily, there was also knowledge gained to manage turbidity in a better way. Today's research is done before a dredging project, to know how the impact of turbidity can be minimized. However, the goal should not be to minimize the impact of turbidity but to avoid turbidity.

It was against this background that the contained dredging system (CDS) was developed. Figure 1.1 illustrates the CDS schematically. The CDS is a novel way of dredging. It has been developed by Hydrex, an Antwerp-based firm. This technique focuses on avoiding turbidity so contaminated sites could be dredged without any risk. The CDS is a dredger that dredges within an air chamber. By using an air chamber, the dredging itself happens inside a contained system. This means that because of this dredging process, turbidity is created inside the chamber but no turbidity can escape to the environment. The CDS will be examined in this thesis because it is crucial to know whether or not it fulfills its promise of not creating turbidity.

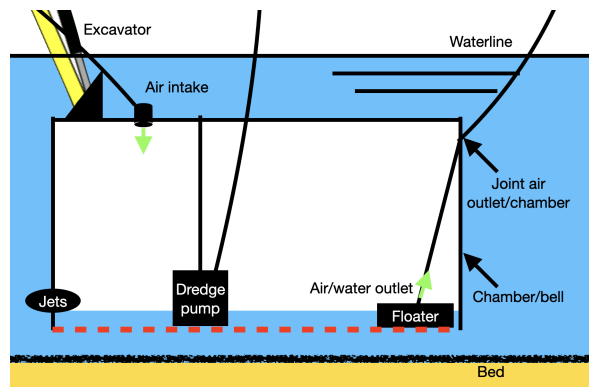


Figure 1.1: Contained dredging system schematically

1.2 RESEARCH AIM AND METHODOLOGY

The aim of this research is to investigate whether or not the CDS is a promising concept of dredging and if it provides a solution to the environmental problems turbidity caused at contaminated sites. The main research question of this thesis is: **"To what extent does the CDS create turbidity?"**.

To reach a conclusion on the main research question, a set of sub-questions is formulated.

1. What can be the impact of turbidity on the environment?
2. How do the existing dredging mechanisms generate turbidity? What existing methods do exist to prevent turbidity and its negative consequences?
3. How does the CDS work?
 - a) How is the pressure in the CDS balanced? As the chamber is filled with air, the pressure inside the chamber must be equal to its surrounding. Therefore, it is interesting to understand the mechanics behind maintaining balanced pressure within the CDS, as the chamber is filled with air and must maintain equilibrium with its surroundings.
 - b) When and how does the CDS generate turbidity during its dredging process? The CDS is designed to avoid generating turbidity. Research is needed to prove that before and after the CDS is placed and is dredging, the CDS does not create turbidity.
4. How does the turbidity induced by CDS relate to turbidity induced by the existing dredging tools?

To answer these question a mixed methodology of literature review, theoretical analysis and real life testing of CDS will be used. In [Chapter 2](#), the existing literature is used to give a definition of turbidity and its impacts on fauna and flora. In this chapter, contaminated sediments and its implications on the environment will also be explained. Moreover, several methods of minimizing the impact of turbidity will be discussed. [Chapter 3](#) discusses existing dredging techniques to places turbidity and dredging in a wider context. In [Chapter 4](#), the CDS will be presented together with its working principles. In [Chapter 5](#), a theoretical analysis will be done to prove whether or not the CDS is capable to do what it is designed for. [Chapter 6](#) reflects on the theoretical basis described in previous chapters by introducing and analyzing real life tests.

2

TURBIDITY AND THE IMPACTS OF DREDGING

This chapter elaborates on the impact of turbidity on the environment. Furthermore, current methods for dealing with dredging induced turbidity will be discussed. In [Figure 2.1](#), a photo is shown of a turbidity plume.



Figure 2.1: Turbidity plume [[Andrady et al., 2016](#)]

2.1 TURBIDITY AND FLORA

Turbidity can harm vegetation by restricting light penetration and decreasing photosynthetic rates. This loss in light can considerably reduce aquatic plant and algal productivity, resulting in changes in the content and structure of the aquatic flora [[Greenwood et al., 2017](#)]. Several studies have found that high turbidity levels can reduce aquatic plant growth and biomass, particularly in shallow water environments [[Wolf et al., 2013](#); [Wagner et al., 2017](#)]. The intensity and length of the turbidity event, as well as the species composition and ecological features of the impacted plant community, will determine the amount of this influence on aquatic flora.

Turbidity's effects on plant communities can also differ depending on the type of plant. Some plants may be more resistant to turbidity events due to adaptations such as deeper rooting systems, whereas others may be more sensitive and experience significant growth and survival declines [[Johnson and Kelble, 2016](#)]. Furthermore, turbidity can influence plant species competition by altering light availability and the availability of nutrients and other resources [[Chen et al., 2015](#)]. This can cause changes in community composition and the dominance of specific plant species, potentially affecting the entire ecosystem.

Turbidity events can also have an indirect impact on aquatic flora by interfering with the food webs that promote plant growth. High turbidity, for example, can diminish zooplankton quantity and variety, which are essential grazers of algae and other small aquatic plants [[Wagner et al., 2017](#)]. Reduced zooplankton populations can cause greater algal blooms and changes in plant community structure, resulting in a cascade of consequences [[Wolf et al., 2013](#)].

One of the best known effects of turbidity is on coral. In murky water, coral-associated damselfish were unable to identify living coral, a function that requires both visual acuity and chemoreception. This is particularly essential for species having a pelagic larval phase in which the capacity to select adequate habitat is critical for development and survival in the early stages of life. If a fish settles in a poor environment, it becomes more vulnerable to predators and grows at a slower pace, which can have serious consequences for the adult population [Coker et al., 2009; Wilson et al., 2008]. For coral the sensitivity to sedimentation and turbidity, depends on the intensity, duration, and frequency of exposure. Coral reefs' ability to recover and their sensitivity depends on their antecedent ecological conditions and resilience. Different coral species have varying degrees of tolerance to sedimentation and turbidity, and site-specific evaluations are necessary to limit the extent of turbidity plumes and their effects on corals [Erftemeijer et al., 2012].

Another well known consequence of turbidity is the effect on seagrasses [Johnston, 1981]. For example, in indigenous species of seagrass. *P. Oceanica*, can be found in protected regions around the Port of Genoa. This species cannot tolerate any sedimentary regime changes greater than the natural sediment fluctuations [Cutroneo et al., 2012].

However, in situations where there is an excess of respiration over photosynthesis, the addition of turbid material to the water column can indirectly boost photosynthesis. The inorganic nutrients in the turbid water can stimulate photosynthesis in such circumstances [Sherk et al., 1975]. Most often, when severe turbidity interferes with photosynthesis, phytoplankton, attached algae, and rooted vegetation are destroyed, removing the food source for estuarine ecosystems [Darnell, 1976]. The clumping and flocculation of resuspended particles that settle out on the bottom could potentially lead to a decline in plankton populations [Simon and Dyer, 1972].

Overall, the detrimental effects of turbidity on aquatic ecosystems emphasize the significance of regulating human activities that might result in turbidity occurrences, such as land use changes and development near waterways. Additionally, efforts to restore and protect aquatic plant communities can aid in the preservation of these ecosystems' integrity and function in the face of turbidity and other disturbances.

2.2 TURBIDITY AND FAUNA

Turbidity is known to have a variety of negative effects on aquatic wildlife. One of the most notable effects is a reduction in the capacity of fish and other aquatic species to identify prey and avoid predators. Visibility is decreased in turbid water, making it difficult for predators to identify prey and for prey to recognize and escape their predators. This can lead to increased predation and worse survival rates for many fish and other aquatic creatures. Fish avoid turbid waters, and studies have shown that increased turbidity levels can induce significant behavioral changes, such as decreased feeding and territorial defense. The presence of turbidity in the Sea of Marmara, for example, caused mackerel to disappear. Similarly, a rise in turbidity caused in the Dutch Wadden Sea resulted in a shift in dominance between Common dab and European plaice [Wenger et al., 2017; De Jonge et al., 1993].

Turbidity can also diminish the quantity of light reaching underwater plants, limiting their growth and reproductive success. As a result, increasing turbidity can have a substantial influence on the food supplies and habitats of many aquatic

creatures. Furthermore, turbidity-induced sedimentation can suffocate and bury benthic organisms such as mollusks and crustaceans, as well as their food sources.

Furthermore, increased turbidity and sedimentation can impair the ability of some aquatic organisms, such as filter feeders, to obtain food, resulting in slower growth and reproduction rates. In addition, increased turbidity can have an indirect impact on aquatic animal health by altering water chemistry and nutrient cycles, which can negatively impact the growth and reproduction rates of many species. Regardless of their environment of origin, several species showed substantial behavioral reactions at turbidity concentrations as low as 20mg/L, suggesting that turbidity is likely to cause major behavioral changes [Wenger et al., 2017]. At increasing levels of turbidity, foraging success usually decreases [Johansen and Jones, 2013]. Fish that are unable to use their whole home range owing to higher suspended sediment suffer fitness penalties in the form of reduced foraging and territorial defense [Wenger et al., 2017].

The capacity of fish to return to a disturbed region is largely reliant on the environment's ability to restore itself to pre-disturbance conditions, the availability of alternative appropriate habitats, and the species' ecological plasticity [Wenger et al., 2017]. One of the consequences of fish avoiding turbidity is a detrimental influence on local fisheries. Large concentrations of turbidity, for example, have been related to a 3-7 fold drop in Atlantic sturgeon (*Acipenser Oxyrinchus*, *Acipenseridae*) catch per unit effort (CPUE) in the Gulf of Saint Lawrence, Canada [Hatin et al., 2007].

Overall, it can be that turbidity may have a considerable detrimental influence on aquatic fauna, altering everything from predator-prey interactions to aquatic plant and animal growth and reproductive rates. To help preserve the health and variety of these sensitive ecosystems, it is critical to monitor and regulate turbidity levels in aquatic habitats.

2.3 TURBIDITY AND POLLUTED SILT

High levels of turbidity can have a deleterious influence on aquatic ecosystems by lowering light penetration and changing water temperature, which can damage aquatic creature growth and survival [Greenwood et al., 2017]. Furthermore, high turbidity levels can cause a drop in dissolved oxygen levels, which can be harmful to fish and other aquatic species that rely on oxygen for survival [Wolf et al., 2013].

Contaminated sediment is defined as sediment contaminated by contaminants such as heavy metals, polycyclic aromatic hydrocarbons, and pesticides. These toxins can harm aquatic species such as fish and benthic invertebrates, and they can even endanger human health if taken through contaminated seafood [Johnson and Kelble, 2016]. The presence of these contaminants in sediment can also contribute to the general degradation of aquatic ecosystems by lowering water quality and changing habitat availability [Chen et al., 2015].

Because the suspended particles that cause turbidity can also harbor contaminants, turbidity and contaminated sediment are frequently linked. Heavy metals, for example, can bind to sediment particles and become suspended in the water column during high turbidity periods, potentially increasing exposure to aquatic creatures [Wagner et al., 2017]. Furthermore, high turbidity levels can reduce the effectiveness of natural sedimentation processes, resulting in contaminated sediment accumulation in aquatic ecosystems [Greenwood et al.,

2017].

Overall, turbidity and contaminated silt can have serious consequences for the health and operation of aquatic ecosystems. Effective management measures, such as limiting pollutant input into aquatic systems and encouraging natural sedimentation processes, are critical for mitigating these impacts and sustaining water quality.

2.4 METHODS TO MINIMIZE THE IMPACT OF TURBIDITY

Various methods have been developed to minimize turbidity. The kind of dredger, dredging cycle (including dredging travel and disposal times), daily production rates, sediment properties, and seasonal current flows are among the assumptions that are typically used to estimate dredging consequences [Savioli et al., 2013].

According to Feola et al. 2016, a platform of integrated technologies is proposed to facilitate environmental impact assessments by helping to estimate the consequences of dredging activity. Dr-EAM (Environmental Assessment Method for Dredging activity), the proposed methodological approach, uses a three-dimensional modeling and data analysis technique that might aid dredging project management during the design phase. Users are given the option to select the most appropriate technical approaches and temporal frames to minimize their impact on the environment.

Nowadays, a case study is done before dredging to find the most optimal conditions to dredge to minimize harm to the environment. In this study several factors should be considered such as the currents should be investigated that can influence the turbidity and its plume. It is also important to consider what time of the year dredging activities can take place. In this way, dredging activities are minimized to influence a certain flora or fauna. According to Bundgaard and Feola 2020, turbidity limits for dredging operations that balance environmental protection with cost-effective dredging must be set. The turbidity limit consists of trigger levels and a threshold level, defined as the level at which an impact can start to occur. The methodology involves identifying sensitive receptors, determining their critical stress levels, and selecting measurable turbidity limits and trigger levels. The limits should be based on a system understanding of the local environment and manageable in a dredging operation and a monitoring strategy should also be defined. According to Bundgaard and Feola 2020, also communication with the stakeholders and experts is important in establishing realistic limits. The outcome of a case study to set turbidity limits is site-specific and ecosystem-based to protect sensitive environmental receptors and make monitoring cost-effective and socially relevant.

In the case study physical, chemical and biological methods to minimize turbidity should also be considered. Physical methods involve the use of physical barriers and structures to prevent sediment and other particles from entering the water column [Oglivie et al., 2012]. The following are some of the physical and chemical methods used to minimize turbidity during dredging:

1. Silt curtains - Silt curtains are barriers placed in the water to contain the sediment and prevent it from spreading to other areas. They are effective in reducing the spread of sediment and minimizing turbidity.
2. Sedimentation ponds or basins - These structures are designed to capture sediment and allow it to settle out before the water is discharged.

Sedimentation ponds are effective in removing sediment and reducing turbidity levels.

3. Dredging in stages - Dredging in smaller stages can help to minimize the amount of sediment disturbed at one time, reducing the amount of turbidity produced.
4. Dredging at the right time - Dredging during calm weather conditions can help to minimize the amount of turbidity produced.
5. pH adjustment - Adjusting the pH of the water can cause the suspended particles to clump together and settle out. However, pH adjustment can also have negative impacts on the aquatic ecosystem if not done properly.

Biological methods involve the use of natural processes to minimize turbidity [Kent and McManus, 2000]. The following are some of the biological methods used to minimize turbidity during dredging:

1. Vegetation buffers - Vegetation buffers can be established along the shorelines to help filter and trap sediment before it enters the water column. Vegetation buffers are effective in reducing sediment runoff and minimizing turbidity.
2. Bioengineering - Bioengineering involves the use of plants and other natural materials to stabilize the sediment and reduce erosion. Bioengineering can help to minimize the amount of sediment disturbed during dredging and reduce turbidity levels.

Despite the predominantly negative effects produced by turbidity, there are sources who report positive effects such as Sherk et al., Darnell, Simon and Dyer, Maragos and Manap and Voulvoulis. But in aforementioned sources they do not talk about contaminated silt which is stirred up. Thus, further research of this, is needed. Furthermore, dredging of contaminated sediments and creating turbidity, shall always be always a trade-off between costs and benefits.

In the end, every case will be different and the methods that should be taken into account as well. It can be seen that there are many manners to minimize the effects of dredging and the turbidity. According to Manap and Voulvoulis 2015, it is hard to set the same trigger levels and threshold level everywhere as all the dredging locations are different and developing countries may take a different strategy to manage their dredging environmental impact.

2.5 CONCLUSION

To conclude turbidity can have a negative effect on the fauna and flora. Especially, whenever the sediment is polluted the effects can be worse. Today, the importance to minimize the impact of turbidity became more important. There are methods to minimize the impact of turbidity, by minimizing the spread, by dredging at the right time and many more. However, with these described methods turbidity remains unavoidable. In the next chapter the current dredging tools will be discussed, how they generate turbidity and what is done to minimize the turbidity.

3

CURRENT DREDGING TECHNIQUES AND TURBIDITY

It is explained what turbidity is and what the impact can be, in this chapter the current dredge techniques will be discussed, how they create turbidity and how the turbidity can be minimized.

3.1 CLAMSHELL

The clamshell or grab dredger, [Figure 3.1](#), is the most prevalent type of dredger in use across the world, particularly in North America and Asia [[Miedema and Vlasblom, 2006](#)]. It is a simple and straightforward stationary dredger that can work from a pontoon or a ship. The latter has a hold where the dredge material is stored; otherwise, the material is transported by barges. Anchors or poles can be used to moor the dredgers (spuds) [[Miedema and Vlasblom, 2006](#)].

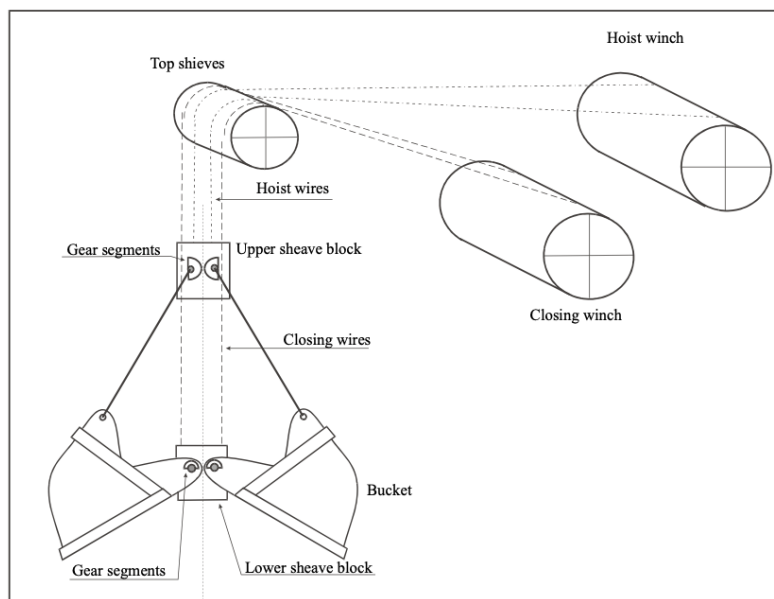


Figure 3.1: Clamshell [[Miedema and Vlasblom, 2006](#)]

The closing and hoisting wires, as well as hydraulic cylinders, regulate the grab's opening. Many cranes include a tag line that runs from halfway up the boom directly to the grab to guarantee that the grab does not rotate during lifting and lowering. The technique of anchoring and the positioning mechanism for clamshell dredgers are critical to the dredger's performance. The volume to be dredged reduces as the angle from the centerline increases. As a result, dredging regions between -90° and $+90^\circ$ from the centerline is not always successful [[Miedema and Vlasblom, 2006](#)].

In a difficult-to-dig soil, a cycle of the grabbing process entails first completely opening the clamshell and laying it on the soil to be dredged. The hoisting wire is left slack when the clamshell is lying on the bottom, allowing the clamshell to sink

vertically into the soil under its own weight. This is referred to as initial penetration. During the first penetration, the gap between the two sheave blocks is at its greatest. Then, the closing wire is tightened in, dragging the two sheave blocks towards each other, causing the clamshell to close. The lifting wire is left slack during the second step, allowing the buckets to penetrate the earth. In soft soils, the hoisting wire may need to be tightened to prevent the clamshell from penetrating too deeply into the earth which would result in a great deal of spillage. The clamshell is closed at the conclusion of the second stage and will be elevated with the hoisting (and closing) wire, [Miedema and Becker, 1993].

3.1.1 Turbidity caused by a clamshell dredger

Clamshell dredging results in a turbidity plume downstream from the dredging site, with the majority of the plume at the bottom [Grimes, 1982]. Further away from the dredging site, the concentration of suspended silt decreases. This is however dependent on the current velocity, as stronger currents decrease the level of suspended silt. The density of suspended particles in the plume is determined by a number of parameters. This includes bulk density, grain size of dredged material, dredging intensity, clamshell size, and the amount of material spilled. [Reine et al., 2007]

Dredged sediment is resuspended in the water column at various points during the dredging and disposal process. When the clamshell closes, and is lifted off the bottom during dredging, silt is resuspended. Usually, the clamshell is not fully closed. Thus, additional silt is resuspended when the clamshell is lifted through the water column. When the clamshell breaks the surface of the water, turbid water rushes out or seeps through the jaw holes, adding additional sediment to the water column. Finally, some silt is resuspended during the disposal of dredged material as the clamshell is emptied. [Tavolaro, 1984]

According to the findings in a study of Vagge et al. 2018, in the Oil Port of Genoa-Multedo (Italy), dredging with a clamshell caused an increase in turbidity in the water. In Figure 3.2, a drawing of the turbidity during this study is shown.

For low-turbidity dredging, closed clamshell buckets of 5 and 7 m³ are used [van Rijn, 2019].

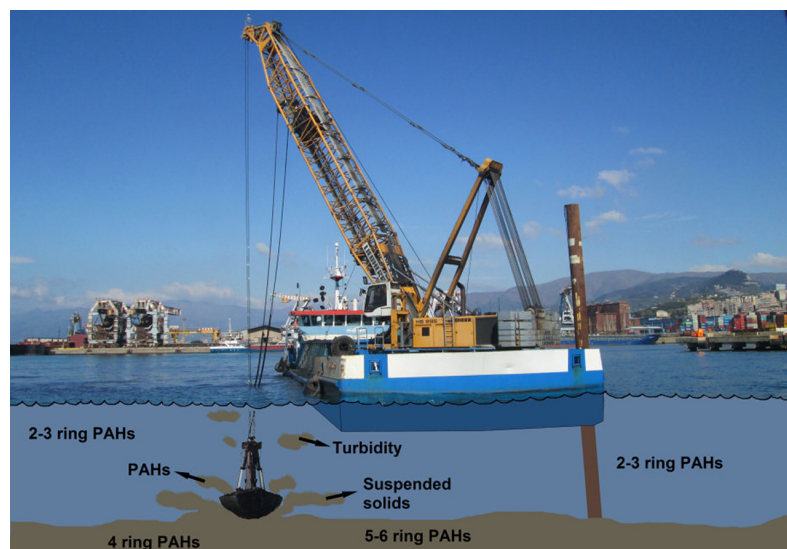


Figure 3.2: Turbidity created by a clamshell [Vagge et al., 2018]

Several considerations may be made while utilizing a clamshell dredger to reduce turbidity. Firstly, it is really important that the operator of the clamshell should be trained and experienced in using the machine and should follow proper dredging techniques to minimize turbidity. This may include using slow and steady movements, avoiding abrupt or jerky motions, and avoiding overloading the dredge bucket. Secondly, turbidity can be minimized by controlling the flow of water around the dredger. This can be achieved by positioning the dredger in a way that minimizes the flow of water around it, using diversions to redirect water flow away from the dredging area, or by installing silt curtains or other barriers to prevent sediment from spreading. Thirdly, the dredger operator could use an appropriate dredging depth that minimizes the amount of sediment disturbed and prevents sediment from being resuspended in the water column. This may involve dredging at a shallower depth or using a smaller dredge bucket [Palermo et al., 1984].

Another way to minimize or avoid turbidity is by using an environmental clamshell. A precise cut that closes and is sealed horizontally characterizes an environmental clamshell bucket, often referred to as a vigor bucket, which can be seen in Figure 3.3. It is a mechanical method of dredging that may both remove debris and lessen the quantity of water that is taken with the sediment. Only then is the bucket dragged out of the water and the sediments released into a barge when the shutter (visor) has been closed after the bucket is full. The shutter or visor in question stops particles from leaking back into the water. The computer system that is employed with the high-precision motion sensors is an important component. They allow the operator to precisely track the removal of debris and check the efficacy of the dredging process [IADC, 2016]. According to Welp et al. 2001, the environmental clamshell's observed depth-averaged turbidity was 79% lower than that of the conventional clamshell.

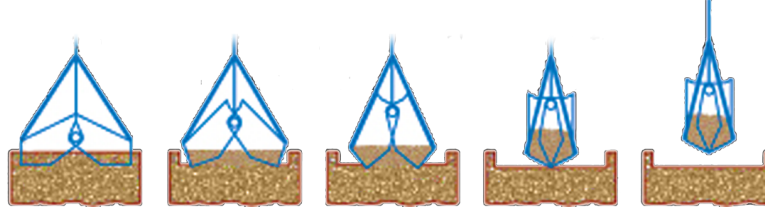


Figure 3.3: Environmental clamshell [Welp et al., 2001]

3.2 BACKHOE

Long stick backhoes are hydraulically powered, modified versions of traditional hydraulic excavators [Chaabani, 2017]. These devices are enhanced by an expanded gigantic arm (stick and/or boom) that allows them to work at greater depths. In backhoe excavators the combination of stick crowd force (FS) and bucket curling force (FB) controls the bucket's penetration into the earth, Figure 3.4. Both forces are caused by hydraulic relief pressure created inside cylinders. However, while bucket curling force is independent of stick length, stick crowd force is inversely proportional to the length of the stick. As a result, the longer the stick, the higher the relieving pressure and machine power required to exert the equivalent force on the bucket tip [Chen et al., 2022].

There are essentially two methods for excavating deep and narrow trenches and slurry walls in common use: in the United States, excavation is typically done with

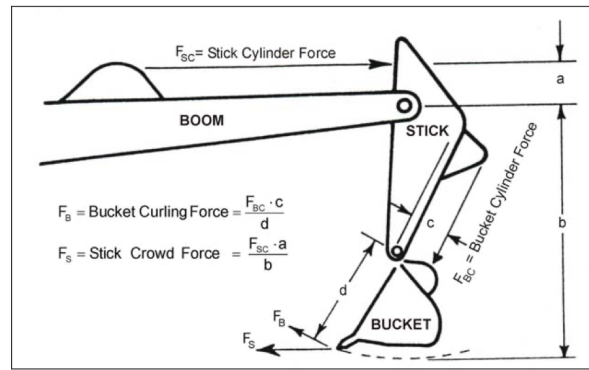


Figure 3.4: Backhoe excavator forces [Di Molfetta et al., 2006]

a hydraulic long-stick excavator (LS excavator) or a backhoe; in Europe, excavation is typically done with a crane and clam bucket [Di Molfetta et al., 2006].

3.2.1 Turbidity caused by a backhoe

Turbidity caused by a backhoe is similar to turbidity caused by an open clamshell. However, the volume is bigger due to the addition that spilled mud at the unloading location may cause substantial mud pollution/turbidity. [Fuglevand and Webb, 2012]

To minimize the turbidity of the backhoe the same points as of the clamshell should be considered such as that it is important that the operator is trained, that the water flow can be controlled well and that it is important to dredge at an appropriate depth. Compared to a clamshell dredger, a backhoe dredger can have a larger bucket capacity, which may allow for more efficient removal of sediment. However, this can also increase the potential for turbidity if not managed properly. Additionally, the methods used to control water flow around the dredger may differ depending on the specific conditions of the dredging site. Overall, the methods for minimizing turbidity when using a backhoe dredger are similar to those used for a clamshell dredger, but may require some modifications depending on the specific dredging conditions.

3.3 TRAILING SUCTION HOPPER DREDGER

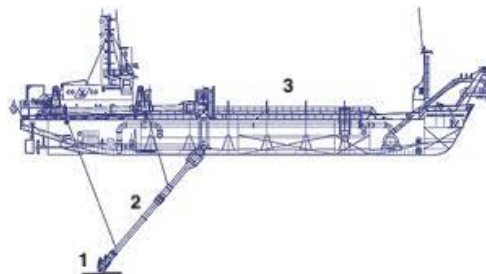


Figure 3.5: Trailing suction hopper dredger

The trailing suction hopper dredger (TSHD), Figure 3.5, is a self-propelled vessel with a hopper, which can be found in Figure 3.5 number 3, and a dredge system that allows it to load and discharge fine material, such as silt [Cutroneo et al., 2012]. The dredging vessel is divided down into sections, each of which will be discussed

separately.

The draghead and suction tube are shown in number 1 and 2 respectively of Figure 3.5. During dredging, a huge steel structure is dragged along the bottom behind the vessel. This is known as the draghead, as can be seen in Figure 3.6. It is hooked at the end of the suction tube's tip. The draghead's cutting teeth, which are connected to the visor, cut a layer of sediment. The main source of the production of the dredging process, jets are mounted in the draghead. These jets already spray the sediment loose before it is dredged Figure 3.6 [Miedema, 2019].

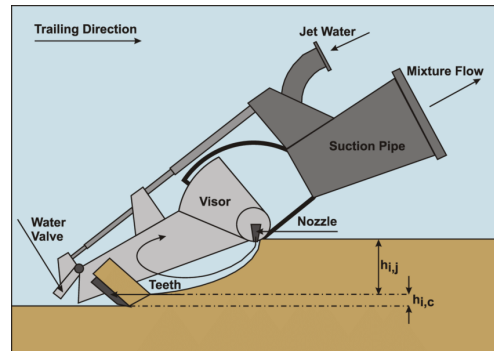


Figure 3.6: Draghead [Miedema, 2019]

The suction pipe, connected to the pump system, transports the dredged sediment and is coupled to the hull. It is lowered to the bed by cables using two gantries. The draghead loosens the sediment, which is subsequently pumped to the hopper. An under pressure is generated at the intake, causing the mixture to be pushed into the pipe [Miedema, 2019].

The TSHD also has a barge with an overflow system. The sediment is given time to settle in the hopper while the process water flows overboard, frequently down a vertical shaft known as the overflow. A turbid plume is created when process water spills because it contains suspended sediment that has not yet settled.

3.3.1 Turbidity caused by a trailing suction hopper dredger

In order to loosen the material that is to be dredged, water is injected at high pressure between the soil grains and into the pores by the jets. The sediment is loosened from its densely packed structure in this way. The sediment is stirred up by the turbulence in the water and is carried into the suction tube, which runs from the draghead to the vessel's hull, due to under pressure generated by the pump [ter Meulen, 2018]. Either the sediment can be pumped up or it can create turbidity in the surrounding water near the bed. The latter can be seen as the draghead plume. The sediment that is loosened, can also be called spillage. [Miedema, 2019; Kirichek et al., 2022]

The overflow plume differs from the draghead plume, both can be seen in Figure 3.7. The overflow plume consists of surplus water spilled out to the sea by a vertical shaft inside the hopper, also the turbidity plume that starts underneath the hull of the ship in Figure 3.7. This is the major source of sediment discharged at a TSHD during dredging [Bray, 2008a]. Sediments in the overflow water produce a plume beneath the keel of the TSHD. A portion of this plume will sink to the seabed and land near the TSHD, while the rest will mix throughout the water column forming a surface plume [van Maren and van Kessel, 2016; Nichols et al., 1990; Spearman et al., 2011; Whiteside et al., 1995]. Because coarser sediment settles

faster in the hopper than finer sediment, an overflow plume contains the finest particles of the dredged material [Van Rhee, 2002]. Surface plume fine sediment settles slowly and might remain suspended for hours or more, during which time it can be carried kilometers away from the dredging site. [Becker et al., 2015; Golbuu et al., 2003]

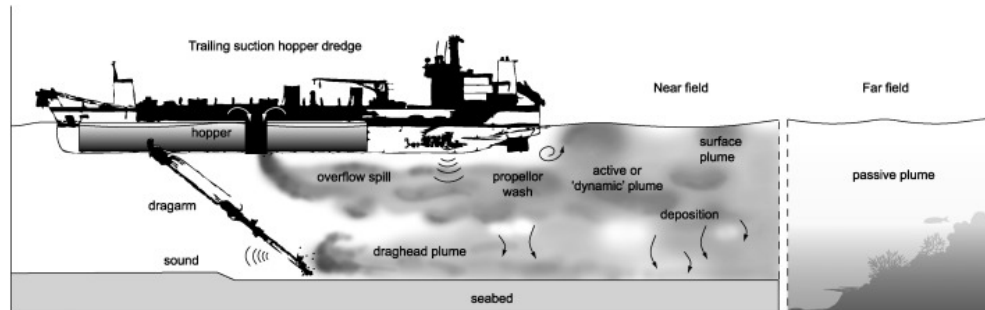


Figure 3.7: Turbidity plume TSHD [Jones et al., 2015]

As the TSHD can create two different types of turbidity plumes, it should be discussed how both plumes can be minimized. To minimize the draghead plume, it is possible to pump with a higher power, but this will have a negative effect on the overflow plume, as more water will be dredged and this will create that more water with small particles will overflow. The most effective way is to avoid spillage by using the jets in the most efficient way that all sediment that is loosened will be dredged without dredging excessive water. To minimize the overflow plume, the goal is to only overflow water without any other substances. The use of the hopper capacity could be maximized by telescopic system that can set the overflow at different levels as can be seen in Figure 3.8. Another way to minimize the turbidity of the overflow plume is to take care that the water level inside the vertical overflow shaft is not much lower than the water level inside the hopper. Significant volumes of air can be entrained into the overflow plume as a result of the spilling water creating a falling jet in the shaft. At a specific distance from the source, the air portion of an air-fluid plume separates from the fluid plume. Separating air bubbles from the main sediment plume can elevate a portion of the sediment plume to the free surface. Entrained air in the overflow decreases the excess density of the mixture, causing the sediment plume to stay higher in the water column. In order to lessen the environmental impact of dredging plumes, some TSHDs have a so-called "green valve" in the overflow [Bray, 2008b]. Furthermore, this valve raises the water level in the shaft by limiting the shaft's flow through area. Air entrainment is lessened and plummeting is avoided in this method. [de Wit et al., 2014]



Figure 3.8: Overflow plumigator [IHC, n.d.]

3.4 CUTTER SUCTION DREDGER

Cutter suction dredger (CSD), in comparison to other dredging methods, can dredge virtually all types of soil, even hard and rocky soils [Tang et al., 2009]. This is because of the usage of a cutter head, as shown in Figure 3.9, [Tang et al., 2009]. A rotating cutter head, at the end of the ladder in Figure 3.10, on a cutter suction dredger breaks up the seabed into pieces. It is meant that are cute, the spillage, is dredged by the by the submerged pump, as can be seen in Figure 3.10. The cutter head sucks up the loosened material, which is then transported via pipelines to a hopper or a disposal location. In some circumstances, split hopper barges anchored alongside the cutter suction dredger bring dredged material to the deposit location and discharge it there [Tang et al., 2009].



Figure 3.9: Cutter head

Cutter suction dredgers act as stationary dredgers when in operation [Tang et al., 2009]. A spud is sunk into the bottom to secure the vessel during the dredging operations. As a consequence, the ship remains stationary, while the dredger ladder is swung sideways, using winches and anchors, and the cutter head cuts and removes the dredged material [Tang et al., 2009].

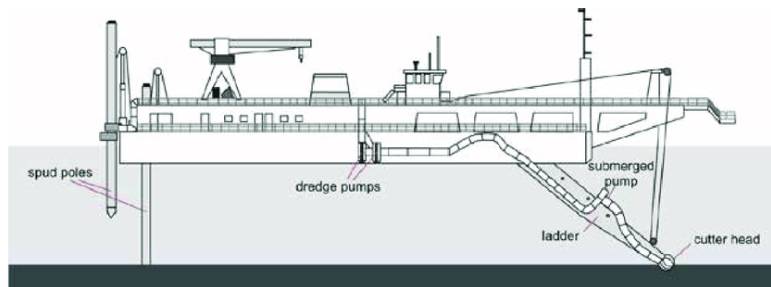


Figure 3.10: Cutter suction dredger [Mills and Kemps, 2016]

3.4.1 Auger cutter suction dredger

The environmental dredger, called auger dredger, is a further evolved cutter suction dredger. It was designed for the sanitation of polluted water bottoms. The key elements of the device are according Eisma 2005 great accuracy and almost zero turbidity of the surrounding water. The device cuts in the soil and transports it to the middle of the auger where it is mixed with water and pumped away by the dredge pump. The auger dredger is able to dredge with an accuracy measured in centimeters, which are only a couple of other dredging devices capable of [Eisma, 2005]. It is able to dredge layers up to one meter thick.

3.4.2 Scoop and sweep dredger

Even at very deep depths, the scoop dredge is very well suited to the removal of heavy layers of silty sediments (4-25 m). The sweep dredge can remove material selectively in layers up to 20 cm and is suitable for depths ranging from 3 to 14 m.

[Vandycke et al., 1997]

Both dredges operate with little disruption to the environment and at competitive prices when compared to other types of conventional dredging machinery, such as cutters dredgers and trailer dredgers. The sweep dredge actually combines the newest internally developed technology in process control, for example, as well as in automatisisation, process control, and trailing dredge heads for fine sediments. [Vandycke et al., 1997]

3.4.3 Turbidity caused by a cutter suction dredger

Like the TSHD, the CSD generates an overflow plume and a plume because of spillage. The quantity of material cut by the cutter but not pumped up by the suction line is referred to as spillage from a cutter suction dredger. This material can either settle to the bottom as a residue or form resuspended sediment (RSS), creating turbidity in the water column. It is possible that a plume will arise when the sediment is resuspended. The plume from the cutter suction dredge usually stays towards the bottom of the water column, but it can move horizontally and impact water quality in certain areas depending on the type of soil being dredged [Henriksen, 2009].

The resuspension of sediment of a CSD leading to turbidity is affected by various factors, such as rotational speed, swing velocity, and suction discharge. The use of a curtain in front of the cutter can reduce the spread of a sediment cloud. It is preferable to identify the flow field and the zone of impact of the suction at the intake if the turbidity is to be contained within a limited region close to the cutterhead. Another way to minimize turbidity is by decrease the cutter rpm or by increasing the suction pipe diameter or decreasing the cutter head diameter. [Brahme and Herbach, 1986; Henriksen and Randall, n.d.]

Another invention to minimize turbidity by using a cutter head is from Dredge Yard. The electric cutter head dredger minimizes turbidity by using a new design that creates a powerful water flow system, which can be seen in Figure 3.11. The cutter head features a number of nozzles that jet water at high pressure, which serves to reduce sediment and prevent the formation of plumes. In addition, the dredger has a specially designed suction head that is able to maintain a consistent depth while dredging, which also helps to minimize turbidity [Electric close blades cutter head, n.d.]. Regardless, little is known about this new technique. There are currently no studies in the literature concerning this new approach, making it impossible to make conclusions about turbidity and this technique.



Figure 3.11: Electric cutter head [Electric close blades cutter head, n.d.]

3.5 COMPARISON TURBIDITY AND THE CURRENT DREDGING TECHNIQUES

According to data shown in Figure 3.12, mechanical dredges such as the clamshell and bucket dredger produce more resuspended sediment than cutterhead and hopper dredges without overflow [Hayes, 1986]. However, in many instances, the sort of dredge that must be employed may be dictated by manoeuvrability requirements, hydraulic conditions, location of the disposal site, and other variables. In these cases, the approach to choose which technique to apply, must be dependent on the reduction of the resuspended material by that dredge. [Sheehan and Harrington, 2012]

The backhoe is not considered in the study of [Hayes, 1986], but since it is an open bucket, it may be assumed that the turbidity caused by SSC is greater or comparable to that of the open bucket.

Dredge Type	Downcurrent Distance- Suspended Solids Concentration, mg/l*		
	Within 100 ft	Within 200 ft	Within 400 ft
Cutterhead	25 - 250	20 - 200	10 - 150
Hopper			
With overflow	250 - 700	250 - 700	250 - 700
Without overflow	25 - 200	25 - 200	25 - 200
Clamshell			
Open bucket	150 - 900	100 - 600	75 - 350
Enclosed bucket	50 - 300	40 - 210	25 - 100

* Suspended solids concentrations were adjusted for background concentrations.

Figure 3.12: Downcurrent distance - suspended solids concentration, mg/l* [Hayes, 1986]

Even if the table shows these values, critical evaluations must be made of them. The data are quite dated, and there is no indication of the precise location or environmental circumstances of the dredging. Depending on the circumstances, the data might change dramatically. For instance, no currents nor tides nor the sort of dredged material are mentioned. Furthermore, the dredging equipment is likewise outdated since the data is. Lastly, nothing is mentioned regarding the usage of the equipment. Turbidity may be significantly influenced by how a machine is utilized, as was previously mentioned.

3.6 CONCLUSION

It may be concluded that all present dredging processes produce turbidity, but that advancements are being made to reduce this turbidity. It may also be argued that comparing the procedures on the quantity of turbidity generated is difficult. Turbidity is influenced by dredging conditions. With this purpose, the contained dredging system (CDS) is designed, which will be discussed in the next chapter.

4

CONTAINED DREDGING SYSTEM

The contained dredging system (CDS) will be discussed in this chapter. This chapter is mostly based on the patent of the CDS and on the existing prototype. In addition, a theoretical analysis of the CDS pressure regulation and how turbidity could be generated will be discussed.

4.1 CDS SYSTEM

The contained dredging system (CDS), [Figure 4.1](#) shows its patent design, is a device and technique designed for removing alluvial deposits from the bed of a body of water efficiently and allegedly without risk of spreading the pollutants present in contaminated silt. Most traditional dredging procedures create turbidity, which resuspends and redistributes silt. The CDS, on the other hand, is a dredger designed to not create any turbidity [[Van Rompay, 2019a](#)]. According to [Van Rompay 2019a](#), this technology could not only be used to remove polluted silt without risk of further contamination. It can also be used for routine dredging of rivers, ports and the like to maintain their depth.

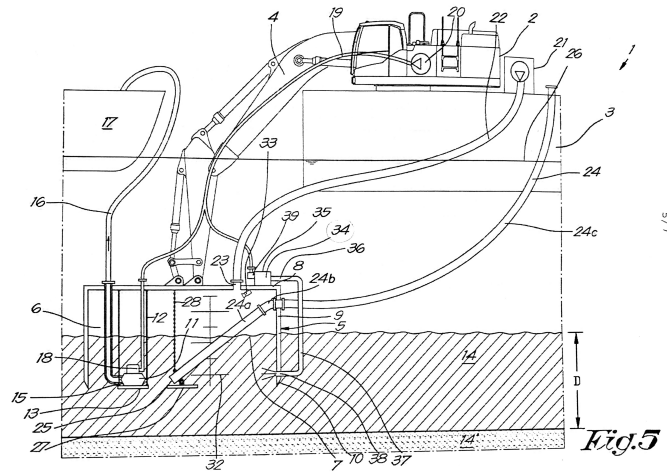


Figure 4.1: Contained dredging system [[Van Rompay, 2019b](#)]

In [Figure 4.1](#), the figure of the patent of the CDS can be seen. The figure represents the (air) chamber (5), with a dredging pump (24), the air inlet (16) and the air outlet (23). The device is handled from a pontoon (3) with an excavator (20). The compressor to compress air into the chamber is placed on a boat (17). In [Figure 4.1](#), there is one mistake, the level of the sea/river bed is above the floater and the air/water outlet. The floater should always rest on the sediment. To explain the CDS more clearly [Figure 4.2](#) will be used. The CDS consists of a chamber or bell, which can be seen in [Figure 4.2](#). The chamber consists of the device's outer walls. It is lowered to the seabed or riverbed by an excavator. [Figure 4.2](#) shows that on top of the chamber an excavator is attached. The area contained by the bell is dredged by a dredge pump and the silt is pumped out when that area has been dredged. The dredge pump is fixed to the roof of the bell, as can be seen in [Figure 4.2](#). It has

a pipeline connected to allow sediment transport to a disposal place. Jets are used to liquefy the sediment. In the prototype of the CDS four nozzles can be found of 4 inch each installed on one side of the chamber.

As the whole dredging process is in a closed system, turbidity is not created outside the bell. In theory as long as the CDS is moved with care, no turbidity is created, but this will be theoretical considered and should be tested. In the bell itself, the turbidity is high, but this should not affect the environment outside the bell.

Furthermore, both a floater as well as an air/water outlet are connected with a joint to the chamber. Both are designed to rest on sediment while dredging, but the lowest point of the floater will never be under the chamber. That is why in [Figure 4.2](#) the red dot line can be seen to mark that neither the floater nor the pump come out of the chamber. Furthermore, the higher the sediment in the chamber the bigger the angle between the shaft and the chamber.

Moreover, the lower part of the floater will never hang below the CDS since the shaft is shorter than the height of the chamber. Likewise, the dredge pump is mounted so that the end of the pump also hangs just above the bottom of the chamber.

Water jets are used to ease the sediment pumping. They do greatly increase the turbidity inside the chamber. However, this does not affect the environment outside the chamber.

The CDS chamber contains a dredging pump capable of pumping all the silt out of the bell. In the current prototype the pump is immobile. However, a system could be built which allows the height of the pump to be regulated to allow for cases where the silt is not soft enough for the pump to dig deeper into it.

Since the bell is dry, it is very easy to place a camera and lights inside to see what is happening during the dredging process. Because there can be other objects on the bed which cannot be dredged, a camera is also useful for mapping big stones or other objects that need to be removed.

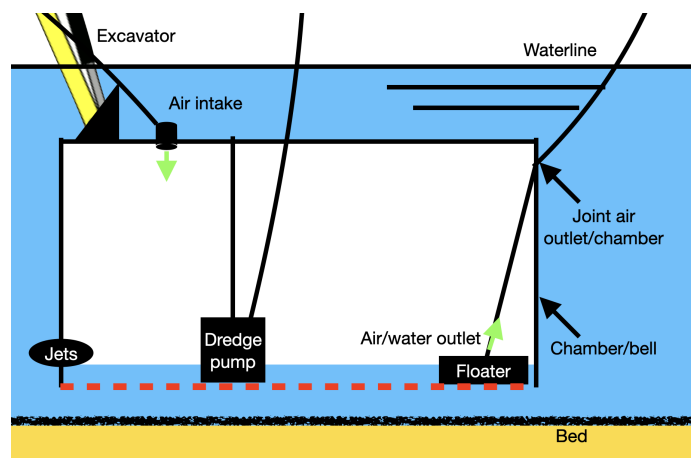


Figure 4.2: Contained dredging system schematically

4.1.1 Applications of CDS

Maintenance dredging

Because the silt in maintenance projects is mostly quite soft, the CDS technology can be utilized for maintenance dredging in its current state. For a tougher or rockier waterbed a cutter head can be used in combination with the CDS. However, it can cause environmental disruption, and maintenance dredging projects can take place in polluted areas. In this thesis it will be investigated whether or not the CDS could be a solution for dredging in polluted areas.

Heavily contaminated silt

The CDS can be suitable to dredge heavily contaminated material such as sometimes can be found in a port or a fish farm [Manap and Voulvoulis, 2015; Van Rompay, 2019a]. As the dredging process of the CDS takes place in a closed bell, the contamination due to the created turbidity should be contained to prevent it from spreading [Van Rompay, 2019a]. This will be investigated further.

4.1.2 Dredging cycle of CDS

The CDS will be explained stage by stage in these sections.

Stage 1: Sail to site

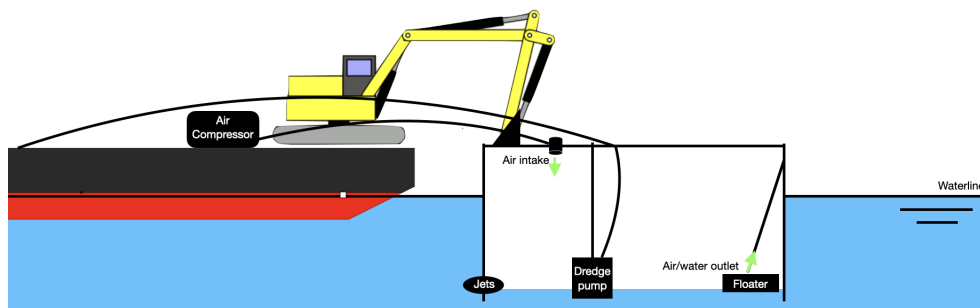


Figure 4.3: Stage 1: Begin of dredging cycle

After the pontoon arrives at the dredging site, the first step is to lower the CDS. This step of the process is similar to that of all current dredging techniques. The only major difference is that the clamshell and backhoe often involve the use of a pontoon, since unlike the TSHD and CSD they are not always incorporated into the vessel. The only CDS mechanism which is switched on when arriving is the air compressor, so that the chamber is filled with air before it is lowered to the bottom, as can be seen in Figure 4.3. Furthermore, it can be seen in Figure 4.3 that the floater hangs on it lowest point.

The dredge pump can be turned on the moment the chamber comes into contact with water. It is not safe to turn on the dredge pump before, since it could be damaged if it only pumps air. This is also the case for the pumps of the TSHD and CSD as they make use of a similar pump system.

Stage 2: Push the CDS to the bottom

The next stage is for the excavator to lower the CDS to the bottom while the pontoon or ship is stationary. This is similar to all current dredge techniques. While lowering the CDS, the air pressure in the chamber needs to adapt to the surrounding water

pressure during the lowering process. Figure 4.4 shows the change in pressure according to depth. As the floater is still on its lowest point, amount of air the air in the chamber should increase and should compress to remain at the right pressure. More information about the hydrostatic pressure can be found in Section 4.2.1.

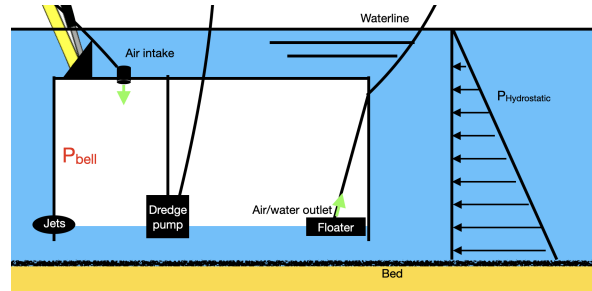


Figure 4.4: Stage 2: Push the CDS to the bottom

Stage 3: Lower the CDS into the silt

In stage three the CDS is pushed into the silt. In Figure 4.5 it can be seen that the angle between the floater and the chamber is bigger as the floater rests on the sediment. In the current prototype, the dredge pump is fixed by a rod to the top of the CDS. This means that the chamber frame and dredge pump need to be pushed into the bed against the resistance from the soil, the arrows upwards indicate the resistance forces in Figure 4.5. Cutting forces, shown by red piles downwards in Figure 4.5, will be created on the sides of the walls as well as a force against pressing the pump into the soil. However, since the dredging pump is already running, this may reduce the resistance forces acting on the pump. As sediment will already leave the chamber via the pump, the resistance declines, resulting in smaller acting forces. In Figure 4.5, the orange piles represent the sediment flow. Sediment resulting from the cutting replace some of the air in the chamber. This requires a greater volume of air to be evacuated from the chamber than is being blown in. In the end, an equilibrium will arise between the pressure in the bell its environment.

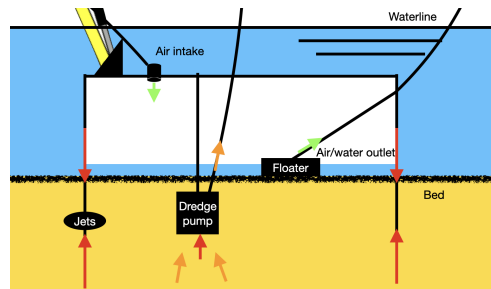


Figure 4.5: Stage 3: Push the CDS into the bed

Stage 4: Start dredging

In Figure 4.6, the actual dredging process is shown. In this stage to ease and fasten the dredging process, the water jets are also switched on. These mix water with silt making it easier to pump out the sediment. In Figure 4.6, the water of the jets is presented by the blue lines and the mixing of the sediment with the water is shown by the blue dots. The silt level will lower because of the pumping, increasing the air volume in the chamber.

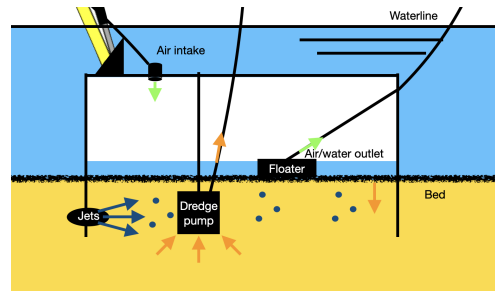


Figure 4.6: Stage 4: Start dredging

Stage 5: Dredging finished

In last stage, the soil material inside the bell is pumped out and the chamber is completely filled with air, as can be seen in Figure 4.7.

Afterwards, it is time to relocate the chamber. This can be done in two ways. Either, the bell can be slowly pulled out of the bed and re-positioned or, in future developments of the CDS, a door can be used. This door should replace one of the walls of the chamber. It can be opened, allowing the device to be dragged along the bottom.

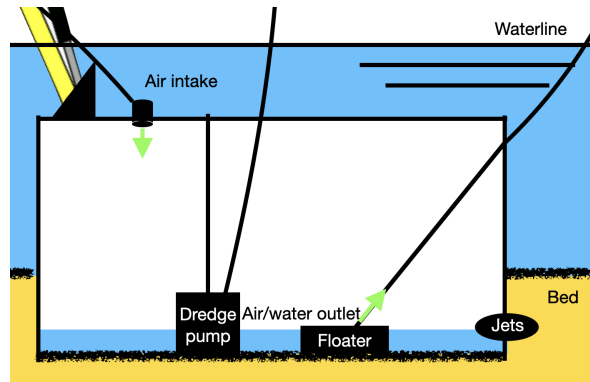


Figure 4.7: Stage 5: Dredging finished

Compared to the clamshell and backhoe, the CDS prototype is hopped further. The clamshell and backhoe must be brought up through the entire water column each time to dump the sediment into the barge and will then be placed in spots around that spot. Whereas with the TSHD and the CSD, the cutter head moves on in one motion.

4.2 ANALYSIS OF CDS PRESSURE REGULATION

The CDS utilizes a confined dredging method that tries to avoid stirring up sediment into the water column. Allowing it to safely dredge contaminated silt. The entire dredging process takes place inside a dry chamber. The chamber is pushed down into the sediment by an excavator on a work barge. The excavator could be provided with a precise automatic localization system, so that it can be programmed to work in the most time efficient manner. [Van Rompay, 2019a]

In order to keep the chamber filled with air, it is needed to have an air pressure inside the chamber, which is equal to the hydrostatic pressure of its under water environment. The CDS is equipped with an air compressor, an air inlet, and an

air/water outlet to control its air pressure. The diameter of the air/water outlet is at all times bigger as the one of the air inlet, so that it is possible for the excessive air to leave the chamber. [Van Rompay, 2019a]

As the interior of the diving bell provides a dry environment, cameras and other sensors can be used to observe and control the processes.

Another key component of the CDS is the floater, which rests on the surface of the silt. Figure 4.8 shows on the left hand sight the floater hanging inside the chamber. The right hand sight of Figure 4.8 shows however that as the CDS contacts the sediment, the floater automatically follows the bed. A joint to which the air/water outlet is attached to chamber allows this movement. Besides that, the air/water outlet prevents the air pressure from building up and pushing the silt out of the bell.

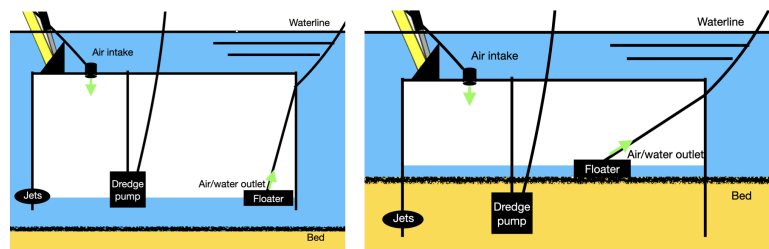


Figure 4.8: CDS with and without floater resting on bed

It is the floater equipped with an air/water outlet that makes it possible to have full control over the amount of compressed air, water and silt in the chamber. These volumes interact in such a way that silt cannot escape from the unit except by the dredging pipe. The floater moves with the surface of the silt and hence allows for a balance between water, air and silt. The air/water outlet in the chamber is used to vent any excess compressed air.

When the dredging pump is activated, the amount of silt will be reduced and therefore the silt level will drop. As the floater will descend simultaneously with the level of the silt. Any excess air will escape through the air/water outlet. The dredge pump will lower the level of the silt. At the same time the floating air outlet prevents the silt from being pushed out of the chamber.

The CDS is capable to remove silt to the required depth, as this can be determined very precisely. Since cameras in the chamber and a floater allow for a very strict monitoring of the dredging process.

The size of the CDS chamber is variable depending on the area being dredged. It could be as small the prototype as 2.5 by 2 meters or as large as 6 by 6 meters or even larger. The only limiting factors, according to Hydrex, are the size of the vessel being used for the dredging and the number and volume of pumps used to remove the silt. Figure 4.10 gives an impression of how it would look to use the CDS in reality.

4.2.1 Air pressure regulation

The bell is filled with air. When being under water the air pressure should be monitored. First, the theory will be explained considering the bell as a closed system



Figure 4.9: CDS in operation

with no air intake nor outlet. Following that, the function of the bell including the air intake and air/water outlet will be explained.

Air chamber

For the CDS, the pressure at point 3 (P_3) and 4 (P_4) in Figure 4.10 are the most important as these indicate the pressure in the bell itself. Note that the difference between P_3 and P_4 is negligible. In Equation 4.1 to 4.5 are all the formulas needed to find the right pressures at each point of Figure 4.10, it can be seen that the hydrostatic pressure relates linearly to depth. The main equation of this theory is the Equation 4.1, the hydrodynamic pressure equation.

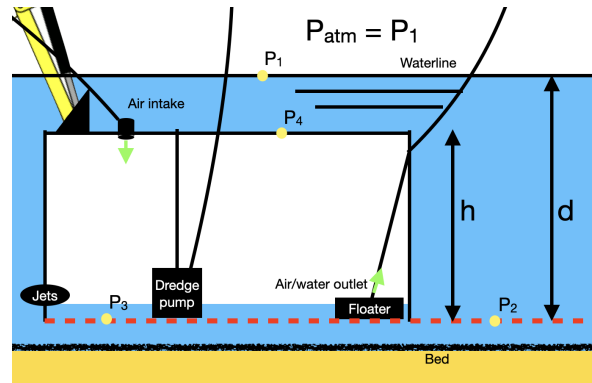


Figure 4.10: Sketch of pressure

Equation 4.1 represents the pressure difference according to the depth, where ρ is the density, g is the gravitational acceleration equal to 9.81m/s^2 and Δh the difference in depth.

$$\Delta P_{\text{height}} = \rho g \Delta h \quad (4.1)$$

Equation 4.2, where P_1 is the pressure on the water surface which is equal to the atmospheric pressure.

$$P_1 = P_{\text{atm}} \quad (4.2)$$

P_2 is the pressure in the water on the same height as the bottom of the chamber, which is equal to the sum of P_1 and the pressure difference along the depth, which can be seen in Equation 4.3.

$$P_2 = P_1 + \Delta P_{12} = P_1 + \rho_{water}gd \quad (4.3)$$

The pressure, P_3 inside the chamber on that lays on the same height as P_2 is equal to P_2 . This is also stated in Equation 4.4.

$$P_3 = P_2 \quad (4.4)$$

P_4 is the pressure inside the CDS at the level of the ceiling of the chamber. This pressure is equal to the P_3 subtracted by the pressure due to the height difference within the chamber. However, this difference is negligible as the density of air is very small. Thus, the pressure in the whole chamber is equal to P_3 . This can also be found in Equation 4.5.

$$P_4 = P_3 - \Delta P_{34} = P_3 - \rho_{air}g\Delta h \approx P_3 \quad (4.5)$$

4.2.2 Floater

Despite being called a 'floater,' the CDS floater should be more accurately described as a 'feeler' because the plate does not actually float. The CDS's floater is made out of polyethylene, which has a lower density ($\rho = 998 \text{ kg/m}^3$) than (sea)water (approximately $\rho = 1025 \text{ kg/m}^3$). For this reason the plate will float, creating an upward or buoyancy force which counters the gravitational force of the mass of the plate plus the mass of the outlet. However, because of the additional weight of the air/water outlet, connected to the plate, the plate will sink. Furthermore, there is also an upward force due to the pressure of the sediment, creating $F_{sediment}$.

Thus an equilibrium is created and the floater rests on the sediment but below the water level, Figure 4.11. This is in order to keep the air/water outlet above the sediment just until it can get enough air through the pipe, so the air level in the chamber is regulated.

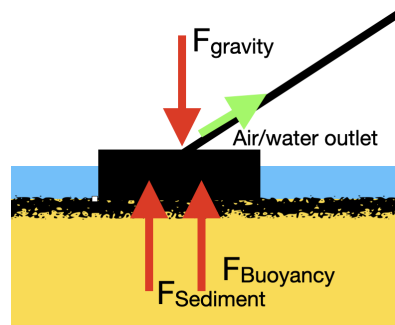


Figure 4.11: Forces on floater

A force analysis can be seen in Figure 4.11, $F_{gravity}$ is the force of the weight of the pipe together with the weight of the plate. $F_{Buoyancy}$ is the upward Buoyancy force and $F_{sediment}$ is also an upward force due to the pressure of the sediment.

4.2.3 Resistance Regulation Pipe

The air/water outlet is needed for the excessive air to leave the CDS, so that the chamber's pressure can be controlled. If only air goes through the pipe a short

circuit would occur. For this reasons an amount of water will regulate itself as a resistor in the pipe to avoid a pressure short circuit and to have an equilibrium within the pipe.

First it is needed to understand how the flow can develop in the water/air outlet. Influenced by the viscosity of flow, liquid flow can evolve into both laminar and turbulent flow. Whereas for gas liquid flow, six common flow patterns (bubbly, slug, churn, annular, wispy-annular and mist) may be seen in an upward vertical pipe depending on the variable volume percentage and varied relative velocities of the gas phase and liquid phase, which can be seen in [Figure 4.12](#).

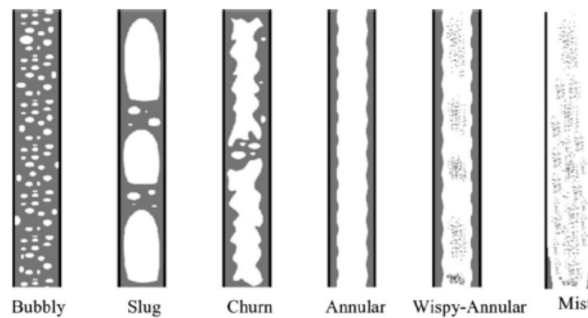


Figure 4.12: Gas liquid flow patterns in a pipe [McQuillan and Whalley, 1985]

[McQuillan and Whalley 1985](#) describe the two phase flows in depth. But to explain the mechanism of the air/water outlet a short description suffices of the different flow types;

- Bubbly flow: In a liquid continuum, bubbly flow is described as the dispersion or suspension of tiny bubbles as separate entities.
- Slug flow: When the gas concentration in a bubbly flow rises, bubbles coalesce, and as they continue to coalesce, the bubble is deformed into the Taylor bubble, which has the shape of a bullet.
- Churn flow is a very chaotic flow regime that results in a frothy mixture because the liquid is moving vertically in oscillatory fashion. The gas slugs resemble huge, elongated forms and are generally unstable.
- Annular flow: The center of the tube is traversed by the gas in an annular flow. The fluid partially moves as a film along the tube's sides and partially as drops in the gas core at its center. The wispy and non-wispy annular flow regimes are further subdivided into the annular flow regime, with the wispy annular flow resulting from the aggregation of the liquid droplets in the gas core.
- Mist flow: The gas core shears at very high gas flow rates, thinning the annular film, and mist flow develops when the interface destabilizes and disintegrates. characterized by a continuous phase of gas with a somewhat homogeneous distribution of liquid in the form of droplets and bubbles.

[Taitel et al. 1980](#) describe with [Figure 4.13](#) the type of gas fluid flow according to the velocity of the fluids. This graph can be used to determine what kind of flow pattern there will be in the water/air outlet of the CDS. For high superficial gas velocities, [Figure 4.13](#) shows that the flow will be annular.

High gas flow rates cause the flow to annularize. It can be assumed that the flow is high as Hydrex prefers to always pump excessive air into the chamber.

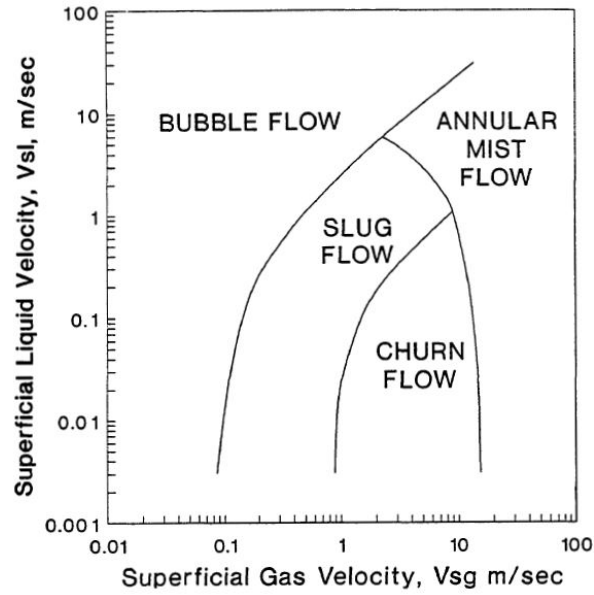


Figure 4.13: Gas fluid flow pattern map [Taitel et al., 1980]

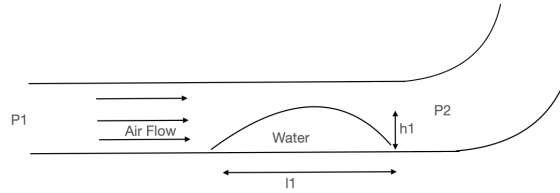


Figure 4.14: Water as Resistor in Pipe

The amount of water contained in pipe, as shown in Figure 4.14 Figure 4.15, can be regarded as a resistor. This results the air to undergo a pressure drop. The water resistor's ability to self-regulate causes the air current to balance itself out.

To calculate the air velocity through the narrowing part of the pipe, the isothermal compressible flow equation of Teng et al. 2014 can be used, which can be seen Equation 4.7. The reason why an isothermal equation can be used in this case, is because of the Reynolds number, Equation 4.6, which is assumed to be high due to the big pressure differences in the pipe. The flow will be turbulent in the pipe. Another assumption is that the water temperature along the water column remains constant. Normally, due to the ideal gas law and due to the pressure differences in the pipe, the volume would increase. This means that the temperature would also increase, but it can be assumed that due to the two assumptions the temperature of the surrounding water of the water column cools down the temperature in the pipe and keeps the temperature constant.

To verify whether or not the flow is turbulent, the Reynolds number in Equation 4.6 should be calculated. This can be done once the air velocity, v , is known and the diameter of the air/water outlet, D_{air} , where the air goes through. The kinematic viscosity of air (ν) is equal to $1.5 \cdot 10^{-5} \text{ m}^2/\text{s}$.

$$Re = \frac{vD_{air}}{\nu} \quad (4.6)$$

The equation of Teng et al. 2014 shown in Equation 4.7 gives the isothermal compressible flow. In the equation the f stands for the friction coefficient is equal to 0.04, the L is equal to the length of the water narrowing. p_2 is the pressure in the chamber and p_1 is the pressure right after the narrowing. To simplify the model,

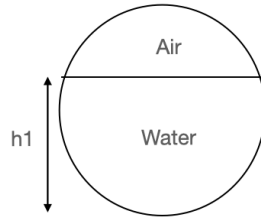


Figure 4.15: Cross-section of water in pipe

the pressure after the narrowing is equal to the atmospheric pressure and the air pressure on this point. In Equation 4.7, the Mach Number (Ma) is also used. The Mach Number is the ration of gas to the local sonic velocity, seen in Equation 4.8, where v is the air velocity, γ the specific heat ratio equal to 1.4, R the ideal gas constant, T the temperature and M the molecular weight.

$$f \frac{L}{D_{air}} = \frac{1}{Ma^2} \left[1 - \left(\frac{p_1}{p_2} \right)^2 \right] - \ln \left(\frac{p_2}{p_1} \right)^2 \quad (4.7)$$

$$Ma = \frac{v}{\sqrt{\frac{\gamma RT}{M}}} \quad (4.8)$$

If the volume flows of the CDS need to be calculated, there are three flows that need to be considered; the one of the air inlet, the flow of the dredging pump that pumps sediment and water away and the flow of the air outlet, the equation can be seen in Equation 4.9. The $Q_{air\ inlet}$ is equal to what the pump can deliver.

$$Q_{airinlet} = Q_{pump} + Q_{air/wateroutlet} \quad (4.9)$$

Thus, in Equation 4.7, the $Q_{air/water\ outlet}$ can be found in Equation 4.10.

$$Q_{air/wateroutlet} = Q_{airinlet} - Q_{pump} \quad (4.10)$$

v of Equation 4.8 in Equation 4.7 needs to be substituted. v of Equation 4.8 has to be rewritten to Equation 4.11.

$$v = \frac{Q_{air/wateroutlet}}{A} = \frac{Q_{air/wateroutlet}}{\frac{\pi}{4} D_{air}^2} = \frac{4Q_{air/wateroutlet}}{\pi D_{air}^2} \quad (4.11)$$

If v is substituted in Equation 4.8, following Equation 4.12 can be found.

$$Ma = \frac{\frac{4Q_{air/wateroutlet}}{\pi D_{air}^2}}{\sqrt{\frac{\gamma RT}{M}}} = \frac{4Q_{air/wateroutlet}}{\pi D_{air}^2} \sqrt{\frac{M}{\gamma RT}} \quad (4.12)$$

The Mach Number of Equation 4.12 should be filled in into Equation 4.7, which can be seen in Equation 4.13.

$$f \frac{L}{D_{air}} = \frac{\gamma RT D_{air}^4 \pi^2}{16 M Q_{air/wateroutlet}^2} \left[1 - \left(\frac{p_1}{p_2} \right)^2 \right] - \ln \left(\frac{p_2}{p_1} \right)^2 \quad (4.13)$$

The diameter of the air opening, D_{air} can be found with Equation 4.13.

4.3 ANALYSIS OF CDS TURBIDITY BECAUSE OF MOVEMENT

The CDS operates in a chamber where it can generate turbidity during dredging. After dredging, the machine is raised, and it is worth investigating whether turbidity is generated during or after this process.

To fully understand this, the movement of the chamber will be explained. Afterwards a couple of theories will be considered such as that the chamber is never fully empty and that the remaining water mixed with sediment would spread out to the environment. Another concept that will be discussed is whether or not the vertical slope after dredging will collapse or not.

4.3.1 Bell movement

Long stick excavator

Section 3.2 describes the use of an long stick (LS) excavator. The accuracy decreases the larger the unit. However, any inaccuracies can be removed by use of a control system. The goal is to place the excavator with the CDS on a pontoon, as can be seen in the render of Figure 4.16.



Figure 4.16: CDS with an excavator placed on a pontoon

Most dredging excavators are controlled by an operator assisted by a monitoring system which uses DGPS (Differential Global Positioning System) to keep track of areas already dredged. To ensure that the intended bottom profile is produced in compliance with the dredging contract and the dredgework principal's quality control system, extensive precautions must be carried out. Nowadays, a dredging accuracy of 10 cm (4 in) is considered standard, [Mourik and Outerkerk, 2011].

It takes a very skilled and experienced operator to accurately keep track of where there is still soil to be removed and where the next dredge bite has to be done, thanks to the DGPS connected monitoring system. The operator has a very good understanding of the equipment being used and the skill to direct the dredging process in a way that maximizes efficiency. Operators of this caliber are not necessarily easy to come by. This is a weak point in efficient operator-driven dredging.

4.3.2 Density currents when hopping CDS

When the CDS is raised after dredging to move, also called hopping, to the next spot, a stirred-up layer of sediment remains in the CDS. This layer in the CDS has a different density relative to its surroundings, as can be seen in [Figure 4.17](#).

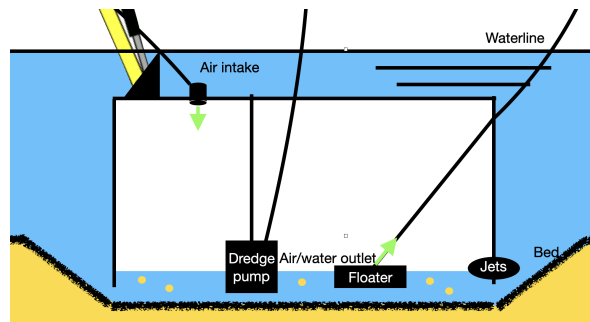


Figure 4.17: CDS when moving

The density difference of the water mixed with sediment remaining in the bell when the CDS is hopped with the surrounding water will create density currents which also means density-driven segregation in a dense grain stream [[Desjardins et al., 2008](#)].

On top of that, it is also true that the floater no longer has a point to rest on and will fall down, [Figure 4.18](#).

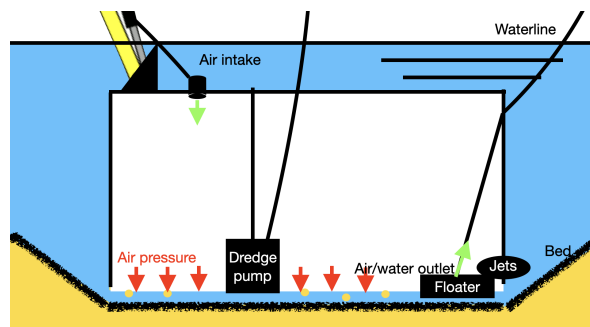


Figure 4.18: CDS when moving with floater down

4.3.3 Shear stresses and currents after pulling up the CDS

The CDS leaves a straight cut after hopping, which can be seen in [Figure 4.19](#). The issue of a vertical cutoff in a purely cohesive material ($\phi = 0$) is a well-known and significant topic of soil mechanics. It must be checked that the wall does not collapse due to stability, creating turbidity.

Both an external force and the volumetric weight of the substance itself can cause stress in soils. One characteristic is that soils cannot transfer tensile loads; only compressing normal stresses can be transferred. Shear stresses must be less than normal stresses in order to be transmitted. Additionally, a feature of soils is that water in the pores helps to transmit some of the pressures.

For a material with a constant cohesive strength, c , and constant volumetric weight, γ , the goal is to establish a lower bound and an upper bound for the maximum height, h_c , that may be dredged and left behind after hopping. By

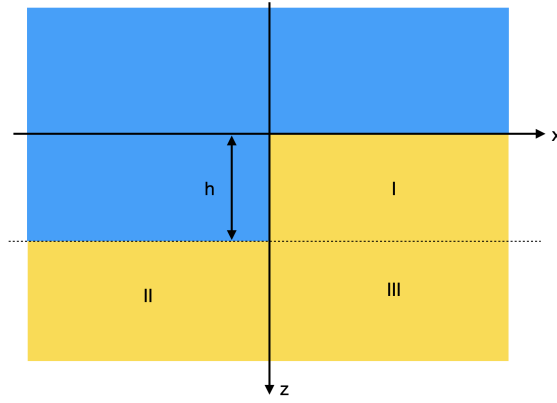


Figure 4.19: Vertical slope after hopping

knowing these bounds, it is possible to know what the maximum dredge depth is in the soil.

Lower bound of vertical slope

The weight of the material is included for the lower bound, resulting in equilibrium equations that may be seen in Equation 4.14 and Equation 4.15.

$$\frac{\delta\sigma_{xx}}{\delta x} + \frac{\delta\sigma_{zx}}{\delta z} = 0 \quad (4.14)$$

$$\frac{\delta\sigma_{xz}}{\delta x} + \frac{\delta\sigma_{zz}}{\delta z} - \gamma = 0 \quad (4.15)$$

As shown in Figure 4.19, the system can be divided into three zones. In Figure 4.20, an equilibrium for the lower bound is shown.

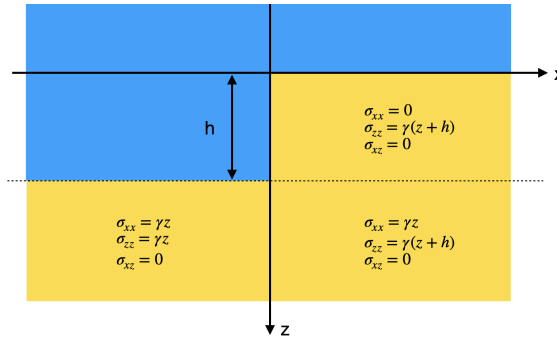


Figure 4.20: Equilibrium of lower bound of CDS

The top surface's shear and normal stresses must both be zero to meet the boundary criteria for the stresses. The stress fields shown in Figure 4.20 fulfill these requirements. Since the shear stress must be zero on the two horizontal boundaries and on the vertical slope, it is possible to construct this field by beginning with the assumption that the shear stress $\sigma_{xz} = 0$ over the whole field. According to the equation of horizontal equilibrium, Equation 4.14, this stress must be zero across zone I in order to satisfy the requirement that on the vertical slope the horizontal stress $\sigma_{xx} = 0$.

By setting $\sigma_{zx} = 0$ and applying the boundary conditions at the top of the soil, the equations for the vertical normal stress σ_{zz} are derived immediately from the

equation of vertical equilibrium, Equation 4.15. However, they must be constant in the x-direction to satisfy horizontal equilibrium, and preferably as close to σ_{zz} as feasible, to keep the maximum shear stress as low as possible. The formulas for the horizontal stress σ_{xx} in zones II and III can be chosen at random.

By setting $\sigma_{xx} = \gamma z$, zone II's lower left-hand corner of the Mohr circle becomes a point. The result is that the stress differential between σ_{xx} and σ_{zz} in zone II's lower right corner is $\sigma_{zz} - \sigma_{xx} = \gamma h$. According to the Mohr-Coulomb criterion, this shouldn't be greater than $2c$, for which c is the cohesive strength of the soil. As a result, the critical height value, or h , is equal to $2c/\gamma$, which is also the lower bound. Hence, the criteria can be seen in Equation 4.16. Other soil mechanics literature indicate that other values for a lower bound can be found. On the basis of more complicated stress fields, greater values for a lower bound can be discovered in the literature on soil mechanics, but these are not taken into consideration in this study. [Verruijt, n.d.]

$$h_c \geq \frac{2c}{\gamma} \quad (4.16)$$

Upper bound of vertical slope

Figure 4.21 illustrates a mechanism with a single straight slip surface at an angle to the vertical direction that can be used to determine a straightforward upper bound.

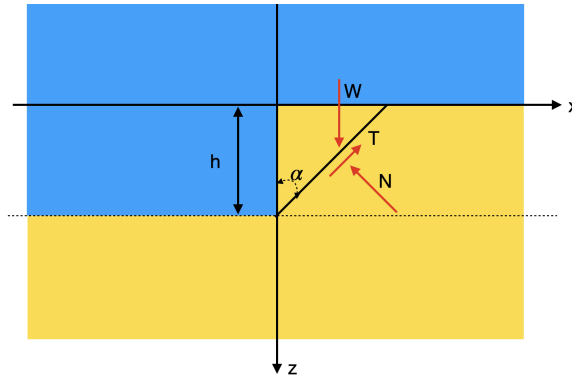


Figure 4.21: Mechanism with straight slip surface

W represents the weight of the sliding wedge. Hence, the friction force, T , which can be seen in Equation 4.18 and Equation 4.19, manifests itself in the sliding direction from the condition of equilibrium. Equation 4.19 is derived from the geometry where $h = T \cos(\alpha)$.

$$W = \frac{1}{2}h^2 \tan \alpha \quad (4.17)$$

$$T = W \cos \alpha = \frac{1}{2}h^2 \sin \alpha \quad (4.18)$$

$$T = \frac{ch}{\cos \alpha} \quad (4.19)$$

When Equation 4.18 and Equation 4.19 are combined Equation 4.20 can be found. Thus, the height of excavation of the upper bound depends on angle α . This entails

that the maximum value of $\sin(2\alpha)$ is equal to one, or that the maximum value for α is 45 degrees, which gives Equation 4.21. [Verruijt, n.d.]

$$h = \frac{4c}{\gamma} \frac{1}{\sin(2\alpha)} \quad (4.20)$$

$$h_c \leq \frac{4c}{\gamma} \quad (4.21)$$

h_c lower and upper bound

Conclusion: Equation 4.23 may be used to determine the critical height h_c of a vertical excavation of the CDS in a cohesive material without internal friction ($\phi=0$). This theory of Verruijt n.d. is applied on dried substances. Dredging takes places in an environment underwater, this means that for the volumetric weight, γ , also the Buoyancy should be taken into account. Therefore, a new volumetric weight (Buoyancy), γ_B , can be calculated with Equation 4.22.

$$\frac{2c}{\gamma_B} \leq h_c \leq \frac{4c}{\gamma_B} \quad (4.22)$$

$$\gamma_B = (\rho_{slib} - \rho_{water})g \quad (4.23)$$

4.3.4 Gravity currents due to removal CDS

According to the theory of lock exchange of Shin et al. 2004, a density current can occur because of the pressure differences. These are instigated by the density differences of the vertical slope, which has been left behind by the CDS after hopping. Meaning that h_c of Equation 4.22 is exceeded. The denser fluid flows in one way along the (sea)bed when the CDS is removed due to changes in hydrostatic pressure. Whereas the lighter fluid flows in the other direction along the top of the water column.

A two-dimensional flow theory for the steady propagation of a gravity current in a rectangular channel was developed by Benjamin 1968. This theory can be applied on the CDS as well due to their similarities. As the theory applies on rectangular channels, the dredging handling of the CDS can be simplified to an operation in a rectangular channel.

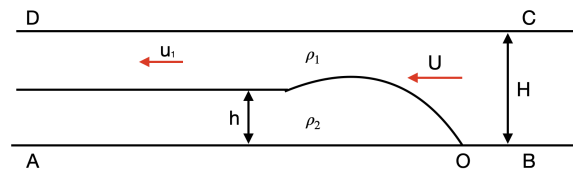


Figure 4.22: Schematic diagram of an idealized gravity current in the rest frame of the current

A fluid with density ρ_1 and a current with ρ_2 should be taken into account. The current ρ_2 is propagating at constant velocity U into fluid with density ρ_1 , as shown in Figure 4.22. It is assumed that the velocity in the surrounding fluid at the rest frame is u_1 and the depth of height of the density current with ρ_2 is h .

Figure 4.23 compares this prediction to a Boussinesq lock-exchange current. The Froude number represents the ratio of the force due to inertia and the force of gravitation and thus can help in understanding about turbidity created, after the CDS is removed. The Froude number, which can be seen in Equation 4.24, which is the driving pressure for the current.

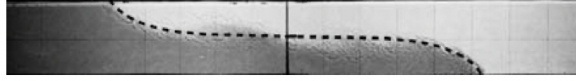


Figure 4.23: Full depth-lock release, where the potential flow solution is dashed [Benjamin, 1968]

$$F_h = \frac{U}{\sqrt{g'h}} = \frac{\sqrt{2}}{\gamma} \quad (4.24)$$

Schematically, the lock release is shown in Figure 4.24. The CDS was dredging at BC, a vertical wall at B is left behind. This instigates a dense fluid with starting height D and ρ_2 . As a result, the total height of fluid on both sides of the lock position is H . Light fluid with ρ_1 is layered on top of the dense fluid as well as in front of the lock or within the CDS. Everywhere is initially at rest, and fluid is contained between two horizontal, smooth, hard barriers. When the CDS is removed or thick fluid is released, a gravity current is created that travels from left to right at a constant speed U . Additionally, a disturbance is created, which moves steadily in the opposing direction at constant speed, U_r .

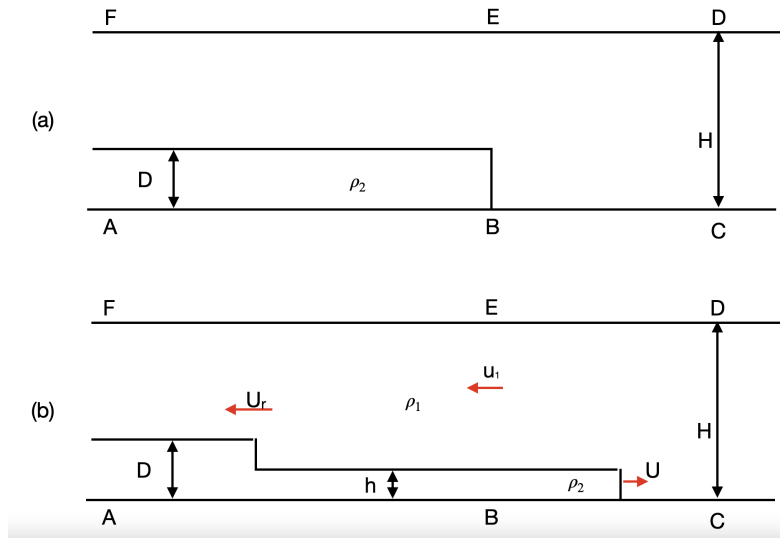


Figure 4.24: Partial depth-lock release before release (a) and after release (b)

In the case of the CDS, the dredging material and the flow are considered to be immiscible and inviscid and to be irrotational in each layer. Two advancing fronts and a horizontal central part of height h roughly represent the geometry of the interface or the wall of the CDS. It is assumed that the two fronts will travel at constant speeds and maintain their forms throughout time. The sides' precise forms are unimportant as long as they hold stable [Benjamin, 1968]. In contrast to a front with a steady shape, the rearward disturbance typically takes the form of a rarefaction wave. The flow is considered to be horizontal away from the moving fronts, and as a result, the vertical pressure gradient is assumed to be hydrostatic.

Similar to Benjamin's approach, another condition is required to fully define the flow. Namely, it is assumed that the flow is energy-conserving. Yet, because there

are no energy fluxes into or out of the control volume ABCDEF in this instance, energy is conserved across the whole volume.

By using the laws of conservation of mass, momentum, and energy of Benjamin 1968, an unique gravity current is produced, the characteristics of which are governed by the starting densities and depths on the two sides of the lock. The half-depth of the channel is typically not occupied by the current, and only when a full-depth lock release occurs. The Boussinesq approximation was not used to generate the aforementioned energy-conserving solution. As a result, it is conceptually sound for any pair of densities ρ_1 and ρ_2 . Nevertheless, it must be anticipated that the aforementioned model will fail for fluids that are not Boussinesq. The model implies that a flat interface in the center part, where velocities are horizontal and circumstances are homogeneous, may match the current and disturbance sides. Although laboratory tests indicate that this assumption is roughly true for cavity and Boussinesq flows, research by Keller and Chyou 1991 indicates that it is probably false for non-Boussinesq dense gravity currents. Lowe et al. 2005 and Birman et al. 2005 both explore the non-Boussinesq lock-exchange problem.

With Boussinesq currents where γ more or less equal to one F_H in Equation 4.25 can be found.

$$F_H = \frac{U}{\sqrt{g(1-\gamma)H}} = \frac{1}{2} \sqrt{\frac{D}{H}} \left(2 - \frac{D}{H}\right) \quad (4.25)$$

For the current CDS prototype a graph is plotted of the velocity of the slib because of the depth lock release to the dredging depth, which can be seen in Figure 4.25. As the current prototype has a height of only 1.6m, it is estimated that it can dredge up to 1m, so $D=1m$. Hence, the maximum speed of the density current is 2m/s.

In Figure 4.27, it can be seen that the dredged walls, that are left behind, will fall with a velocity U and eventually will collapse too, so the soil, from both sides create a new layer on the bottom of the bed. The CDS is created to dredge very accurately and could be used especially for polluted sites, but due to this depth-lock release, this will not be possible. Furthermore, as the depth-lock release could create even more turbidity because of collapsing soil particles, a turbidity plume could be created. However, further investigation is needed to confirm this notion.

The associated froude number as the depth at which the CDS dredges, can be seen in Figure 4.26.

4.4 CONCLUSION

The contained dredging system (CDS) is discussed in this chapter. It is possible to conclude that the CDS is a dredging tool which operates in an air chamber. Because the volume flow of the prototype's air input is known, the gas flow pattern of the outlet is likely to be churn or annular. The air/water outlet is filled with water to act as a resistor for air flow. The isothermal compressible flow equation may be used to compute the diameter of the the opening through which air can flow. Further calculations will be performed in the following chapter to check the flow pattern and the diameter of the air in the outflow.

An excavator is moving to the CDS. Following dredging, it is possible to conclude that when CDS is removed, a residual layer of water combined with silt will be

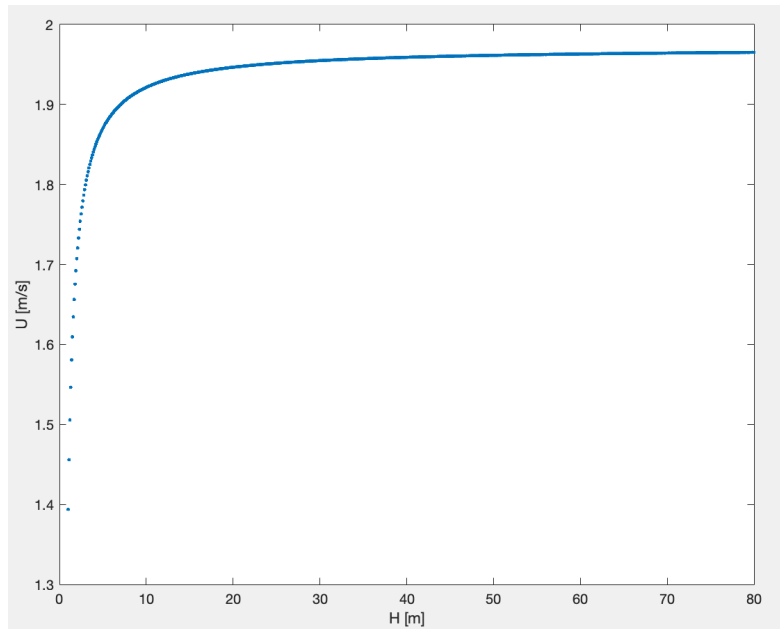


Figure 4.25: Speed of density current according to dredge depth

discharged into the environment, causing turbidity. Furthermore, vertical slopes have a lower and upper bound, and it is within these bounds that the critical height of the wall lies, in which it might collapse. This critical dredge height should be calculated in the next chapter to determine the maximum dredge height for the prototype. However, this height is also affected by the soil, thus particular soil conditions must be addressed. According to the depth lock release theory, it can also be concluded that gravity currents will be induced by the CDS, with a certain velocity.

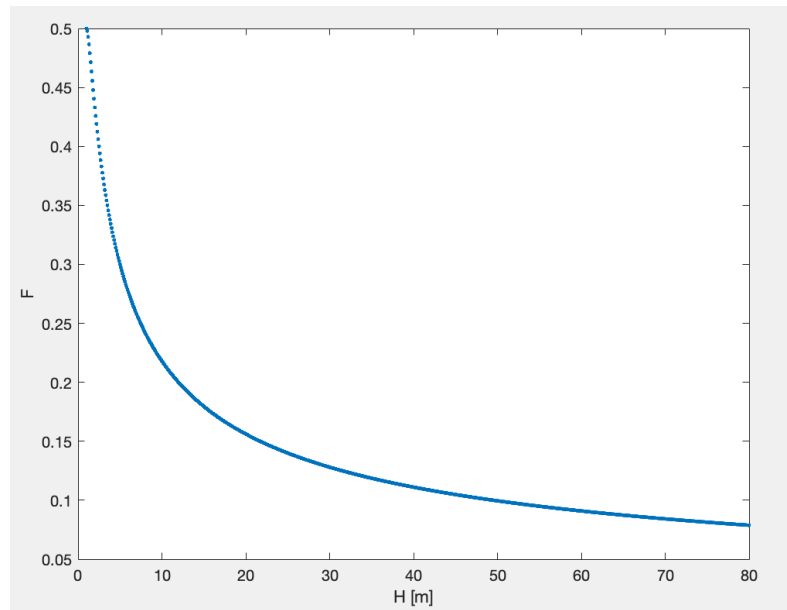


Figure 4.26: Froude number according depth

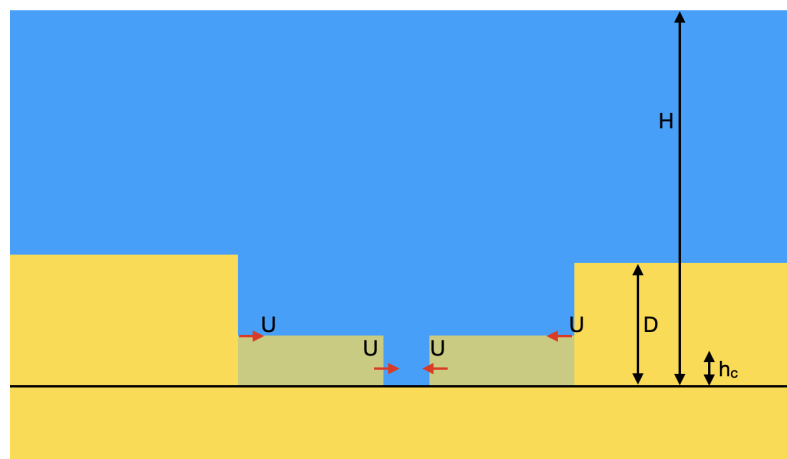


Figure 4.27: Sketch of depth-lock exchange

5

APPLICATION THEORY CDS

In [Chapter 4](#), a theoretical approach of the CDS is given. In this chapter the theory will be applied on the existing prototype of the CDS.

In this chapter calculations are done how the pressure in the chamber remains constant. Furthermore, calculations are done, what the critical dredge height is to dredge of the CDS and what the consequences can be.

5.1 GENERAL INFORMATION

To apply the theory on the CDS some unknowns need to be set. In the table below all the variables and known values can be found.

Variable	Symbol	Value	Unit
Volume flow compressor/inlet	Q_{inlet}	0.375	m ³ /s
Volume flow pump	Q_{pump}	0.03	m ³ /s
Volume flow air/water outlet	$Q_{air/wateroutlet}$		m ³ /s
Friction coefficient	f	0.04	
Kinematic viscosity air	ν	$1.5 \cdot 10^{-5}$	m ² /s
Length of narrowing part in the outlet	L		m
Length of air/water outlet	L_{outlet}	5.2	m
Length of horizontal part of air/water outlet	$L_{horizontal}$	0.2	m
Pressure behind narrowing part	p_1	$101.3 \cdot 10^3$	Pa
Pressure in chamber	p_2		Pa
Water density	ρ_{water}	1025	kg/m ³
Air density at atmospheric pressure	ρ_{airatm}	1.20	kg/m ³
Density	ρ		kg/m ³
Air density in chamber	$\rho_{airchamber}$		kg/m ³
Dredged sediment density	ρ_{slib}	1300	kg/m ³
Average air density over narrowing part	ρ_{avg}		kg/m ³
Diameter air/water outlet	D_{pipe}	0.14	m
Diameter of the air flow through the outlet	D_{air}		m
Dredging depth	d	4	m
Gravitational acceleration	g	9.81	m ² /s
Molecular mass	M	28.97	g/mol
Average temperature on earth	T	289	K
Gas constant	R	8.314	J/K/mol
Cohesive strength	c	200	Pa
Volumetric weight Buoyancy	γ_B		N/m ³
Volumetric weight	γ		N/m ³
Weight	W		N
Volume	V		m ³
Area that will collapse	$A_{collapse}$		m ²
Volume that will collapse	$V_{collapse}$		m ³
Perimeter of CDS	P	4.5	m
Length CDS	l_1	2	m

Width CDS	l_2	2.5	m
Dredge height of CDS	h	1	m
Mass	m		kg
Superficial gas velocity	v_{sg}		m/s
Area of air/water outlet	$A_{air/wateroutlet}$		m ²
Mach Number	Ma		
Specific heat ratio	γ		

5.2 AIR SPEED AIR/WATER OUTLET

To understand how the pressure regulation of the chamber, the theory of [Morrison 2004](#), can be used as explained in [Section 4.2.3](#). With this theory, it can be estimated what happens in the air/water outlet. However, there was also mentioned that the volume flow for this theory should be turbulent. Thus, firstly this needs to be confirmed by calculating the Reynolds number.

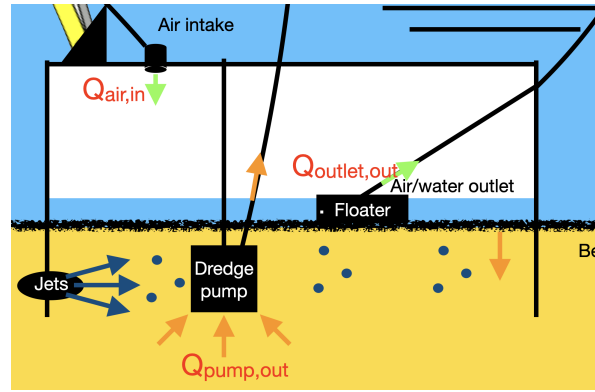


Figure 5.1: Volumetric flows CDS

As there are many volume flows within the CDS; the air that is compressed into the chamber, the dredging pump that dredges water and silt away, which can also be seen in [Figure 5.1](#). The air that is compressed into the chamber remains constant at 22.5m³/min or 0.375m³/s. The dredge pump also works at a constant pace of 1.8m³/min or also 0.03m³/s. The volume flow of the jets is not considered as it is expected that the influence is small. The volume flow that leaves the chamber is calculated in [Equation 5.1](#).

$$Q_{air/wateroutlet} = Q_{airinlet} - Q_{pump} = 0.375 - 0.03 = 0.345m^3/s \quad (5.1)$$

By using the air outflow, Q_3 , the superficial gas velocity that passes through the outlet pipe can be calculated. [Equation 5.2](#) the flow velocity according to the air velocity and the diameter is shown. [Equation 5.2](#) rewritten to the superficial gas velocity in [Equation 5.3](#) can help estimate the minimum required liquid flow pattern. The diameter of the entire pipe is used for this calculation, thus v_{sg} can only be higher and the gas flow pattern depends on the superficial gas velocity, as shown in [Figure 4.13](#). The map shows that the higher the velocity the pattern will be annular.

$$Q_{air/wateroutlet} = v_{sg} \cdot A_{air/wateroutlet} = v_{sg} \cdot \frac{\pi d_{pipe}^2}{4} \quad (5.2)$$

$$v_{sg} = \frac{4 \cdot Q_{air/wateroutlet}}{\pi \cdot d_{pipe}^2} = \frac{4 \cdot 0.345}{\pi \cdot 0.14^2} = 22.4m/s \quad (5.3)$$

By knowing the volume flow through the air/water outlet, the Reynolds number can be calculated. In Equation 5.4, D_{air} is the maximum diameter where the air can flow through. As D_{air} is in the denominator and the maximum value is taken, the outcome of the Reynolds number can only increase whenever the real D_{air} is taken. The air velocity, v , of the formula can be substituted by $v = \frac{Q}{A}$.

$$Re = \frac{vD_{air}}{\nu} = \frac{\frac{Q}{A}D_{air}}{\nu} = \frac{\frac{Q}{\frac{\pi D_{air}^2}{4}}D_{air}}{\nu} = \frac{4Q}{\pi D_{air}\nu} = \frac{4 \cdot 0.345}{\pi \cdot 0.14 \cdot (1.5 \cdot 10^{-5})} = 2.0918 \cdot 10^5 \quad (5.4)$$

A flow is turbulent when the Reynolds number is larger than 3500, which is the case for the CDS' prototype. Thus, the Morrison's theory of the isothermal compressible flow can be applied.

The air will leave the chamber via the air/water outlet. In this outlet water will behave as a resistor for the air, but how this happens is an uncertainty and to know the exact answer tests should be done. For this reason, three scenarios will be considered. However, for all the scenarios Equation 5.5, the isothermal flow equation, will be used to calculate what the diameter is where air will flow through.

$$f \frac{L}{D_{air}} = \frac{\gamma R T D_{air}^4 \pi^2}{16 M Q_{air/wateroutlet}^2} \left[1 - \left(\frac{p_1}{p_2} \right)^2 \right] - \ln \left(\frac{p_2}{p_1} \right)^2 \quad (5.5)$$

In Equation 5.5 only the D_{air} should be the unknown. As Equation 5.5 is a fifth degree equation, it is not easy to solve it numerical. For this reason an equation will be plotted against the length of the pipe, which can be seen in Equation 5.6.

$$L = \frac{\gamma R T D_{air}^5 \pi^2}{16 M f Q_{air/wateroutlet}^2} \left[1 - \left(\frac{p_1}{p_2} \right)^2 \right] - \ln \left(\frac{p_2}{p_1} \right)^2 D_{air} \quad (5.6)$$

p_2 , p_1 and ρ_{avg} should be calculated. For p_1 , the atmospheric pressure is taken, 101.3 kPa, as it is considered that after the resistance of the water, the pressure should be equal to the atmosphere. p_2 can be calculated according to the hydrostatic pressure laws as shown in Equation 5.7 and explained in Section 4.2.1.

$$p_2 = p_1 + \Delta P_{12} = p_1 + \rho_{water} g d = 101300 + 1025 \cdot 9.81 \cdot 4 = 141.5 \text{ kPa} \quad (5.7)$$

ρ_{avg} is depending on the air density at a atmospheric pressure, ρ_{airatm} and in the chamber, $\rho_{airchamber}$. Equation 5.8 shows how ρ_{avg} can be calculated.

$$\rho_{avg} = \frac{\rho_{airatm} + \rho_{airchamber}}{2} \quad (5.8)$$

ρ_{airatm} is known, $\rho_{airchamber}$ is depending on the pressure inside the chamber and can be calculated by the ideal gas law, shown in Equation 5.9.

$$\rho_{airchamber} = \frac{p_2 M}{R T} = \frac{(141.5 \cdot 10^3) \cdot 28.97}{8.314 \cdot 289} = 1.71 \text{ kg/m}^3 \quad (5.9)$$

By knowing $\rho_{airchamber}$, ρ_{avg} can be calculated in Equation 5.10

$$\rho_{avg} = \frac{\rho_{airatm} + \rho_{airchamber}}{2} = \frac{1.2 + 1.71}{2} = 1.45 \text{ kg/m}^3 \quad (5.10)$$

1. The first case that is considered, the water in the pipe divides itself over the whole length of the pipe, as can be seen in Figure 5.2. So that the L in Equation 5.5 is equal to L_{outlet} .

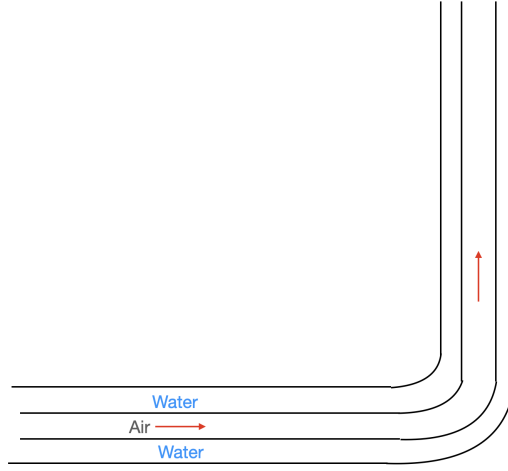


Figure 5.2: Variable diameter over whole length of outlet

Equation 5.11 shows the equation filled in for the diameter of the air flow to go through. In Figure 5.3 the blue line shows the right-hand side equation (RHS) of Equation 5.11 and the red line the length of the obstruction (L). The intersection of the two lines shows that the diameter for the air flow will be at 0.0594m or 5.94cm.

$$L = \frac{\gamma R T D_{air}^5 \pi^2}{16 M f Q_{air/wateroutlet}^2} \left[1 - \left(\frac{p_1}{p_2} \right)^2 \right] - \ln \left(\frac{p_2}{p_1} \right)^2 D_{air}$$

$$\Leftrightarrow$$

$$5.2 = \frac{1.4 \cdot 8.314 \cdot 289 \cdot D_{air}^5 \cdot \pi^2}{16 \cdot (28.97 \cdot 10^{-3}) \cdot 0.04 \cdot 0.345^2} \left[1 - \left(\frac{101300}{141500} \right)^2 \right] - \ln \left(\frac{141500}{101300} \right)^2 D_{air} \quad (5.11)$$

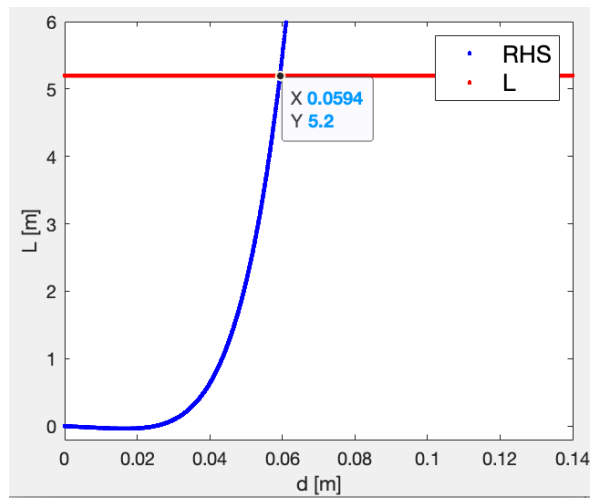


Figure 5.3: Isothermal flow equation with an obstruction over whole length outlet

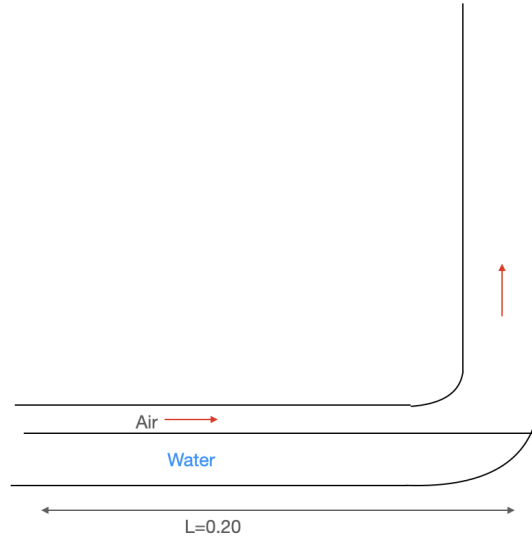


Figure 5.4: Horizontal part of outlet obstructed

2. In scenario 2, the water only obstructs the horizontal part of the air/water outlet as shown in Figure 5.4. D_{air} can be found by using the isothermal flow equation. The difference compared to the first scenario is that L is not the whole length of the obstruction but only the horizontal part so 0.2m. Equation 5.12 shows the equation filled in for the air opening in the air/water outlet and Figure 5.5 shows the right-hand side equation (RHS) and the length of the obstruction (L) intersecting each other. The intersection shows that the air opening will be 0.0329m or 3.29cm. The air flow will go through a diameter of 3.29cm in case 2.

$$L = \frac{\gamma R T D_{air}^5 \pi^2}{16 M f} \left[1 - \left(\frac{p_1}{p_2} \right)^2 \right] - \ln \left(\frac{p_2}{p_1} \right)^2 D_{air}$$

$$\Leftrightarrow$$

$$0.2 = \frac{1.4 \cdot 8.314 \cdot 289 \cdot D_{air}^5 \cdot \pi^2}{16 \cdot (28.97 \cdot 10^{-3}) \cdot 0.04 \cdot 0.345^2} \left[1 - \left(\frac{101300}{141500} \right)^2 \right] - \ln \left(\frac{141500}{101300} \right)^2 D_{air}$$

(5.12)

3. The third scenario that is considered is when the length, L , of the obstruction and air diameter, D_{air} , are variable. Equation 5.13 shows the equation with the two variables. All the other unknowns are known and can be filled in.

$$L = \frac{\gamma R T D_{air}^5 \pi^2}{16 M f} \left[1 - \left(\frac{p_1}{p_2} \right)^2 \right] - \ln \left(\frac{p_2}{p_1} \right)^2 D_{air}$$

$$\Leftrightarrow$$

$$L = \frac{1.4 \cdot 8.314 \cdot 289 \cdot D_{air}^5 \cdot \pi^2}{16 \cdot (28.97 \cdot 10^{-3}) \cdot 0.04 \cdot 0.345^2} \left[1 - \left(\frac{101300}{141500} \right)^2 \right] - \ln \left(\frac{141500}{101300} \right)^2 D_{air}$$

(5.13)

As Equation 5.13 has two variables, this can be plotted into a diagram as can be seen in Figure 5.7.

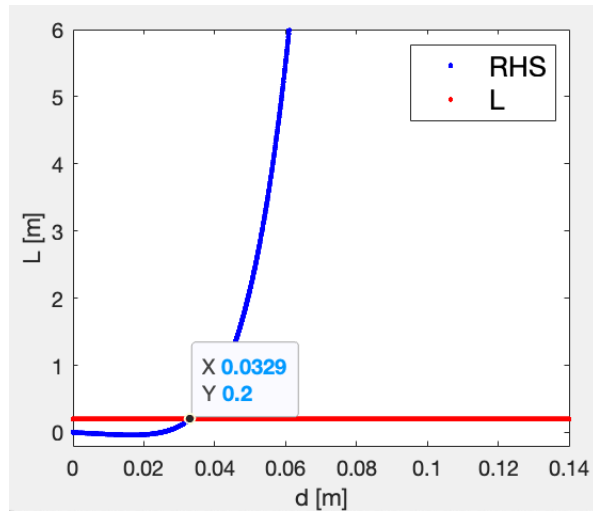


Figure 5.5: Isothermal flow equation with an obstruction over horizontal length outlet

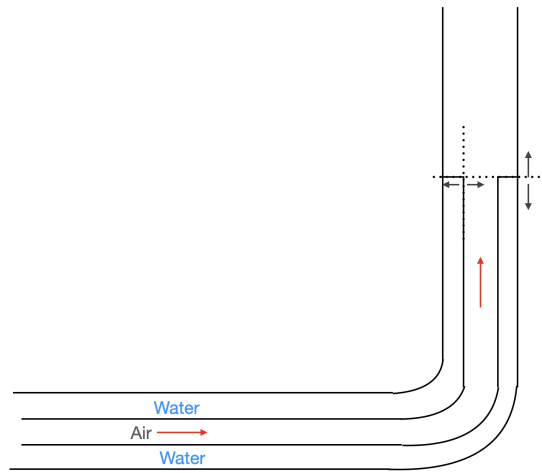


Figure 5.6: Variable length of obstruction through outlet

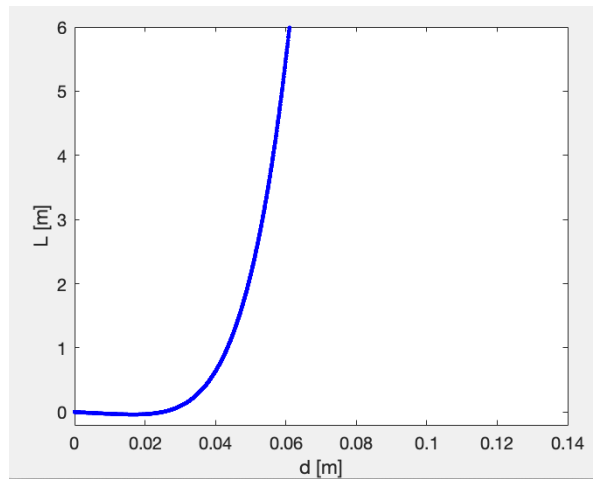


Figure 5.7: Variable length of obstruction through outlet

5.3 CRITICAL DREDGING HEIGHT

The critical dredge height, the height that can be dredged before the vertical wall that is left behind collapses, should be calculated. The theory can be found in

Equation 4.3.3. When the critical dredge height is known, it can be known whether or not the CDS exceeds this dredge height and will create turbidity. If the CDS creates turbidity a calculation can also be done of the volume that will shove away from the vertical wall.

In **Equation 5.14** the boundary conditions for the critical height are set as explained in **Equation 4.3.3**.

$$\frac{2c}{\gamma_B} \leq h_c \leq \frac{4c}{\gamma_B} \quad (5.14)$$

In a case study for the prototype of the CDS, the volumetric weight, γ , should be calculated. **Equation 5.15** shows this equation. The volumetric weight is the weight to the volume. The weight can be rewritten to mass multiplied by the density and mass is equal to the volume multiplied by the density. In this way the volumetric weight can be calculated by the gravitational acceleration multiplied by the density.

$$\gamma = \frac{W}{V} = \frac{mg}{V} = \frac{\rho Vg}{V} = \rho g \quad (5.15)$$

It is assumed that the density of the soil that needs to be dredged is 1300kg/m³. This number was measured in the Port of Rotterdam by the TU Delft. In the calculation for the volumetric weight the Buoyancy can not be forgotten, in **Equation 5.16** the density of the slib is subtracted with the density of the sea water.

$$\gamma_B = (\rho_{slib} - \rho_{water})g = (1300 - 1025) * 9.81 = 2649N/m^3 \quad (5.16)$$

If the result is applied to **Equation 5.14**, the boundary conditions are filled in in **Equation 5.17**. For the cohesive strength, c , a value of 200Pa is taken. The result can be found in **Equation 5.18**.

$$\frac{2 * 200}{2649} \leq h_c \leq \frac{4 * 200}{2649} \quad (5.17)$$

$$0.151m \leq h_c \leq 0.302m \quad (5.18)$$

Given the outcome of these calculations and knowing that the current prototype is capable to dredge easily up to one meter, the vertical wall that is left behind after dredging will collapse as it is larger than the critical dredge height. Furthermore, this theory only applies on purely cohesive material ($\phi = 0$). In reality, due to the theory of lock exchange, a density current can occur because of the pressure density difference.

Thus, it can be stated that the critical dredge height for the prototype is only 15.1-30.2cm. This means that if large areas need to be dredged, this technique might not be appropriate, as the CDS is designed to avoid creating turbidity.

Now **Verruijt's** theory of can be used further to calculate the amount of slib that will collapse from the wall. **Figure 5.8** shows what part will shove away from the vertical wall by using **Equation 5.19**. As the critical dredge height is exceeded with for angle α of 45 degrees. It can be assumed that in **Equation 5.19**, α is equal to 45 degrees.

$$h = \frac{4c}{\gamma} \frac{1}{\sin(2\alpha)} \quad (5.19)$$

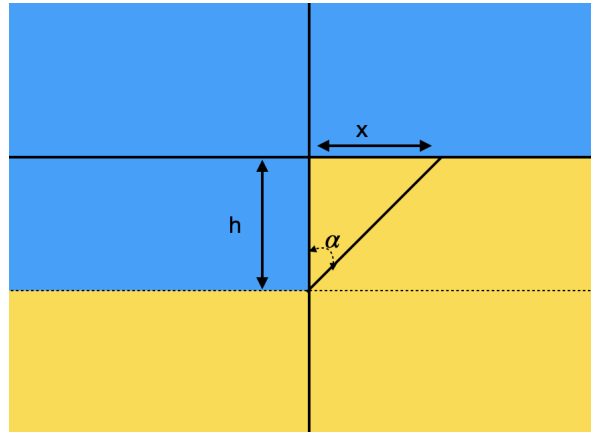


Figure 5.8: Volume that will collapse

Figure 5.8 shows what area of the vertical wall that will collapse after dredging. As α is known and h is equal to the dredge height, the width of the part that will collapse, x , can be calculated. By knowing x the area of the triangle can be determined and by multiplying this outcome with the perimeter, P , of the area of the CDS, the total volume that will collapse can be known.

$$A_{collapse} = \frac{hx}{2} = \frac{h \tan^{-1}(\alpha)h}{2} = \frac{1 \cdot \tan^{-1}(45) \cdot 1}{2} = \frac{1}{2} \quad (5.20)$$

By using Equation 5.20 and Equation 5.21, the volume that could collapse is determined and is equal to $4.5m^3$. If this volume collapse according the lock-exchange theory, its vertical velocity will can be determined by using Figure 4.25.

$$V_{collapse} = A_{collapse} * P = A_{collapse} * 2(l_1 + l_2) = \frac{1}{2} \cdot 2 \cdot (2 + 2.5) = 4.5m^3 \quad (5.21)$$

There can be done an estimation of the volume of the slib that will collapse. As the dredged walls are opposite against each other the slib will clash in the middle of the dredge area, this can create an upward movement. The moving slib is turbidity, but it is not possible to guess how a turbidity cloud will be formed and how long it will remain in the watercolumn.

Furthermore, it is also unknown how the slib will shove away and how the shear wall will evolve. To determine this, further tests are needed. In this way, it can better understand how turbidity is formed by using the CDS.

5.4 CONCLUSION

This chapter concludes that the diameter through which air can pass through the air/water outlet is determined by how the water is distributed along the pipe. Every instance analyzed has a different outcome. When the diameter of the air flow path is known, the surface gas velocity is calculated, and for the first case, the gas fluid pattern is annular. Another finding is that the critical dredge height for the CDS at Rotterdam's port is between 0.15-0.30m. Because the prototype can dredge up to one meter, dredging with the CDS without causing turbidity is impractical.

6

TESTING OF CDS

In the [Chapter 4](#), the working principles and dredging cycle of the CDS is explained. To verify whether the CDS works as described, testing is needed. In chapter 5, it is tested if all the subsystems of the device are crucial and it also needed to test whether or not the CDS generates turbidity.

6.1 TEST PLAN

The testing will consist of two phases. Phase 1 has the aim to examine if the CDS' operation creates any external turbidity. Phase 2 addresses a close study of each of the CDS' mechanisms while operative. These two phases are explained in more detail below.

6.1.1 Test location

Firstly, a suitable location must be found for these experiments. The location should meet the following conditions: the bottom should consist of silt, sand or clay; the visibility underwater should be good (approximately one meter or more); it should have a quay strong enough to support a 35-ton crane; and the depth should be around 3-4 meters.

Several locations were considered to conduct the tests. In this section the decision of which location to use for each test phase is explained. For test phase 1 it is crucial to have a good visibility for observing any turbidity created outside the chamber. For test phase 2, the type of sediment is more important in order to examine all the mechanisms of the CDS.

Werkhaven Bommenede

The first option is at a location of Staatsbosbeheer Grevelingen, Zeeland Noord where the Werkhaven Bommenede is located and which could be available. Its location at the Grevelingen makes it ideal for the visibility required for the phase 1 test. The quay is also strong enough to hold the crane which is required and the depth of the water is around 4 meters. However, the bottom consisting of sand with many rocks and shells is not ideal for both tests. During test phase 1 only the influence external wants to be shown and no dredging height conditions are set. During phase 2, testing the CDS working mechanisms is more important, which requires silt, mud or clay.

6.1.2 Albert Canal

Albert Canal, near the Hydrex headquarters in Antwerp, would be a good option as the quay is strong enough to hold a crane of 35 tons and the proximity to Hydrex is convenient from the point of view of the equipment and personnel. The sediment at this location is soft, which is ideal to assess all the sub systems and mechanisms of the CDS. However, the visibility of this location is inadequate for phase 1 of the testing as it is only a few centimeters.

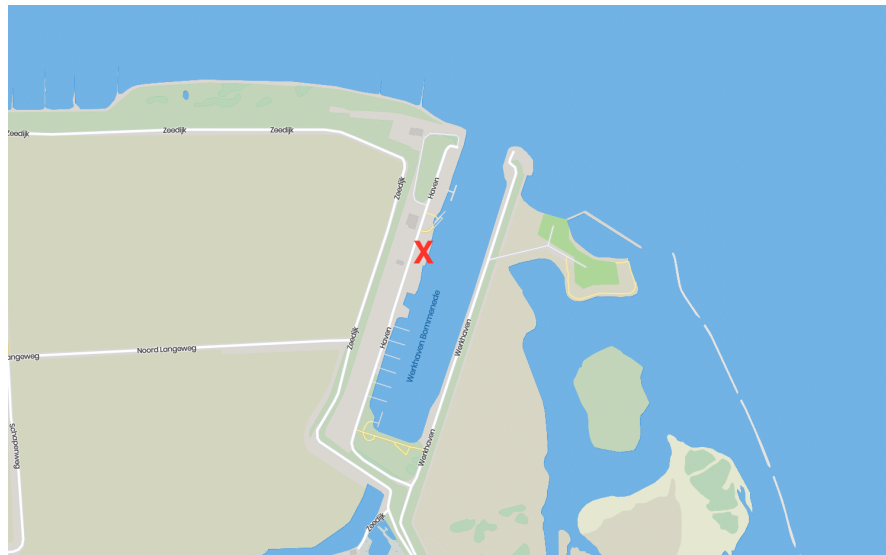


Figure 6.1: Werkhaven Bommenede

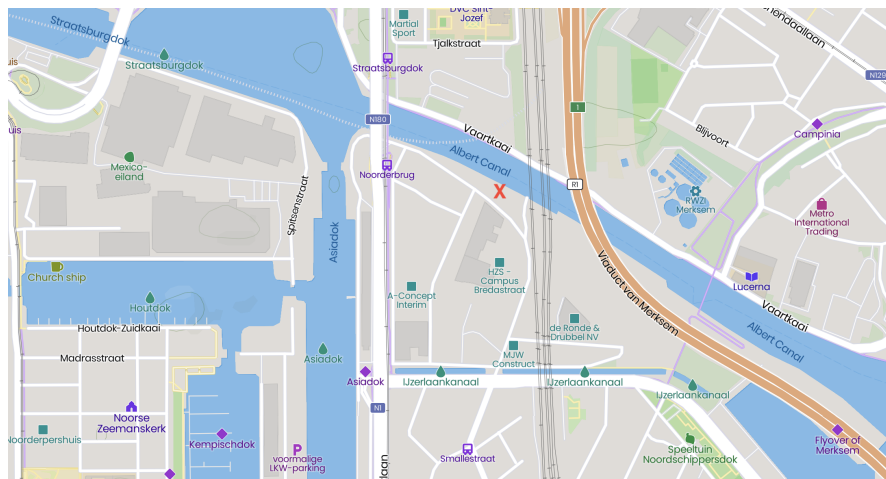


Figure 6.2: Albert Canal

Test location decision

Figure 6.2 and Figure 6.1 should the two locations mentioned above on the map.

To decide on the best location for each phase of the testing the decision matrix in Table 6.1 is used. Neither of the considered options is perfect for both test phases. Each has the same number of advantages as disadvantages. This resulted in choosing two locations, one for each phase. One to verify whether or not the CDS creates any turbidity, as per test phase 1 and the other for observing the CDS working principles per test phase 2. For phase 1, the visibility is really important, so the Werkhaven Bommenede is the better choice. To test the systems and the working principles of the device per phase 2, the bottom conditions at the Albert Canal are ideal. The bottom at Werkhaven Bommenede has too many stones and shells which can cause damage to the relatively small size pump of the model CDS. For testing the working principles, the inside of the chamber needs to be observed rather than the outside.

	Werkhaven Bommenede	Albert Canal
Visability	+	-
Depth	+	+
Bottom conditions	-	+
Strength of quay	+	+

Table 6.1: Decision matrix test location

6.1.3 Test equipment

Hydrex will take care of all the equipment, logistics and personnel required for the testing. This includes the model of the CDS, and the two 250hp power packs required, one for the dredging pump and the other for the jets. Also an air compressor for the air, pipes for the dredged silt, the air inlet and the air/water outlet, and electrical cables. Hydrex personnel will help during testing with setting up and handling the machinery and coordinating and filming the process. This includes divers for filming the outside of the chamber. Hydrex will also provide GoPro-cameras, lighting and monitoring equipment for observing in real time and recording what is happening under water [Figure 6.3](#).



Figure 6.3: Monitoring system

For the dredging experiments Hydrex will also rent a hydraulic excavator. For phase 1 the Volvo ECR355EL, [Figure 6.4a](#), was used with an arm width of 22'4" ft which is equal to 6.8 m. For phase 2 in Antwerp, another excavator was used, the Doosan DX340LC-5, [Figure 6.4b](#), which has a digging depth of 7.5 m.



(a) Volvo ECR355EL



(b) Doosan DX340LC-5

Figure 6.4: Excavators used during testing

6.1.4 Phases of testing

Phase 1: CDS turbidity

During phase 1, the test will be done at Werkhaven Bommenede. The main goal is to see in the clear water whether or not the CDS creates turbidity outside the chamber. A diver will be under water with an underwater camera to film everything that happens, as can be seen in [Figure 6.5](#). The purpose is to test the whole system in its full capacity as described in [Chapter 4](#) and [Section 4.1.2](#). To verify whether the CDS will cause any external turbidity at all.

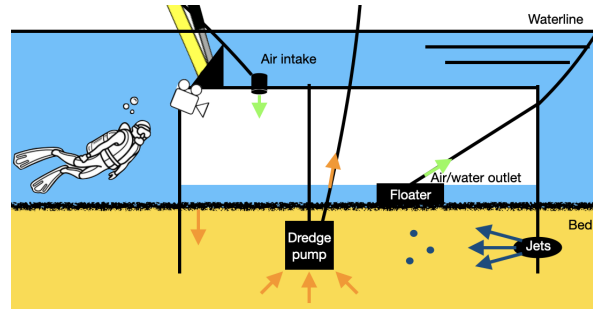


Figure 6.5: Drawing of diver around CDS for verifying turbidity

Phase 2: CDS working mechanisms

The working mechanisms of the CDS will be examined by reviewing all the dredge stages as mentioned in [Section 4.1.2](#) and observing all the criteria. All the sub-systems should also be tested. If any of the mechanisms or sub-systems do not work as predicted, detailed inquiry is necessary to detect any malfunction. This should be performed to enable further development.

Dredging cycle

In [Section 4.1.2](#) the working principles of the CDS are explained. The dredge stages should be observed and the following factors reviewed:

1. The accuracy of the device in full operation mode should be tested.
2. Air intake and air/water outlet
The volume of air that the compressor can pump into the chamber needs to be able to escape through the air/water outlet and not be forced out another way. Furthermore, the effect that different positions of the air/water outlet have should be observed.
3. Floater
It must be verified that the floater always rests on silt and not on water.
4. Dredging pump
The current configuration of chamber and pump needs to be checked to make sure that the pump is pushed down into the silt. It should be ascertained how fast the pump can dredge the contents of the chamber.
5. Jets
The effects of the jets on the soil should be tested. How does the water that is pumped into the silt behave? This could be observed by filming in the chamber.

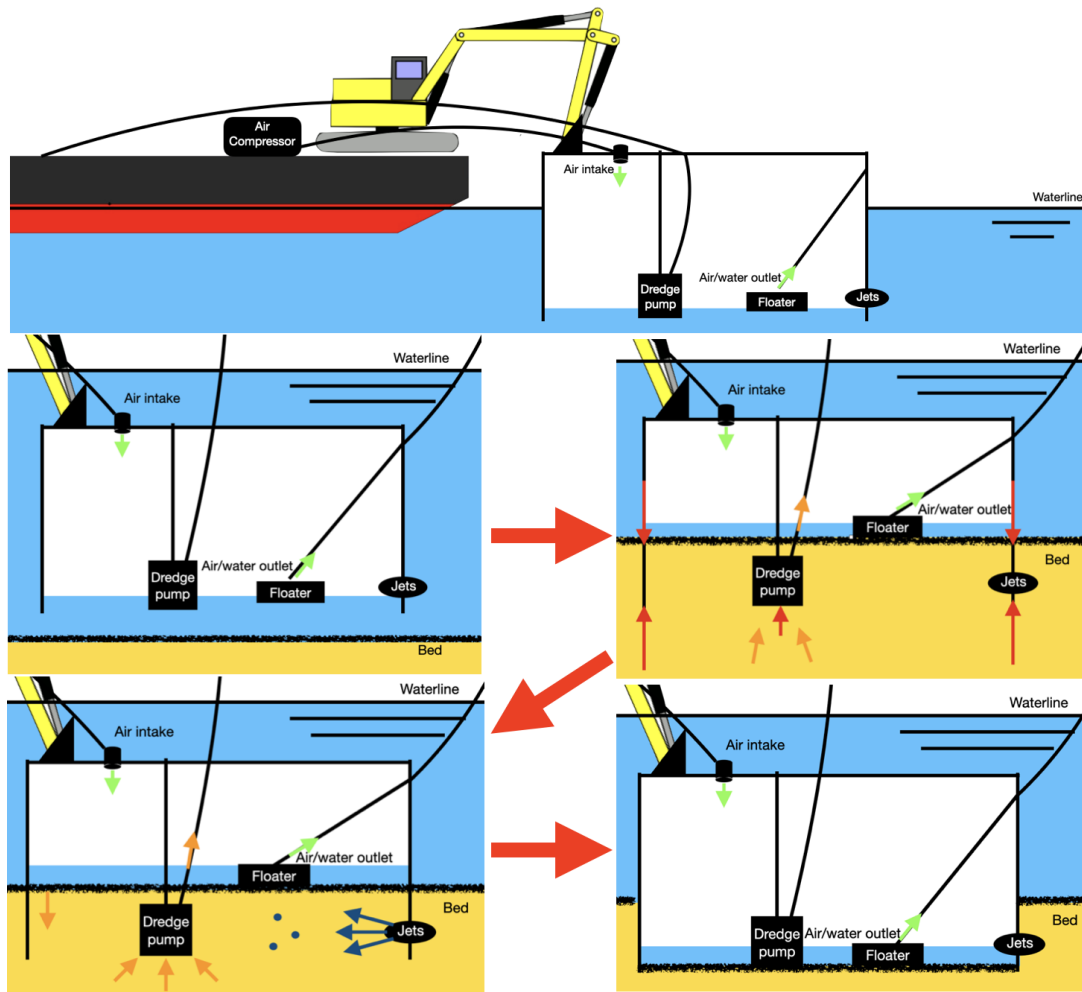


Figure 6.6: All the dredging cycles

Sub-systems

Each of the sub-systems needs to be evaluated in phase 2:

1. Air intake and air/water outlet

The air intake and outlet together with the compressor are responsible for the air in the chamber. This system must allow a change in pressure and volume. To test the necessity of these systems, the CDS will be tested first with a blocked outlet and later on with the air compressor switched off.

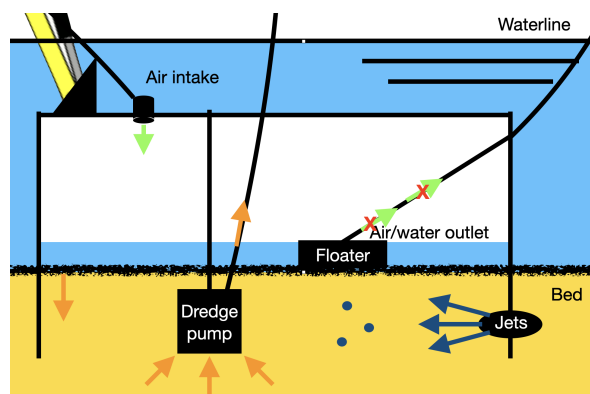


Figure 6.7: Blocked outlet

2. Floater

The floater will have to float on silt and not on water. The floater is a critical tool to maintain the air level in the chamber. The air level is always maintained at the level of the floater in the chamber by allowing excess air to escape through the outlet. In this test, the floater will be fastened to the ceiling to see if the water level would rise all the way to it.

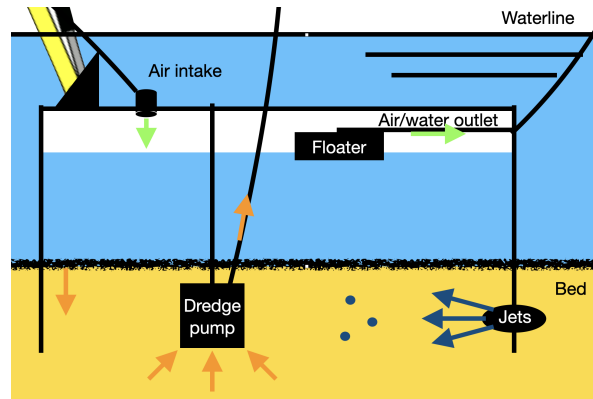


Figure 6.8: Floater attached to ceiling

3. Dredging pump

The dredging pump needs to be attached to the chamber strongly enough so that it can be pushed into the silt, so that silt can be dredged.

4. Jets with the pump

The jets are needed to fluidize silt in the chamber. This process needs to be checked as part of phase 2.

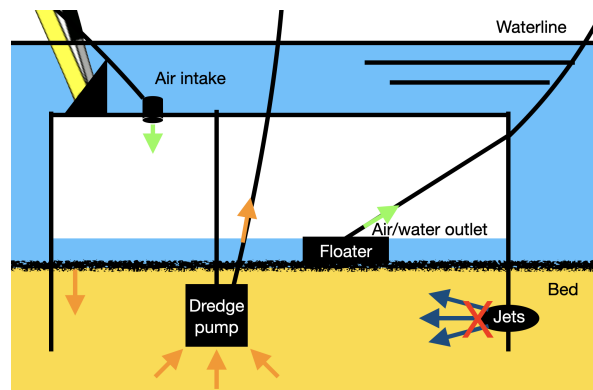


Figure 6.9: Jets are switched off

6.1.5 Data collection structure

The data will mainly be collected by filming throughout the procedure. Only during phase 1, the area outside the chamber must be recorded. In both phases the activity inside the chamber must also be recorded. Cameras will be placed inside the chamber and a diver will handle the external filming in phase 1. Figure 6.5 shows the set up of the cameras. Due to recording throughout testing, all of the footage can be carefully studied afterwards, which allows for more careful analysis.

6.2 OBSERVATIONS

6.2.1 Testing for turbidity

The goal of phase 1 was to observe if any turbidity was created by the CDS. The good underwater visibility at Werkhaven Bommenede made it easy to observe the presence or absence of turbidity. The first step was to set up the entire CDS system at the site. The CDS was attached to an excavator arm in order to lower it to the bottom and raise it as needed. The excavator was stably positioned on the quay next to the water. Pipes were connected to the CDS to drain the sediment while pumping. An inlet pipe was connected from the air compressor to the top of the chamber and the air/water outlet pipe was attached to the chamber as well. Cables from the camera in the chamber were connected to the monitor on the quay. Power packs were connected to the dredging pump and the jets. In order to record any turbidity occurring outside the chamber, the testing at Werkhaven Bommenede also included a diver who could video the exterior. [Figure 6.10](#) shows the setup of test phase 1.



Figure 6.10: Testing at Werkhaven Bommenede

Once the first setup step was completed, the next step was to place the CDS in the water. Before the CDS entered the water, the air compressor was switched on and the camera inside the chamber was started so that the activity inside the chamber could be recorded throughout the entire process. In order not to damage the CDS model's pump, the bottom of the chamber was immersed in the water before the pump was activated.

With these setup steps completed, the next phase of the test was to lower the chamber to the seabed. It was not pushed into the seabed as it would have been with normal dredging because the purpose of this phase was only to establish whether or not negative pressure was created inside the chamber with relation to the surrounding water so that silt and any turbidity would be sucked into the chamber rather than pushed out of it. Also, to establish whether or not any turbidity was created outside the chamber during the dredging process.

While the chamber was being lowered, the diver was already in position observing whether the fact of lowering the chamber itself created turbidity and the

diver did not observe any turbidity created by this action.



Figure 6.11: Photo of CDS on the bottom without turbidity with pump on

With all the sub-systems, except the jets, switched on, it could clearly be seen that the chamber developed a negative pressure in relation to the outside marine environment, as sand, pebbles and shells outside the chamber were sucked into it. This relationship of the inside to the outside pressure had been predicted but the test demonstrated it conclusively. With the pump running, there was no tendency for any material inside the chamber to be pushed out to the surrounding water. Rather, the opposite occurred. Figure 6.11 shows the chamber on the bottom without any turbidity being created outside, while on the inside, the pump was creating a great deal of turbidity around the pump, Figure 6.12. Only the area around the pump was turbid since the jets were not turned on. These two figures show a clear comparison of the outside and inside of the chamber, while the pump is running.



Figure 6.12: Photo inside chamber with pump on

Afterward, the influence of the jets was also tested. Even with the jets on, no turbidity was created outside the chamber and sand, pebbles and shells from the outside continued to be sucked into the CDS despite the considerably increased turbidity inside, Figure 6.13.

For the next step of the test the CDS was raised 5 cm above the bottom to see if in this position turbidity would be created outside the chamber. With the chamber raised slightly and the pump running (but not the jets), it could be seen by the diver that no turbidity was being created, Figure 6.14.



Figure 6.13: Photo inside chamber with jets on



Figure 6.14: Photo of CDS pushed of bottom without turbidity

Note, that the CDS was only standing on top of the bed and was not pushed in. Furthermore, when the CDS was raised out of the sediment with the pump switched on, an over pressure was created which released turbidity into the surrounding water outside the chamber. This shows that in order to avoid turbidity, at least with this model, the pump needed to be switched off for as long as the chamber is raised from the bottom.

6.2.2 Testing the whole system

The whole working principle of the CDS was examined at the Albert Canal. The setup at the Albert Canal was the same as in [Section 6.2.1](#) except that no diver was present to observe what was going on under water outside the chamber. The diver's absence is due to the phase 1 testing. There, it has been demonstrated that no turbidity was created outside the chamber when the CDS was working on top of the bed.

As with the phase 1 test, the air compressor and camera were already switched on before the CDS was lowered into the water. As soon as the bottom of the chamber was below the surface of the water the pump was switched on and the CDS lowered to the bottom of the canal.

A key difference between the phase 1 test and the phase 2 test is that in this case the chamber was pushed about forty centimeters into the silt. When the CDS was pushed into the silt and all sub-systems were activated, it could be seen that the

silt/water level in the chamber was dropping. Because of the activation of the jets, a great deal of turbidity was observed inside the chamber, [Figure 6.15](#).



Figure 6.15: Photo of the CDS while testing with all sub-systems activated

When the air/water outlet was at the waterline and the water inside the chamber was not stirred up but standing still, only air from the chamber came through the pipe. However, the water was mostly stirred because of movements of the excavator, or because of the influence of the pump or jets. Resulting in the air outlet often being blocked by water. Thus, both air and water were expelled from the chamber through the pipe due to pressure differences. Meaning that, when there was a change of pressure in the chamber due to the hydrostatic pressure change outside the chamber, as a result of lowering or rising the chamber, water was also expelled through the pipe. In [Figure 6.16](#), the turbulence, created by the jets, causes water to obstruct the opening of the air/water outlet and resulted in water being pushed through the pipe. A theoretical explanation of how the air/water outlet could regulate itself can be found in [Section 4.2.3](#), although this is an assumption.



Figure 6.16: Air/water outlet underwater

6.2.3 Sub-systems

During the subsystem test each subsystem was switched off in turn in order to verify whether it was crucial to the functioning of the CDS.

Floater

To determine the importance of the floater and its position, it was tied to the top of the CDS by experiment, as shown in [Figure 6.17](#). When the CDS was pushed down with the floater out of use, and all systems were turned on, the air/water outlet could not function. The result was that the entire chamber filled with water. Also, since the floater was not there to determine the level of the silt, the CDS was unable to dredge precisely.



Figure 6.17: Floater attached to top of the CDS

Air/water outlet

To test the need of the air/water outlet, the end of the pipe was blocked, as can be seen in [Figure 6.18](#). This prevented the excess air in the chamber from escaping via the outlet. Thus, the air was forced out from the bottom of the chamber. This resulted in silt also being forced out from the bottom of the chamber.



Figure 6.18: Closed air outlet

Dredging pump

The influence of the dredging pump was tested at the Werkhaven Bommenede site and is described in [Section 6.2.1](#).

Jets

When the jets were not operating, the pump only pumped up the nearest silt. Silt located further away from the pump could not be stirred up and dredged away. In [Figure 6.15](#), the jets are not switched on yet. Thus, it can be seen that in the left lower corner the silt is not liquefied and therefore cannot be pumped out of the chamber.



Figure 6.19: Photo of the CDS while testing without jets activated

6.3 ANALYSIS OF RESULTS

6.3.1 Turbidity caused by the CDS Model

In [Section 6.2.1](#), the turbidity around the CDS chamber is observed and recorded. When the CDS model was operated in the prescribed manner no turbidity was observed by the diver outside the chamber. In fact, the CDS acted as an underwater vacuum cleaner, sucking nearby outside silt.

However, when the dredge was hopped, elevated for more or less 10 cm and all the sub elements were in operation, turbidity escaped from the chamber to its surroundings. One reason to explain this phenomenon could be that, due to density differences, this turbidity drifted outward. In addition, due to a slight pressure difference inside the chamber relative to its surroundings, the turbidity plume received an additional acceleration to escape due to Newton's second law, action is reaction.

6.3.2 Accuracy of the CDS model

The current CDS model used for the testing had both jets and pump fixed. (Plans already exist to make both pumps and jets fungible in future versions.) With jets and pump fixed while dredging a seabed consisting largely of pebbles, rocks and shells, it was not possible to leave the dredged area perfectly smooth after dredging. This was due to the large size and consistency of the bottom material which the

jets were not able to liquefy sufficiently for everything to be pumped out. Thus, employing a fixed pump entails that a small accumulation of silt remains around the pump head. This is more pronounced for the rocky seabed than with mud.

Therefore, it can be stated that in order for the CDS to be more precise in its dredging operations, the pump or pumps and the jets need to be fungible within the chamber. Plans are already in existence to do so ¹.

Apart from this, the model of the CDS proved to be adequate where it is positioned. Nevertheless, a better way on how to complete a dredging area, still needs to be examined. Since it was not possible to get a clear image of the dredged place at Albert Canal and at Werkhaven Bommenede the underground was not optimal to dredge very smoothly.

6.3.3 Depth of the CDS model

The depth of the bottom in both testing locations was around 4 meters.

In the first test location, Werkhaven Bommenede, the rocky seabed meant that the CDS could not be pushed deeper into the sediment without possible damage to chamber itself. However, this did not affect the test since phase 1 of the test was only concerned with turbidity around the chamber.

In the second test location, Albert Canal, the sediment on the bottom was soft and it was easy to push the CDS into it to a depth around 40 cm. It was clear that the chamber could have been pushed deeper into the silt, but this was not needed for the purposes of testing all the subsystems and working principles which was the aim of phase 2 of the testing.

The phase 2 testing pointed out that when a full scale CDS is build, there will be no practical limitation to the depth of dredging apart from the crane arm's length.

6.3.4 CDS model volume and time

During testing, a relatively small 15 cm pump was used. This is capable of only pumping 150 m³/h. The full scale CDS will have a number of larger pumps and will therefore be capable of pumping 4000 m³/h.

Phase 1 testing

The CDS is capable of dredging without creating turbidity in the surrounding marine environment. But when hopping, turbidity was observed by the diver escaping from inside the chamber to the environment.

Phase 2 testing

The CDS system and sub-systems are all required for proper functioning and can be improved from the existing model mainly by making the existing pump or pumps and the jets movable within the chamber.

¹ For more information, please contact Hydrex.

6.4 CONCLUSION

It may be concluded that the CDS functioned during testing. According to the results of turbidity testing, the CDS has little impact on the environment. The reliability of this finding is limited, since, the CDS was only pushed up around 10cm during the test. It should also be mentioned that the CDS was not used as intended during the turbidity testing.

7

DISCUSSION

Dredging can create turbidity where it is not supposed to occur and especially not in large amounts with contaminated sediment. This can be damaging to the marine environment, its ecosystems, fauna and flora.

The four main current dredging techniques, as previously discussed in [Chapter 3](#), are the clamshell, backhoe, trailing suction hopper dredger (TSHD) and cutter suction dredger (CSD). For a useful discussion of dredging to verify whether or not the contained dredging system (CDS) could be a better alternative to avoid turbidity, the CDS and its tests first need to be discussed. Then the current techniques need to be compared to each other and to the CDS. So, a conclusion can be drawn to what extend the CDS can be an improvement to the current dredging tools.

7.1 DISCUSSION OF APPLICATION OF THEORY ON CDS

The CDS consists of a chamber which can be lowered to the seabed or riverbed by means of an excavated arm or some other device. In short, the CDS works with a chamber, in which the dredging process takes place and an air supply and exhaust system. The air system is mainly added to counteract turbidity.

According to [Chapter 5](#), to remain the air pressure in the chamber the isothermal compressible flow theory can be used. However, this should also be verified by testing.

Furthermore, in [Chapter 5](#), the critical dredge height is calculated for the CDS. The critical dredge height is depending on the type of soil, not on the dredge tool. It might be that the pulling and pushing velocity of the CDS by the excavator could also influence this height. Additionally, an estimation is done of what the volume would be of the amount of turbidity that is created. Tests should be done of how the vertical walls collapse exactly and how it spreads.

7.2 DISCUSSION OF TEST

During phase 1 of the testing at Werkhaven Bommenede, it was observed that the CDS prototype works without creating turbidity outside the chamber in the surrounding marine environment. Even though the seabed at the test site consisted largely of shells, pebbles and rocks, a diver present stirred up a great deal of finer material with his hand. This was sucked into the chamber and again no turbidity was observed by the diver outside the chamber. However, these observations do not secure that the CDS does not create any turbidity. As a vacuum cleaner is placed on the ground just like the CDS on the bed, then of course it sucks everything along with it and so it does not create turbidity, as the CDS was not used in a proper way. Actually, tests should be done for turbidity when the CDS is completely pushed into the soil and then pulled up by the excavator. The CDS should dredge more than the critical dredge height. That way it can be seen what happens, that would

be a more appropriate environment to test the CDS for turbidity.

While no turbidity was observed during testing of the CDS by the current test setup, it cannot be said with certainty that the machine does not generate turbidity. There is still an uncertainty if the machine is used as described then turbidity could occur due to instability at the dredged environment. As the CDS dredges more than the critical dredge height, the vertical wall that is left behind will collapse.

Furthermore, the CDS was placed on a horizontal surface, tests should also be done on a surface with an incline.

7.3 COMPARISON CDS TO CURRENT DREDGING TECHNIQUES

Regarding the comparison of the CDS to the four main dredging techniques currently in use, it is important to keep in mind that a model is being compared to fully developed, industrialized machinery.

In [Section 3.5](#), it can be found that an enclosed bucket clamshell creates a small amount of turbidity. The clamshell generates turbidity when grabbing sediment and generates turbidity in the water column during bucket retrieval. The backhoe creates more turbidity than the clamshell as the clamshell bucket is more enclosed. For the clamshell counts that when the sediment is contained in an environmental closed bucket, turbidity is minimized. The operation is not affected from the outside, since the extraction of the sludge is conducted in a closed system. To really compare the existing dredge techniques more studies are needed. Furthermore, if it is not allowed to create turbidity that can affect the environment, then the further developed techniques should be considered.

However, in this thesis it is theoretically approached that the CDS will create turbidity. The CDS leaves a vertical wall behind after dredging. The critical height before it will collapse is rather small and is not practical to dredge with. This means that when the wall will collapse, the sediment will move with a certain velocity further to the dredged area. Implying that after dredging the CDS itself might be the cause of turbidity. However, the extent of the CDS affecting the environment is yet unknown. Density currents can thus occur after dredging, as previously stated. With regard to this, it needs to be pointed out that both the auger cutter suction dredger as well as the Scoop & Sweep dredger cause little environmental disturbance [[Eisma, 2005](#); [Vandycke et al., 1997](#)]. The Auger Cutter Suction dredger is able to dredge with great accuracy while minimizing turbidity [[Eisma, 2005](#)]. As does the Scoop & Sweep dredger scoops dredge, creating little disruption to the environment [[Vandycke et al., 1997](#)]. Additionally, the CSD has been improved such that the electric close blades cutter head produces little to no turbidity, and there are strategies for reducing turbidity in the overflow system.

Furthermore, the current dredging techniques have been improved. Unfortunately, it is not possible to use these improvements to adapt the CDS. As the main factor why the CDS generates turbidity is, that it leaves a vertical wall behind after dredging.

To come to a conclusion of this thesis, the sub-questions are first answered.

1. What is the impact of turbidity on the environment?

The definition of turbidity is sediment stirred up in the water column, what can have a negative impact on the environment. If turbidity is caused by men, it is mostly caused by dredging. As discussed, turbidity can have a significant detrimental impact on the ecosystem.

2. How do the existing dredging mechanisms generate turbidity? What existing methods do exist to prevent turbidity and its negative consequences?

The current dredging techniques (the clamshell, the backhoe, the trailing suction hopper dredger (TSHD) and the cutter suction dredger (CSD)) create turbidity according to this study. An enclosed clamshell creates a small amount of turbidity. The clamshell generates turbidity when grabbing sediment and generates turbidity in the water column during bucket retrieval, the same accounts for the backhoe. The TSHD and the CSD both generate turbidity by the overflow system within the barge and create a turbidity plume at their dredging head.

Even though traditional dredging techniques cause turbidity, these techniques have been altered and other advances have been made so that they may also be used with reduced turbidity. The existing dredging tools to prevent turbidity, discussed in this thesis, are the sweep and scoop dredger, the auger dredger, the environmental clamshell and the electric cutter head. To minimize the overflow turbidity an overflow plumigator can be used.

Turbidity during dredging can have negative impacts on aquatic ecosystems and the quality of water. Before dredging operations take place, a case study is done what the impact of dredging can be. Whenever turbidity because of dredging can have a negative effect on the environment, it should be tried to minimize turbidity during dredging and its impact on the environment. Physical, chemical, and biological methods can be used to minimize turbidity during dredging. Physical methods such as silt curtains and sedimentation ponds are effective in reducing the spread of sediment and minimizing turbidity. Chemical methods such as polymer flocculants and pH adjustment can promote settling of suspended particles and reduce turbidity levels. Biological methods such as vegetation buffers and bio-engineering can help to stabilize sediment and reduce erosion, minimizing the amount of sediment disturbed during dredging and reducing turbidity levels. In the end there will mostly be looked at the most cost-efficient method and sometimes trades have to be made.

3. How does the CDS work?

The contained dredging system (CDS) is a system that dredges within an air chamber. The testing procedure of the CDS showed that all the components

of the CDS are necessary to let the system function how it is designed. The main reason to develop the CDS was to not disturb the environment. During tested it was proven that no turbidity was created, although it is not possible to draw a conclusion out of these tests as the test conditions are questionable.

a) How is the pressure in the CDS balanced?

The air/water outlet is added to maintain the right pressure in the chamber. In the outlet water will act as a resistor. The water and the air flow will be balanced. How the air volume flow behaves is unknown. Although, there are many possible solutions for the way the flow behaves, the volume flow will be constant as the air compressor compresses at a constant rate and the dredge pump dredges at a constant pace.

b) When and how does the CDS generate turbidity during its dredging process?

The CDS generates turbidity when its being hopped away after it has dredged. The theories of the critical dredge height and lock-exchange predict that silt pertaining to the wall will move with a certain speed. The movement can be seen as turbidity. Moreover, the critical height to dredge for the existing prototype is very small. This means that it is not realistic to dredge without creating turbidity using the existing prototype. This entails that the same issue might occur when bigger devices of the CDS system are developed.

4. How does the turbidity induced by CDS relate to turbidity induced by the existing dredging tools?

The CDS generates turbidity after dredging by leaving a vertical wall left behind. This wall will collapse. While the existing techniques create turbidity during dredging. The existing techniques are improved, to minimize their turbidity. Unfortunately, these improvements can not be applied to the CDS. The main reason is that the improvements to the current techniques minimize the turbidity that is generated during dredging, while for the CDS the turbidity in the environment is generated after dredging by pulling up the device.

Further research must be done to quantify which technique is the most beneficial in minimizing turbidity.

The main research question of this thesis is: "To what extend does the CDS create turbidity?"

The CDS will create turbidity as the critical height of a vertical wall is rather low and will be exceeded. By exceeding this height, the walls that are dredged will collapse. How much turbidity that the CDS will create cannot be calculated exactly. However, the CDS was designed to minimize turbidity and the theory and calculations in this thesis have an opposite outcome.

The final conclusion is that the CDS does not fulfill its requirement for which it was designed; not creating turbidity. However, the CDS purpose of dredging works and the CDS could be used to dredge in areas where the environment is not sensitive to turbidity. Furthermore, in very polluted areas where accurate dredging is necessary up to a couple of centimeters, the CDS could be a good alternative. In this case the CDS could also be used together with methods to minimize turbidity.

9

RECOMMENDATIONS

The testing set-up of phase 1 is biased, it is recommended to conduct new turbidity tests. The new test should focus on the critical dredge height, how the vertical wall collapses after dredging and what the volume is of the turbidity. In this way, it can be better investigated how the CDS creates turbidity. For further research it might be useful to develop measurement techniques in order to determine the hindered settling velocity and slib velocity due to the lock-exchange.

Furthermore, more tests should be done to compare all the dredge techniques. In this way, a better understanding of which technique generates the least turbidity under specific circumstances can be obtained.

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