Experimental research: Filling process of a river plough

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Bulldozer forces induced by under water ploughing explained.

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Abstract

This report describes and analyses small scale plough process. This research is initiated by Deltares and the Delft University of Technology as an experimental way to gain insight in the ploughing of the river bed in rivers. The main target of this thesis is to gather information on the plough process as applied in the maintenance of the Waal river. Using small scale experiments, several methods of improvement can be tested and the main principles of buffer formation in front of a plough are investigated. Investigated is the discrepancy found in testing a prototype plough in the Waal river where ploughing in the same direction of the current resulted in lower pull forces than in opposite direction. An answer for this situation is found and explained. Furthermore, a large set of data and videos is collected in various experiments which can help to better understand the plough process and can help to further improve the plough process in the Waal river.
Acknowledgement

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## Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_{\text{sand}}$</td>
<td>Density Sand</td>
</tr>
<tr>
<td>$\rho_{\text{water}}$</td>
<td>Density Water</td>
</tr>
<tr>
<td>$\rho_g$</td>
<td>Density Sand under water</td>
</tr>
<tr>
<td>$b$</td>
<td>Width model plough</td>
</tr>
<tr>
<td>$k$</td>
<td>Permeability Coefficient</td>
</tr>
<tr>
<td>$d_{50}$</td>
<td>Grain Diameter</td>
</tr>
<tr>
<td>$v_c$</td>
<td>Cutting velocity</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Blade angle</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Shear angle</td>
</tr>
<tr>
<td>$G$</td>
<td>Gravity</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>Angle of internal friction</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Angle of external friction</td>
</tr>
<tr>
<td>$h_i$</td>
<td>Cutting height</td>
</tr>
<tr>
<td>$h_b$</td>
<td>Height cutting blade</td>
</tr>
<tr>
<td>$H_b_{-\text{mean}}$</td>
<td>Average (virtual) height blade</td>
</tr>
<tr>
<td>$\text{TFA}$</td>
<td>Total Frontal buffer Area</td>
</tr>
<tr>
<td>$c$</td>
<td>Cohesion</td>
</tr>
<tr>
<td>$a$</td>
<td>Adhesion</td>
</tr>
<tr>
<td>$S_1$</td>
<td>Friction stress</td>
</tr>
<tr>
<td>$k_i$</td>
<td>Initial permeability</td>
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<tr>
<td>$n_i$</td>
<td>Initial porosity</td>
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<tr>
<td>$n_{\text{max}}$</td>
<td>Maximal porosity</td>
</tr>
<tr>
<td>$e$</td>
<td>Volume strain</td>
</tr>
<tr>
<td>$p_{1m}$</td>
<td>Average water sub pressure shear zone</td>
</tr>
<tr>
<td>$p_{2m}$</td>
<td>Average water sub pressures on blade</td>
</tr>
<tr>
<td>$K_1$</td>
<td>Grain force</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Dynamic viscosity</td>
</tr>
</tbody>
</table>
\[ V_{\text{current}} \] Speed current
\[ V_{\text{plough}} \] Speed plough
\[ U_{\text{current}} \] Water speed
\[ U_{\text{plough}} \] Speed plough
\[ U_{\text{total}} \] Total water speed
\[ U_{\text{maxplough}} \] Maximum plough speed
\[ U_{\text{maxcurrent}} \] Maximum current speed
\[ Q \] Flow rate pump
\[ F_{\text{drag}} \] Drag force
\[ C_{d} \] Drag coefficient
\[ A \] Drag inducing area
\[ A_{\text{buffer}} \] Drag inducing area buffer
\[ A_{\text{plough}} \] Drag inducing area plough
\[ F_{v} \] Vertical force
\[ F_{w} \] Wire force / pull force
\[ F_{wh} \] Wire force horizontal component
\[ F_{\text{pull}} \] Wire force
\[ F_{\text{pull, horizontal}} \] Wire force horizontal component
\[ F_{\text{load}} \] Load in plough
\[ F_{wv} \] Wire force vertical component
\[ F_{c} \] Cutting force
\[ F_{ch} \] Cutting force horizontal
\[ F_{cv} \] Cutting force vertical
\[ F_{\text{current}} \] Current induced drag force
\[ F_{\text{buffer}} \] Buffer force
Extended abstract

Introduction Due to the projects within the ‘Room for the River’ program, the flow profile of the river Waal will widen. This causes a lowering of the flow velocities. This decrease in flow velocity will result in more sedimentation. Especially in areas with the lowest flow velocities. This means that more maintenance activities will be needed to secure a safe water depth. Estimated is that the necessary dredging works will increase with 10% for the entire river Waal. Exceptions at several points can reach up to an increase of 40%. One of the options to cope with this increase is researched in 2011 by Hein Bots. Ploughing the bottom of the Waal river instead of using hopper dredgers was already a suiting solution. Tim van der Lugt has tested several plough versions in situ in order to test whether the efficiency of the plough could be improved. Here a discrepancy has been found in the measurements, when a plough was ploughing in the same direction of the current, higher pull forces have been measured. These forces could be as high as 150% of the pull forces when the plough was ploughing against the current. As explanation for these forces, the buffer in front of the plough was designated as the source but not proven. Investigation on the buffer and the plough process will be executed on a small scale so that the whole process can be made tangible. Goal of the small scale experiments is to prove that the buffer actually exists and can cause this discrepancy and furthermore test several adaptations in order to increase the efficiency of the plough process.

Setup Using the dredging lab provided by the TU Delft, small scale experiments can be executed. Using a 1:20 scale the plough process is simulated. By using a see-through tank and a cart travelling on top of the tank, a small plough can be pulled through a flat sand bed. This plough is fixed with an cutting blade which cuts a height of 6 mm at an angle of 45 degrees. The overall dimensions are similar with the plough used in the experiments of Tim van der Lugt. The small scale plough had an closed bottom. In order to prevent a crooked cutting path and friction forces, the plough is hanged inside a frame. This frame keeps the plough horizontal and at a fixed height. It is pulled by two wires, these two wires are attached to an load cell. This load cell measures the forces in the two pull wires. These pull wires are fixed under an angle of 20 degrees. The plough and plough frame are hanged on another load cell. This load cell measures the vertical forces. The speed of the cart which pulls the plough can be set to different speeds. Using different speeds one can see the influence of the speed on the buffer. By adding pumps to the tank an current can be introduced. This is done by pumping water out of the tank at one side and discharging the water in at the other side of the tank. This introduces a current. This is no uniform current. By switching the pump from side the current can be set so that the plough is in the same direction of the current (with-current) or in opposite direction of the current (against-current). Using the current as a parameter one can investigate what the influence of the current is on the buffer. This current can be set between 0.05 $\frac{m}{s}$ with and 0.05 $\frac{m}{s}$ against. Testing with several plough speeds and different current direction will give an insight in the parameters which define the size and shape of the buffer in front of the plough. Examining several different versions of the plough will give insight on which plough is the most efficient and which plough configuration is best suitable as an prototype plough. In the test fase, four different plough versions have been tested, within these tests a test sequence of 8 different plough speeds varying from 0.07 $\frac{m}{s}$ to 0.20 $\frac{m}{s}$ have been run through with an installed counter current. This sequence is repeated with the current in the opposite direction. Several parameters have been adjusted during testing, under those parameters are
the speed of the current, the cutting depth of the plough and testing with an already filled plough. In all these tests, the vertical force and the pull force have been measured and each test has been filmed in order to quantify the size of the buffer. These tests are labeled as the main experiments. Also several stability adjusting adaptions to the plough has been done after the main experiments, these are the stability tests. Here, the build up of the buffer is of lesser importance. The goal here is to look at the stability of the plough under several circumstances. These experiments are not within the primary subject of the thesis and can be found in the Appendices.

**Analysis**

As expected before the experiments commenced, the buffer in front of the plough is very much present. The buffer can be considered as an heap of sand that has a top above the blade. This mean that if the buffer grows, the front limit and the back limit reach further. Due to the continuous feeding of sand to the plough the buffer can grow very large. The blade pushes the sand toward the top of the buffer. Here, the buffer grows in height. This causes that the slope of the buffer increases. When the slope is to steep sand starts rolling downward to both the front and the back of the buffer. The back of the buffer is inside the plough and the front of the buffer is at a certain distance from the blade. This slope of the buffer is normally around 40 or 30 degrees. This behavior can be seen at slow speeds. Here, the inertia or the current does not play a role in the build up of the buffer. When increasing the speed of the plough the build up of the buffer changes. Where the sand normally would roll continuously to the front of the buffer the sand is now affected by the current. This is due to the speed of the plough. When the speed of the plough is higher than 0.05 \( \frac{m}{s} \), the induced current can always be considered against the direction of the plough. At plough speeds above the 0.10 \( \frac{m}{s} \) the shape of the buffer is affected. The slope in front of the buffer is steeper than the natural slope since the current prevents the sand from rolling down. The buffer grows in height and breaks like a wave to the front of the plough. Now a larger volume of sand falls down the front of the buffer. This is how the buffer grows to the front. This pattern is only seen at the beginning of the build up. After the first wave sand stretches to about 6 cm in front of the blade. Here the buffer starts to grow more at the front of the buffer. Here sand is being pushed upwards at the front of the buffer causing the buffer to have a small bulge in the front. The slope is now very low. This bulge grows further in height. However, the top of the slight bulge is pushed toward the back. Here the small bulge reaches the highest point of the buffer. The buffer is now shaped like it would have been at lower speeds. The speeds of the plough has a small influence on the position of the front limit of the buffer. Although the build up of the buffer is different, at the end of the plough track the front limit is similar. The current has influence however. The current has influence on the buildup of the buffer since the current prevents the rolling down of the sand. Is also has an influence on the amount of sand that is being spilled. At the end of the plough track one can see that the influence of the current is present. When introducing a higher counter current, the front limit can differ from a situation where there is a low current by 2 centimeters. Although 2 centimeters seem small compared to the 12 cm the buffer can reach the influence is noticeable. In the set up of the experiments the plough is designed to have only a few acting forces. The cutting forces, buffer forces and the drag forces. The drag forces are low, neglectable compared to the current and buffer forces. In the total force model, the dominant forces are the buffer forces. A noticeable difference in the size of the buffer translates to a noticeable difference in the total forces. Now one can make an effort to explain the behavior found in the Waal river where the pull forces could get up to 50% more compared to the downstream plough sessions. Comparing two experiments where the only difference is the current. Here, in both experiments, the plough speed is equal. The induced current is in both cases a counter current. To compare two experiments one must first subtract all forces but the buffer forces. In the horizontal equilibrium equation one has the drag forces, the pull forces, the cutting forces and the buffer forces. The drag forces are very small compared to the buffer forces and cutting forces. The cutting forces are not easily calculated. In the standard cutting forces equations one considers that sand that is being cut only reaches the height of the blade, \( H_b \). This is normal in dredging where sand in sucked away. However, in the plough sand will reach far above this blade. This affects the cutting forces. In order to calculate the cutting forces one needs to replace the fixed \( H_b \) parameter with an dependent parameter \( H_{b-mean} \). This parameter is determined by the video footage of the experiment. By measuring the height of
the buffer above the blade one can calculate the mean height of the sand buffer. One can not just take the height of the buffer since the buffer is not equal in height over the width of the plough. By replacing $H_b$ with $H_b - \text{mean}$ one can see that the cutting forces always increase during ploughing. If one now takes the horizontal pull forces and subtracts the drag forces and the horizontal cutting forces one can see that in the scenario where the plough has the biggest counter current, the buffer forces are 20% lower than in the situation where the counter current is low. It can also be seen that the front limit of the buffer makes a translation of 2 centimeters under the influence of the current. Although the difference in forces is not the 50% as seen in the Waal river one can explain that the difference in forces can get up to 50%. Considering that the Waal plough has an open bottom plough, here the buffer forces are much higher since all the weight of the sand is contributing to the buffer forces. In the experiments one can see that the weight of the sand inside the plough is some 60% of the total weight. This translates to a bigger difference in the buffer forces. However, the behavior of the buffer will be different so it hard to make a solid statement. It is seen that the buffer in the higher counter current situation loses more sand and has a lower height. This lower height contributes to lower cutting forces. This causes the decrease in total horizontal forces in the higher counter current situation. Adding to that is that the two experiments compared is at a low speed. If the speed increases, the shape of the buffer changes. This translates to a front limit of the buffer lying closer to the plough. This also decreases the buffer forces. If one considers all these factors one can explain the difference in pull forces as a result of the plough direction.

**Conclusions & recommendations** The acting process behind the difference in forces between the with and counter current is the buffer. measurements tell that the buffer can cause a large difference in the pull forces between the plough sessions against and with the current. The influence of the current on the size of the buffer can be considered small. In a comparison between two experiments where the speed of the plough is equal and the only difference is the speed of the current, the buffer reduces in size slightly. Although the buffer reduces in size slightly due to the current difference, the buffer forces are strongly influenced. This is due to the fact that the buffer forces are the prevailing forces in the total plough process. The horizontal buffer forces account for 85% of the total forces. A small difference in the size of the buffer has a direct influence on the total force model. The build up of the buffer can be described as follows: Sand that is being cut by the blade and is pushed straight upwards. This creates a heap with the top of the heap above the cutting blade. Sand is being pushed upwards creates steep slopes on the sides of this heap. When the slope is higher than the natural angle of the sand, between 40 and 30 degrees, the sand starts to roll down the slope. This rolling occurs on all sides of the buffer. This process of sand being pushed upwards and rolling down is a continuous process. Sand that rolls down to the front of the buffer, in front of the plough, is fed again to the plough inside the buffer. Sand can also roll to the sides where it spills. This creates heaps of sand next to the freshly cut plough path. The influence of the current can be seen in the end of the plough track where the front limit of the buffer is translated but also in the build up of the buffer during the plough session. When an induced counter current of 0.15 $\frac{m}{s}$ is present, the build up of the buffer is influenced. Where the sand could roll to the front of the buffer the current now prevent the sand from rolling down. The continuous rolling of sand is now replaced with a wave like motion. A larger amount of sand now falls down the slope. This is seen in the beginning of the plough track, when the buffer is already established, this pattern does not occur. Bigger influence on the build up of the plough is the speed of the plough. Speeds lower than 0.10 $\frac{m}{s}$ will give a symmetric buffer, where the sand that rolls down is nicely distributed to the front and the back of the plough. At speeds higher than 0.10 $\frac{m}{s}$, the start of the build up is different. Here, the inertia of the sand causes that the front slope is much steeper and sand is more like a wave that breaks. After the initial breaking the buffer builds up similar as in the lower speeds with the difference of the current. Although higher speeds influence the start of the buffer build up, the outcome is similar. Also, the top of the buffer is in most cases vertically above the blade. It is not found that a higher speed pushes the sand more to the back of the plough. The build up of the buffer also does not support the theory that sand inside the plough is being pushed. Spillage of sand is always present in all adaptations of the plough that have been tested. Spillage is mostly present at the sides of the plough. Small heaps of sand form at...
the sides of the plough where sand rolls down at the front to the side. These heaps are higher than the original sand-bed. Increasing the speed of the plough will disperse the sand more, preventing the small heaps. This sand however always lays on top of the original sand-bed.

In order to better understand the buffer process more data has to be processed. These is a bulge of information available from the large amount of tests that have been done. The method used to compare experiments is however not suitable to process the large amount of data. To process the date another method than using Excel has to be used. This can give more insight on the forces of the buffer and the most suitable speeds and plough adaption. With the various adaptions done in the model plough one can consider adapting the existing plough in order to improve the efficiency with the adaptions that have been proven to improve the process. Trying to remove the buffer completely would demand a dramatic change to the whole process and this can not be realized using the existing plough.
Chapter 1

Introduction

1.1 River Waal

The Waal river, a busy an important shipping route for the dutch transport, starts at the village Pannerden. Here the Rhine splits into the Waal and the Pannerden canal. The 82 kilometer long Waal is the biggest branch of the Rhine, transporting 65 % of the Rhine’s total flow. The Rhine, being a sedimentation river, brings a large amount of sand and coarse sand into the Netherlands. The sediment that reaches the Dutch border in the Rhine is about $3.1 \times 10^6$ tonnes per year (Asselman et al., 2003). The spring of the river Rhine is located in the Alps the discharge of the river is mainly fed by rain and melt water. The discharge of the Rhine is strongly seasonally bound. In the summer 70% of the water originates from the Alps. A large part of the stream is melt water from the mountains, a smaller part is rain water. The smaller part of the rain water due to evaporation. In winter time, the evaporation is much lower and the result is a larger contribution to the total flow by the rain water. In the winter the discharge of the river Rhine is largest, the evaporation of rainwater is low. Here about 30% of the water comes from the Alps. Due to the mixed origin of the water the discharge is relatively constant and shipping is possible throughout the year. (Van der Meulen et al, 2008) The higher mountains and hills in the Alps induce a high flow velocity. This is due to the higher fall the river had in these areas. In the higher parts erosion is large, here large boulders, gravel and coarse sand are also eroded. Smaller particles are also picked up in these areas. In the lower parts, erosion in the river banks occurs. Here the flow velocity and the fall of the river is lowered. The lower flow speed causes the larger particles to settle, lower particles become bed load and are still transported. Smaller particles like clay and organic material are suspended. For the river Waal, these particles are under 0.5 mm in diameter.

1.2 Room for the river

A reasonably recent change in the flow of the river Waal is the Ruimte voor de rivier project. In the Netherlands water plays an important role in the landscape. There are several big rivers and the land has a big coast line in the West. Also, due to the changing climate, rainfall has to be accounted for. The need to control the water becomes more and more important since the sea level rises and the rainfall increases. In order to protect the land behind the dunes and the dikes, the government has started the project Ruimte for the rivier or room for the river. The measures resulting from this project are all intended to let the rivers cope with the increasing amount of water they have to transport. The main objectives are flood protection by 2015 and overall improved environmental quality in the river basin region. The Room for the river measures to be taken in the river Waal is lowering of the groins. Groins are stone banks, like a breakwater, which lay cross in the river. The function of these groins is to maintain a functioning drain of the rivers water and sediment and to keep the river in place. These groins prevent erosion on the banks. Over the years, an increase in water flow has caused the groins to become higher( relative to the river bottom) due to bottom
erosion and have to be lowered to maintain a proper work-ability. Lowering these groins also gives the river the ability to cope with larger amounts of water. Placing the dykes more landward at certain points in the Waal is also a solution to cope with the larger amounts of water. This is seen in figure 1.1. At these places, the river can be wider at higher water levels. The project will enable the Waal to cope with discharges of up to $16,000 \text{m}^3/\text{s}$ of water.

1.3 Maintenance

Due to the changing depth, width and discharge of the river Waal, the sediment will settle at different locations. Widening the river induces a lower mean velocity at that location, the result is the deposit of materials. A standard meandering river deposits sediment on the inside of bends and erodes in the outside of bends. The Waal also has this principle but has groins so it doesn’t meander.

The deposit of sand and coarse material can be hazardous for the ships in this busy shipping lane. A shipping channel of 150 [m] wide and 2.8 [m] deep is guaranteed by Rijkswaterstaat. Maintenance of the waterway is key in order to keep the shipping channel within the correct dimensions. The maintenance of the waterway must be done with the least amount of hindrance for the shipping traffic. Dredging is the customary technique in order to provide a sufficient depth and width of the waterway. A trailing sucker hopper dredger removes the sand by sucking it up and storing it inside the hopper. This is a costly technique and a hopper is also a nuisance since it blocks the waterway during operation. There is also another disadvantage of the hopper.

The river Waal has the problem that it suffers from bed level drop. Bed level drop is the lowering of the bed over several years. Due to the increase of discharge in the river, while the old groins are still present, the sediment deposit stops in several locations and the bed level lowers. This could be seen as an advantage since the dykes are relatively higher. The downside effect of bed level drop is that fixed structures like bridges, sluices and tunnels will rise, relative to the bed level. This is not desirable since this will prevent proper flow. To prevent this situation, the dredging contract
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states that the removed material has to be dumped within 1500 meters from the dredge site. All measurements taken in the Room for the river project cause a higher maintenance schedule. The total volume which has to be moved per year is about 400,000 m$^3$ at a total cost of 3 to 4 million Euro. For the total river (Lobith - Werkendam) it is estimated that the amount of dredging works increase with 10% Locally (Midden Waal (km 885 à 915)) the increase is 40%. There is still a big uncertainty in the total amount of maintenance works. The prospect of the increased amount of dredging work is expected to conflict with the nuisance requirements. So a more effective dredging method is needed to cope with the new situation. In general the dredging can be divided in two kinds; topping of dunes in straight reaches and dredging of shallow inner bends as seen in picture 1.2. Dunes in straight reaches are the result of depositing sediment in a low flow profile. The constant erosion at the upstream side of the dune and the deposit at the lee side causes the dunes to be moving constantly. This process is seen in figure 1.3

Dune tops can reach an amplitude of 1.5 m. With tops this high, the minimal depth of 2.8 m can not be guaranteed. While the mean bed level in these cases can be under the 2.8 meter. Topping these dunes with an underwater plough prevents high dunes. Here, a plough is pulled by a tug boat with steel cables. The plough cuts in the sand and transports this to a dune valley where the depth is bigger. By lowering the plough on a specific depth, the minimal depth of more can be set. The plough is fixed to a boom at the end of the tugboat where it can be lowered and lifted. And eventually, pulled out of the water. The plough principle is a fitting solution in the maintenance of the straight parts of the Waal. The process does not remove material but displaces it. A big advantage of the plough is that it is much more agile than a hopper. A hopper is a bigger ship which is a nuisance for the shipping lane. The tugboat is a much smaller vessel which is more movable and cause therefor less hindrance for other ships. Another advantage are the costs.

A hopper is a costly operation, the price per day is much higher and the hopper is not always in operating mode. A hopper needs to unload when it is full and needs to sail to this unloading area. A ploughboat is not as effective as a hopper but it operates at a fraction of the costs. In figure 1.4 one can see a plough. These ploughs are mostly used in harbors and low depth water gully’s and are done by multiple smaller marine contractors. Previous research of H. Bots has shown that ploughing is a technique that is promising since it is simple and effective. In his thesis: Efficient maintenance on the Dutch fairways, he has shown that maintaining the river with a plough is much more cost efficient. Following from the thesis of H. Bots a research on
the efficiency of the plough was originated. By testing prototype ploughs in the Waal river and measure the efficiency one could justify the use of the plough as a method of maintenance. Proven in the research of T. van der Lugt was that the process of ploughing was not as efficient as thought and several discrepancies arose during this research. Though the principle of ploughing is simple, the complete process under water is not yet fully understood. Many parameters influence the efficiency of the process and the result of done work can not totally be determined. The research on the ploughing process could not clarify all questions related to the subject and several unknown are still left. However the research has shown that ploughing is a promising technique to maintain a certain water depth but it has several point to improve and questions that need to have answered. One question that arose during the research was that during plough sessions against the current, lower pull forces were measured. These pull forces are measured in the front wire as seen in figure 1.5

![Figure 1.5: Plough tug boat Dintel. Source: T. van de Lugt, 2013](image)

The front wire pulls the plough forward while the vertical wire keeps the plough at a constant depth. In the measurements of T. van der Lugt the forces in the pulling wires could be up to 50% higher in a plough track along the current compared to a plough session against the current. Expected was the opposite. In a counter current, the drag forces increase drastically, this would presumably result in higher forces. The reason for the 50% higher forces was assumed to lie within the plough process. The hypothesis was that the sand heap inside and in front of the plough was influenced by the current. The high counter current would wash away a part of the sand heap, the so called buffer. This would result in a smaller buffer in the counter current plough sessions and, as a result, lower total pulling forces. In the opposite direction, the sand would not be washed away leaving a larger buffer and causing the 50% higher pull forces. This however could not be proven in the research set-up of T. van der Lugt. An explanation is sought for this discrepancy and more information on the so called buffer is necessary in order to further improve the plough type river maintenance. The efficiency of the prototype plough is still far from optimal and in order to design a new, more efficient plough the plough process must be researched. In order to make the process more tangible and visual, a small scale experiment will be set up to comprehend the plough process.
1.4 Hypothesis

Small scale research is needed in order to understand what the 50% increase in pulling force causes on downstream plough sessions. As said before, it is expected that there is a phenomenon called a buffer or bulldozer in front of the plough. Here a heap of sand is continuously pushed upward and forward instead of pushed into the plough. The buffer in front of the plough can cause a sand on sand friction which is causing the increased tensile forces to the downstream plowing. In the counter current plough session, it is expected that the flow of water pushes against the buffer. This force pushes the buffer more into the plough and changes the shape an size of the buffer. Also, a flow picks up the particles and carries them over and out of the plough. It should be understood how this buffer is built up, and what volume and shape the buffer is. It is therefore important to know how the sand is distributed within and in front of the plough. Based on these findings, an explanation can be argued on the discrepancy in pulling forces. The research question needs to be answered here is:

"How does the buffer build up under the influences of the speed of the plough and the speed of the water flow?"

Within this lies the answer on the discrepancy in the pull forces. Furthermore, the speed of the plough, and therefore of the energy which is supplied to the process is of great importance for the plough process. It is important to be able to distinguish in the different forces that play a part in the process: Cutting forces, buffer forces, friction plow / soil and resistance through water flow. The end goal of the study is to optimize the ploughing process. The aim here is to construct knowledge to argue an improvement of the plough. Furthermore, several adaptations will be done in order to improve the plough process.

The question will be answered using an experimental research. This concerns a study on scale because it is practically not possible to observe the processes in the actual process and to adapt the variables. In the test setup to adjust the variables easily (speed and direction of water, speed and dimensions plough)

To be expected is that there will be a difference in the size of the buffer under the influence of the current and the speed of the plough. The size of the buffer will be decisive for the total plough forces. Expected is that in a plough session in the same direction of the current the buffer itself will not be moved to the rear of the plough where the streaming water prevents this. This buffer prevents further filling of the plough and will result in a greater pulling power. The result is that the yield of the plough is not enlarged. On the other sides can be expected that a counter flow prevents the build up of any buffer, and therefore no higher tensile forces are created in the pulling cables. However, this may also have the effect that the yield of the plough is reduced. The streaming water, in opposite direction of the ploughing process, prevents a higher build up of sand in the plough, this reducing the volume of sand. The influence of the speed of the plough will have influence on the speed at which a buffer is set up. A smaller speed gives lower powers and thus a slower build up. This is one of the possible explanations given in the thesis of T. van der Lugt as a cause for the discrepancy in the measurements. Since the cutting depth is held at a constant height, the filling of the plough over the length of the ploughing track will be similar for different plough speeds. Here, the flow will be decisive for the filling of the plough. Since this will be decisive for the build up of the sand buffer.
Also expected is a difference in shape of the buffer. This shape also reflects a volume of the buffer. With a counter current flow, the height of the buffer will be lower and having a lower gradient. On the other side, a higher buffer is expected in the with-flow situations, giving higher gradient slopes. Expected is that the current will also influence the location of the front of the buffer. The distance in front of the plough where the buffer is visible as one can see in figure 1.6. To be expected is that this distance is a function of the speed of the water and the speed of the plough. A higher plough speed in combination with a counter current will result in a higher water flow resistance. This higher total flow resistance will place the front of the buffer closer to the front of the plough. In the contrary, a small total flow resistance will give a higher distance from the front of the plough. For the plough design, a high yield at low energy dissipation is preferred. A large distance gives a higher surface where sand-sand friction occurs, this wastes energy. This will however always occur. A small surface is therefor preferred over a large sand-sand surface under the buffer.
Chapter 2

Theory

In the chapter theory we will explore the knowledge used in this thesis and link this to the subject of this thesis. Starting with the known information from the previous thesis of Tim van der Lugt and the thesis of Hein Bots. This is important to know since this thesis is a sequel of these researches. To be known is what they tested and the conclusions that have been drawn. Also of importance is how this thesis continues their research. Furthermore in this chapter, one will find theory used further on in this thesis. Theory on the cutting forces, ploughing in sand, the influence of several parameters, erosion and plough stability. This will start with the Thesis of Hein Bots[2010]?

2.1 Previous Research

Already, two studies have been done regarding the maintenance in the Waal river. The study of Hein Bots has shown that ploughing is a maintenance method that is very promising but has to be more researched in order to show the real efficiency. This thesis of Hein Bots exists of several maintenance methods in order to keep the river up with the required depth. Here, the ploughing method has shown to be a relatively cheap way to do maintenance works. Bots has already done some small scale tests in order to comprehend the forces acting on a plough and to enrich in knowledge to give a thought-out recommendation on a full scale plough. Following from this thesis, the research of T. Van der Lugt has been started. In this research, the efficiency of the plough process has been tested. In this thesis, research has been done at an actual site with several different types of ploughs. Here several parameters have been monitored during the ploughing process. In the test, at a part of the Waal, depth measurements have been done before and after a ploughing session. This gave an indication of the sand moved or removed. The method here was to scan the bottom of the Waal. This scan gave a precise depth plot over the sand surface. After this, ploughing this site started and another depth measurement was done to finish the experiment. With the change in depth the total material moved by the plough could be calculated and therefore, the efficiency of the process. Here, ploughing sessions have been done with the flow and against the flow in order to prove a difference in efficiency. Also load forces and pull forces have been measured in order to understand the complete process. Here a discrepancy in the expected forces showed. Lower pulling forces in the against-current situations occurred. This happened while the expectancy was that pulling forces in with-current situations would be lower. An explanation for this has not yet been found. In order to understand the ploughing process under water, an waterproof camera has been placed on the plough. This camera tells that in both situations the plough gets filled. Following the thesis of Hein Bots on Efficient dredging and Tim van der Lugt’s thesis ”Pilot innovative ploughing” further research is needed to explain phenomena which occur during the ploughing of the riverbed of the River Waal.
An explanation is sought for the fact that a downstream ploughing session demands more power of the towing tug. This stands against the upstream ploughing session. This occurs when plough fills equal. With the flow of the river in the back, the force sensor gives a 50% greater tensile force relative to the plough against the stream. Expected was that the total ploughing forces in either direction would be equal. This is due to the fact that the drag force induced by the current is neglectable. However, this is not the case and there is no clear explanation for these research results.

To continue with the innovation of the plough, it is necessary to find an explanation for this phenomenon. Further research on what can cause the discrepancy will provide a base on which the plough method can be made more efficient. It is particularly important that the forces required to pull the plough will be made as small as possible while the production of the plough is increased. A small study already has been done to decrease the friction between the plough and the sand by adding a low friction plastic bottom. Also, the implementation of jetting has been studied to create a water film on which the plough can float in order to decrease the friction. New conclusions and these older findings are the base on which a new design concept of the plough can be developed. To continue with the discrepancy in the measurements, it is expected that there occurs a phenomenon which is called a bulldozer. A bulldozer is made up of a mass of sand which is pushed out in front of the plough in which a lot of energy is lost in the continuous movement of the sand without filling the plough. In this thesis, this bulldozer is the main subject.

### 2.2 Under water ploughing

As mentioned before, ploughing under water is no new technique. Several contactors in river maintenance use this form of soil modification. This is the form of maintenance when other modes like dredging are not suitable. Ploughing under water is practically similar as ploughing above the water. By using a cutting blade, sand or clay is removed and being pushed to the front of to the sides. A big difference with dredging is that soil is not removed, it is only pushed away. A plough boat is mostly used to remove soil from shallow waters like harbours. It is also used to level a certain area. When material is dumped to use as a subsoil for a structure, a plough can be used to create a nice, horizontal flat surface on which a stucture can be build. By setting the depth of a plough, the desired depth of the soil can be accomplished. If one compares this to an above ground technique, one can compare this to a ground leveling device is seen in 2.1. Here, the height of the equaliser is kept to a constant using an infra-red reference or even a satalite gps reference. Where the surface is so high, sand is pushed away toward a lower surface. And thus equalizing the ground. In the water this principle is the same. Where the soil is to high, it gets pushed away toward lower ground. Here the sand in motion fills the cavity. In maintaining the river Waals depth. The plough is set to a precise depth so that soil above this depth is pushed away and pushed towards a cavity. Where, above the ground, the contractor can see where sand need to go, the captain of the plough boat needs to rely on a depth plotting device or its own experience. For small harbors precision is not key but for building a subsurface, precision is more important. In the Waal river, important is that the under water dunes are removed. Leaving the surface horizontal is of lesser importance. An other technique for removing soil is using a pushing boat. This is for very shallow waters like ponds and canals. Here, a simple flat surface pushes soil in one direction. Here, soil will be removed by an excavator or pump. Here, the material removed is mostly organic and saturated with water. Here, forces are smaller in comparison to sand cutting( which is in the Waal river). A similarity to a river plough is that material build up in front of the pushing barge as one can see in figure 2.2. While the cutting...
forces for this material are not high, the forces which are introduced by the build up of material is. These forces are called bulldozer forces. Material in motion is pushed over material in rest. This introduces a friction factor, this friction force is dependent on the internal friction coefficient and the weight of the buffer. This bulldozer or buffer determines the total forces. In this thesis, these forces are to be examined.

Figure 2.2: pushing barge
2.3 Bulldozer effect

An important effect in underwater ploughing is the bulldozer effect. Also called the snowplough or the buffer. This bulldozer effect is just like the bulldozer one imagines. Sand is being pushed by a bulldozer using a large flat surface. Sand builds up in front of this surface and is being pushed in a direction. This sand in front of the bulldozer is called the buffer. Here, the sand in motion in front of the bulldozer introduces a friction with the sand underneath (which is stationary). This creates a large friction force. A bulldozer driver can adjust the blade surface in order to rule the height and size of the buffer so that the machine can still power the movement. A bulldozer can be seen in figure 2.3. This buffer is important in the ploughing of sand under water. The same principles count for under water.

Sand is pushed in front of the plough introducing a friction force. Sand also builds up in height, creating a bigger buffer. In water, the cutting of sand is also important. While, in the dry situation, cutting of soil is not the dominant force. And in fact, small in comparison to the total buffer force. In water however, subpressures are present which contribute to the total buffer force. Here, cutting forces are higher than in the dry situation. Also, in water the drag of a present water current is contributing to the buffer force. If a plough moves counter current with a big surface area, drag forces can build up. These will be very small compared to buffer forces or the cutting forces. The water current that introduces the drag can also introduce another effect. This effect is known in dredging as transport. Smaller sand particles are picked up by the water stream and are being transported with the stream. Here, the particles roll with the current or get suspended. This bed load transport occurs precisely here. If one follows the train of thought. In this section of the Waal, particles which are suspended fall down due to the decrease in current. These particles are at the border of the regime in which they are transported or suspended. Then the plough pushes the buffer forward, the particles in the buffer have the speed of the plough. In a counter current ploughing session this translates to a total water speed of \( V_{\text{current}} + V_{\text{plough}} \). This speed is higher than the speed of the current. Since we are at the border of the transport regime, the smaller particles in the buffer will start to suspend again. Larger particles will start to roll again. This will influence the build up of the buffer and will therefore influence the buffer force. This cautious conclusion has also been drawn by Tim van der Lugt to explain discrepancies in the buffer forces.

Figure 2.3: Bulldozer in action

Figure 2.4: particles in bedload (source: Arizona state University)
In the Hjulstrom diagram, figure 2.5 one can see how the transport of particles takes place. If one takes a particle size of 0.1 mm and a speed of 0.01 $\text{m/s}$ one can see that the particle is in the settling regime. When the current increases, the particle will come in the transport regime. This is what happens with particles in the buffer of the under water plough. For a plough which is ploughing in a counter or with-current situation this can have an influence on the total forces of the plough since the direction of ploughing decides whether the particles will transport of will stay settled. In this thesis, this will be examined. Also of influence is the size of the sand particles. If particles are bigger, the increase in current will no longer have an influence. Smaller particles will be picked up more easily. The size of the particles have another affect. With a smaller particle diameter sand tend to get more packed. This influences the permeability of the sand. This permeability is of influence on the cutting forces. In low speed cutting regime, the prevailing parameters are gravity, cohesion and adhesion. In a higher speed cutting regime, the volume strain is the decisive factor in cutting forces.

Figure 2.5: Hjulstrom curve(source: Physical geology-Stephen Earle http://open.bccampus.ca)

Here, the volume strain rate is high in relation to the permeability of the sand. This means that when sand is being cut, dilatancy occurs. This can be seen at the beach when one steps on saturated sand. When one puts pressure on the sand, water disappears as if the sand sucks up the water. This phenomenon can be explained. The sand starts as a nicely arranged pack. Here, the sand particles fit nicely between other sand particles, leaving a minimal space between them. When cutting, the nice, interlocking, arrangement changes. This creates more voids between the sand particles as one can see in 2.6. These voids have to be filled with water. For a coarse material, this is not a problem. For a small diameter material, this is harder. Water needs to fill these voids but can not reach these voids easily due to the low permeability of the material. If this all happens slowly, then these is no problem, at higher speeds this dilatancy creates sub-pressures. These sub-pressures influence the cutting forces. This will all be more revised in the section cutting
forces. In this research, where a small scale experiment will take place, it is important to keep these acknowledgments in mind. In the buffer, the main force acting is the friction force. This force is caused by the internal friction of the sand. The sand in the buffer slides over the sand of the surface. This introduces a large friction. The friction is dependent on the angle of internal friction $\varphi$ and the mass of the sand. The surface area has no influence on the friction force. If one takes a look at the following picture 2.7.

![Friction force](image)

Figure 2.7: Friction force

Here, one has the mass of the sand ($M$) and the speed of the bulldozer. This induces a friction force $F$. This friction force is calculated by the following formula:

$$F_{\text{friction}} = M \cdot \tan(\varphi)$$

(2.1)

This friction force calculation is similar under water. Here, the assumption should be made that the friction surface is flat and horizontal and the buffer is considered a solid mass, so no soil is exchanged.
2.4 Cutting forces

For this thesis, of great importance are the calculations on the cutting forces. In dredging, a lot of studies have been done on sand cutting and clay cutting. Miedema has a large number of papers in cutting theories in different situations. One can consider the plough process as a saturated sand cutting process. On this topic, large quantities of information can be found. Firstly, information on cutting is discussed and further on in this thesis, cutting forces will be calculated for the model plough.

According to Miedema, 1987 the process of cutting sand can be divided into five typical situations. The first two areas are, respectively: 1: Very low cutting velocities, a quasi static cutting process. The cutting forces are determined by gravitation, cohesion and adhesion. 2: The volume strain rate is high in relation to the permeability of the sand. The volume strain rate is however so small that inertia forces can be neglected. The cutting forces are dominated by the dilatancy properties of the sand. Here, the cutting forces increases linear with the cutting speed. The next three areas contain (local) cavitation. This phenomena exists when the volume strain rate is high and possibly the pore pressure reaches the saturated vapor pressure. This is due to the permeability being much lower in relationship to the volume strain. Here, a further increase of cutting velocity will not increase the cutting forces. Due to the relatively high permeability of the sediment in combination with the relative low cutting velocities, cavitation will not occur during ploughing. The three areas where cavitation occurs will therefore not be of importance in this research.

The process of cutting sand with a plough is a combination of the first two areas described in Miedema, 1987. The cutting forces are determined by influence of gravitation, cohesion, adhesion and the influence of dilatancy. The influence of the cutting forces in the plough process will be described and the cutting forces will be calculated for the plough process. The forces on the cutting blade during cutting sand are transmitted onto the blade by grain stresses and water pressures. Figure 2.8 shows the forces, stresses and pressures on the blade and on the part of the cut layer in front of the blade. The most important forces are:

- The forces \(N_1\) and \(N_2\) caused by normal stresses.
- The force \(S_1\) caused by the shear stress as result of the internal friction of the sand.
- The forces \(S_2\) caused by the shear stresses between the cut soil and the steel blade.
- The force \(A\) caused by the adhesion between the soil and the blade.
- The force \(W_1\) caused by the water sub-\(\mu\)-pressures in the shear zone.
- The force \(W_2\) caused by the water sub-\(\mu\)-pressures on the blade.
- The force \(C\) caused by the cohesion of the cut material.
- The force \(G\) as result of the mass of the soil.
- The force \(T\) caused by the acceleration of the material.
Cutting sand will result in friction forces. Internal friction is the friction between a moving sand-pack and a stationary sand pack. The external friction is the friction between the sand and the steel cutting blade. Both friction forces are calculated by the friction angle. For the internal friction angle applies:

\[
S_1 = N_1 \cdot \tan \phi \tag{2.2}
\]

Where \(S_1\) represents the friction stresses, \(N_1\) stands for the normal stresses and \(\phi\) stands for the angle of internal friction. The resulting grain force \(K_1\) is calculated using Pythagoras:

\[
K_1 = \sqrt{N_1^2 + S_1^2} \tag{2.3}
\]

A horizontal and the vertical force equilibrium on the cut layer will give the opportunity to determine the grain forces \(K_1\) and \(K_2\). If one relates the horizontal forces in the same direction as the cutting direction so that the horizontal axis points in the direction of the cutting velocity and the vertical axis is perpendicular to this. The gravity force is therefore not necessarily directed vertically, but can make an angle \(\gamma\) with the vertical. This is done by Miedema to ease the determination of the vertical and horizontal equilibrium. From the vertical and horizontal equilibrium the resulting grain forces \(K_1\) and \(K_2\) are determined. The important grain force for the blade is \(K_2\). For \(K_2\) applies:

\[
K_2 = K_{21} + K_{22} \tag{2.4}
\]

Where \(K_2\) is divided into two more sub terms. For these terms applies the following:

\[
K_{21} = \frac{W_2 \sin(\alpha + \beta + \varphi) + W_1 \sin \varphi}{\sin(\alpha + \beta + \varphi + \delta)} \tag{2.5}
\]

And:

\[
K_{22} = \frac{G \sin(\beta + \varphi) + T \cos \varphi + C \cos \varphi - A \sin(\alpha + \beta + \varphi) - W_4 \cos(\beta + \varphi - \chi)}{\sin(\alpha + \beta + \varphi + \delta)} \tag{2.6}
\]

Here, the \(K_{21}\) is the contribution to the cutting forces by the water sub-pressures. The \(K_{22}\) consists of the following contributions: The acceleration of the sand (T), the gravity (G), cohesion
(C) and adhesion (A) and the water current $W_4$. In cutting sand the terms adhesion and cohesion can be neglected. Cutting at low velocities, the influence of current on the sand part during cutting is low, therefore $W_4$ can be neglected in the calculations of the cutting forces but will be added later on when calculating the drag on the total buffer.

If one now writes an equation for the horizontal and vertical forces this yields:

$$F_{ch} = -W_2 \sin \alpha + K_2 \cos(\alpha + \delta) + W_3 \sin \alpha \quad (2.7)$$

$$F_{cv} = -W_2 \cos \alpha + K_2 \sin(\alpha + \delta) + W_3 \cos \alpha \quad (2.8)$$

At the low speeds of the plough cavitation does not occur. The water pressure forces $W$ at non-cavitation conditions can be written as:

$$W_1 = \frac{P_{1m} \cdot \rho_w \cdot g \cdot V_c \cdot e \cdot h_i^2 \cdot b}{(a_1k_i + a_2k_{max}) \sin \beta} \quad (2.9)$$

And

$$W_2 = \frac{P_{2m} \cdot \rho_w \cdot g \cdot V_c \cdot e \cdot h_i \cdot h_b \cdot b}{(a_1k_i + a_2k_{max}) \sin \alpha} \quad (2.10)$$

Sub-pressures behind the blade result in a force $W_3$. This is a force dependent on $W_2$ as stated in the formula:

$$W_3 = 0.3 \cdot \cot \alpha \cdot W_2 \quad (2.11)$$

Equation 2.11 has a limit that $W_3$ can not exceed the value of $W_2$. For a blade of 45 degrees this does not occur.

Still unknown in equation 2.6 is the inertia component and the gravity component. Moving sand which is in rest results in an inertia force. Wismer and Luth researched the inertia forces as part of the total cutting forces. The following equation is derived for $T$:

$$T = \rho_g \cdot v_c^2 \cdot h_i \cdot b \cdot \frac{\sin \alpha}{\sin(\alpha + \beta)} \quad (2.12)$$

Last is the gravitational component which equals:

$$G = (\rho_s - \rho_w) \cdot g \cdot h_i \cdot b \cdot \frac{\sin(\alpha + \beta)}{\sin \beta} \cdot \left( \frac{h_b + h_i \sin \alpha}{\sin \alpha} + h_1 \cdot \cos(\alpha + \beta) \right) \quad (2.13)$$

Having the contributing forces for the cutting process creates the opportunity to solve the vertical and horizontal cutting forces at all speeds. In the thesis, the exact cutting forces for the plough will be calculated.
2.5 Drag forces

For under water ploughing, an understanding must be made on the drag forces. Since ploughing under water in the Waal brings in rather large currents around the plough. Calculations on drag have to be done in order to better understand the total plough force. Also for the smaller scale experiment, drag forces are not to be neglected forehand.

The current drag is dependent on a couple of factors. Some factors are constant during a plough session. The plough has a constant speed during the session and the current is considered constant. The shape of the shape of the plough and the parts that raise the plough are in this case a constant factor. In the small scale experiment, and for the Waal plough a buffer starts to grow in front of the plough. This buffer also induces drag. This buffer is however not constant. A note to take is that when the buffer builds up, the plough itself is being buried. This changes the drag force of the plough. To calculate the drag, the speed of the current in respect to the plough must be established. In the experiments, one has the current speed \( U_{\text{current}} \) and the plough speed \( U_{\text{plough}} \). Taking the direction of the plough positive and the counter current positive, the total current \( U_{\text{total}} \) can be calculated as one can see in formula 2.14.

\[
U_{\text{total}} = U_{\text{plough}} + U_{\text{current}} \tag{2.14}
\]

In the case where the current is in the same direction as the plough the formula will be as formula 2.15.

\[
U_{\text{total}} = U_{\text{plough}} - U_{\text{current}} \tag{2.15}
\]

Using the next formula to calculate the drag force for the plough. This is the standard drag force calculation as seen in formula 2.16.

\[
F_{\text{drag}} = \frac{1}{2} \cdot C_d \cdot A \cdot \rho \cdot U^2 \tag{2.16}
\]

Here \( U \) stands for the \( U_{\text{total}} \) used in the total current formula 2.15 and 6.2. Capital \( A \) stands for the total front surface area. In this case, the submerged part of the frame, the plough, the wires and the buffer. The \( C_d \) stands for the drag coefficient. The drag coefficient is dependent on the shape of the area. This coefficient is thus different for the before stated, drag inducing items. To calculate the total drag forces, the total body is divided into smaller parts. Here, the drag of these parts is calculated individually. In 2.16 the \( \rho \) stands for the density of the water hitting the plough with the speed \( U_{\text{total}} \). For the model scale plough calculations will be done on the drag force in the chapter Forces on the plough. Next, we will start with the setup of the research on the buffer forces.
2.6 plough process forces

To investigate the forces during ploughing one must understand all the different forces acting on the plough. These forces are investigated within a larger perspective; the force balance of the plough. First part is to give a broad view of all the acting forces on the plough. Secondly is to add all forces together into a force balance. The goal here is to be able to calculate the buffer forces from the measurements and video footage.

In the picture below, figure 6.17 one can see the forces acting on the model plough. After an overview of the acting forces, a model will be created for the plough process. Starting first with the acting forces for the plough process.

![Figure 2.9: acting forces on plough model](image)

2.6.1 Acting forces in the plough process

To investigate the horizontal forces and the vertical forces during ploughing it is necessary to look at the fundamentals of the plough process. In this section the forces acting on the plough are mentioned and thereafter, the force balance of the plough is constructed. In this paragraph the fundamentals of the acting forces are treated. Take note that some forces can be calculated, i.e. cutting forces and drag forces. Other forces can only be calculated using the measurements. The sought after horizontal buffer force is one of those values.
• F vertical \((F_v)\)

The vertical force that supports the weight of the plough and the sand inside the plough. The plough will be hanged on wires or on a frame. This is supported by a load cell which measures the vertical forces accounts for the vertical forces. This frame translates all vertical forces acting on the plough to the vertical load cell. This force is the vertical resulting force of the plough process, and depends mostly on the cutting and filling forces acting on the plough. The frame will be hanged in a rolling bearing. The vertical force will be given as \(F_v\) further in this thesis.

• Pull force / wire force \((F_w)\)

The pull force is the second resulting force of the ploughing process. This is also described as the wire force. The pull force is not a horizontal force but is a force under an angle. The wires account for the pulling of the plough. The pull force is the only force which pulls in the direction of the plough path. Derived from this wire force can be the horizontal force component and the vertical force component. The angle of the pull wires with the horizontal plane is indicated with the angle \(\alpha\). The two components, the horizontal and vertical will be referred as, respectively, \((F_{wh})\) and \((F_{wv})\).

• cutting forces \((F_c)\)

Cutting forces are the most fundamental forces of the ploughing process. Cutting sand gives a vertical and a horizontal forces component. The fundamentals have already been given three sections above. Since the cutting forces are an important component in the plough process, they will be discussed to a bigger extend in the next paragraph. The horizontal and vertical cutting forces will be referred as, respectively, as \(F_{ch}\) and \(F_{cv}\).

• Current drag \((F_{current})\)

The current can be changed in direction and can be changed in flow rate. Expected is that the flow rate has an influence on the buffer. Not yet described is the influence of the flow on the total plough model. The plough itself has a certain surface area which produces drag. The vertical wires or frame which hoists the plough also induced drag. When cutting the sand, the buffer builds up. This buffer also contributes to the drag of the plough. At the end of the plough process, the drag contribution of the buffer will probably be the biggest component. Calculations on the drag force are given two sections above. The current drag force will be referred as \(F_{current}\).

• mass plough \((G)\)

The mass \(G\) is the underwater weight of the empty plough and the underwater weight of the collected sand inside the plough. This is the part of the buffer that is inside the plough. The part of the buffer that is in front of the cutting blade is considered to be outside of the plough and has therefore no influence on the mass of the filled plough. The total mass of the plough increases while ploughing since it keeps on filling during the run.

• buffer force

The buffer force is caused by the movement of sand which is in front of the plough. This sand moves over the sand bed and causes an extra force. This forces is called the buffer force. The buffer force can originate from a sand-sand friction force. The buffer is pushed by the movement of the plough and the dynamic sand (buffer) moves over the stationary sand (sand bed). The angle of internal friction is high for sand so this movement gives a high friction force. As the buffer grows, the friction force grows along. However, a clean straight boundary between the buffer and the bed is not likely. The horizontal buffer force is not easily calculated.
with a friction factor and a mass since the mass is continually changing and the motion is
dynamic. The buffer force is therefore calculated by subtracting all horizontal forces from the
measurement. This follows here below.
2.6.2 Calculating buffer forces

In order to calculate the buffer forces one must understand that the buffer forces will be the product when subtracting all known forces from the total force equation. In formula form we derive this:

\[ F_{\text{buffer}} = F_{\text{wh}} - F_{\text{current}} - F_{\text{ch}} \] (2.17)

In horizontal direction, as one can see in 6.17 in the section above, we have the pull force \( F_{\text{w}} \). The horizontal component is \( F_{\text{wh}} \). This is easily taken from the \( F_{\text{w}} \). This is done by multiplying this with the cosine of the wire angle \( \alpha \). The pull forces is measured during a test. This will give a series of values. ( The values are stored as an notepad file. This can be put in excel to be able to do some calculations and extractions.) This will give the following graph, where the pull force is given over the time. Seen in 2.10.

![Figure 2.10: force measurement over time](image)

![Figure 2.11: force measurement normalised](image)

In order to be able to compare different tests it is necessary that the scale of the measurement samples is in the same order. Since a longer test run will result in a longer set of values one needs to normalise the measurement. Normalising gives the graphs shown in 2.11. Normalising the time allows different speed tests to be comparable. Here, on the x-axis, the number one is always the end of a test run. One can also see the x-axis as the path traveled where the number one represents the end of the track.

Continuing with the current drag, \( F_{\text{current}} \), this will be calculated before and after a test. The drag force consists of multiple components. The plough itself, the wires that pull the plough, the wire or frame that hoists the plough and the heap of sand inside the plough. In surface area, this heap is the biggest drag inducing component. The drag force is also dependant on the speed of the water and the speed of the plough. With a counter current and a high plough speed, the drag force can be considerable. Expected however, is that the drag force component is very small compared to the buffer force and the cutting forces. Drag forces will be calculated and will be taken into account. They will however be simplified. If one takes a plough in the water, the drag is calculated with the following formula:

\[ F_{\text{drag}} = \frac{1}{2} \cdot C_d \cdot A \cdot \rho \cdot U^2 \] (2.18)

This has already been discussed in the section on the drag force. So we will start right away with the surface area of the plough \( A \). This is the total frontal surface area of the plough, this is a constant drag force over the entire plough session. This is also the case for the wires that pull the plough and hoist the plough. Apart from the drag coefficient, the calculation is similar. The drag factor that is not constant over the time is the drag induced by the buffer. Since the buffer grows over time, the drag by the buffer starts with zero and is at a maximum at the end of the plough track. Here, the buffer is probably the biggest. In order to ease calculations the buffer is considered constant over time. Here, the maximum buffer size is taken as the value for the total surface area. Two reasons to defend this short cut is that the plough session starts with the drag of the plough. As one can see in 2.12. So the session starts already with a drag component.
As the plough cuts sand, the buffer will grow. This cannot be added to the drag force induced by the plough since the frontal area of the buffer $A_{buffer}$ replaces the area of the plough $A_{plough}$ as one can see in 2.13. Although the buffer will be higher, the drag coefficient $C$ is lower. The second reason to consider the drag force constant is that the drag force is very low considered to the buffer and cutting forces and will therefore have no influence on the buffer force calculation. The drag force will be calculated by the size of the buffer at the end of the track.

The last component that has to be calculated are the cutting forces, $F_{ch}$. These have been discussed in the section cutting forces in this chapter. These are calculated easily in the manner Miedema describes. This is however not suitable for the calculation of the cutting forces in the plough situation.

If one takes a look at the gravitational factor $G$:

$$G = (\rho_s - \rho_w) \cdot g \cdot h_i \cdot b \cdot \frac{\sin(\alpha + \beta)}{\sin \beta} \cdot \left( \frac{h_b + h_i \sin \alpha}{\sin \alpha} + \frac{h_i \cdot \cos(\alpha + \beta)}{2 \sin \beta} \right) \quad (2.19)$$

This gravitational factor is used in the grain force $K_{22}$ as one can see in 2.6. Whereas $K_{22}$ is used in the calculation in the horizontal and vertical cutting forces, $F_{ch}$ and $F_{cv}$. This gravitational factor $G$ is calculated using the weight of the sand above the blade as one can see in 2.8. This is calculated up to the height of the blade, hence the value $h_b$ in 2.19, the blade height. In dredging it is usual that the sand is sucked away above this blade. As it is done in a TSHD. So normally it is not necessary to calculate the gravitational factor above this height. In the case of the river plough, this sand builds up above this blade. To give a reliable calculation on the cutting forces, the gravitational factor has to be adjusted. To account for the weight of the buffer above the blade, one can replace the constant $h_b$ for a variable $h_{b-mean}$. This $h_{b-mean}$ is the mean height of the sand taken from the underside of the blade. By using this method, the blade height is virtually increased and thus accounting for the constant increase in the gravitational factor. This means that at a constant cutting speed, the cutting forces increase where they would normally be constant. The new formula is now:

$$G = (\rho_s - \rho_w) \cdot g \cdot h_i \cdot b \cdot \frac{\sin(\alpha + \beta)}{\sin \beta} \cdot \left( \frac{(h_{b-mean} + h_i \sin \alpha)}{\sin \alpha} + \frac{h_i \cdot \cos(\alpha + \beta)}{2 \sin \beta} \right) \quad (2.20)$$

expected is that the height increase of the buffer is not constant over time. A constant volume of sand is fed to the plough but sand starts to spill and the height of the buffer grows slower. Also, the height of the buffer is not constant over the width of the blade. The buffer is always at a maximum in the middle of the plough while spillage from the sides creates a lower height. The next figure can help explain that phenomenon. In 2.14 one can see a representation of the buffer seen from the front. In gray the cutting blade and the factors $h_b$ and $h_{b-mean}$. 

Figure 2.12: frontal area empty plough

Figure 2.13: front area buffer

M.P.J. Wildenberg
One can see in figure 2.14 that the buffer in the middle of the plough is expected to be highest and at the sides the height is much lower. To use the adaptation of blade height $h_b$ in the gravitation formula we must convert to the mean buffer height $h_{b-mean}$. This will give an more suitable and convenient approach in calculating the buffer forces. The shape of the buffer represents a simple trapezoid (when seen from the front) Using the trapezoid shape, one can calculate the mean height of the buffer.

Using the video of an experiment, one can use the video material to measure the height of the buffer. By doing this measurement every 30 cm one gets an reasonable assumption of the growth of the buffer and therefor a reasonable Gravitation factor. This provides a list of heights at several moments in the ploughing process. Here, the researcher takes the height of the buffer at the grid ruler in the plough. This height measurement is done in the middle of the plough, where the buffer is highest. One must convert this value to a mean height. At the blade, the spillage will start when the buffer reaches the height of the side walls. In the plough the side walls are 2 cm high. In the plough models where the side walls are 2 cm high one can assume that the height of the buffer is constant over the width of the blade (this is only true up to a buffer height of 2 cm. Using the trapezoid shape on can calculate the mean buffer height. Assuming that the buffer has a 2 to 1 slope at the sides one can easily derive the mean buffer height over the width of the plough. Provided is a figure to explain.
As one can see in figure 2.15 a simplification of the frontal view of the buffer is provided. With B being the width of the plough, $h_b$ being the height of the buffer, $h_s$ being the height of the buffer above the 2 cm side walls. This gives the relation $h_b = h_s + 2\text{ cm}$. If one measures the height of the buffer at the beginning of the track in the middle of the plough blade $h_b = h_{b-mean}$. One can see the front of the buffer as a rectangle. If the buffer grows higher, spillage occurs and the shape transforms to a trapezoid. To use the measurement $h_b$ to get to the mean height $h_{b-mean}$, one needs to subtract the red parts shown in figure 2.15. Assuming a 26 degree slope on the sides (a 2 to 1 slope gradient) the 2 dimensional area of the red parts is $2 \cdot h_s^2$. To convert the measured $h_b$ to $h_{b-mean}$ one uses the following equations:

$$h_b = h_s + 2\text{ cm}$$

(2.21)

This yields:

$$h_s = h_b - 2\text{ cm}$$

(2.22)

$$TFA = h_b \cdot b - 2 \cdot h_s^2$$

(2.23)

In equation 2.23 the TFA stands for the total frontal area [cm$^2$]. This is the black part of the figure provided in 6.13 where $4 \cdot h_s^2$ is the area of the red parts. Substituting formula 2.22 in 2.23 gives:

$$TFA = h_b \cdot b - 2 \cdot (h_b - 2)^2$$

(2.24)

$$TFA = h_b \cdot b - 2(h_b - 2) \cdot (h_b - 2)$$

(2.25)

$$TFA = h_b \cdot b - 2(h_b^2 - 4h_b + 4)$$

(2.26)

$$TFA = h_b \cdot b - 2h_b^2 + 8h_b - 8$$

(2.27)
By dividing the total frontal area with the width of the plough, one gets a mean buffer height $h_{b-mean}$:

$$h_{b-mean} = \frac{TFA}{b}$$

(2.28)

$$h_{b-mean} = \frac{h_b \cdot b - 2h_b^2 + 8h_b - 8}{b}$$

(2.29)

If one uses the measurements $h_b$ from the video footage every 30 cm one will result in a list of $h_{b-mean}$. For example, a list is provided below.

<table>
<thead>
<tr>
<th>path traveled</th>
<th>$h_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 cm</td>
<td>0 cm</td>
</tr>
<tr>
<td>30 cm</td>
<td>2 cm</td>
</tr>
<tr>
<td>60 cm</td>
<td>3 cm</td>
</tr>
<tr>
<td>90 cm</td>
<td>4 cm</td>
</tr>
<tr>
<td>120 cm</td>
<td>5 cm</td>
</tr>
<tr>
<td>150 cm</td>
<td>5.5 cm</td>
</tr>
<tr>
<td>180 cm</td>
<td>6 cm</td>
</tr>
<tr>
<td>210 cm</td>
<td>6 cm</td>
</tr>
<tr>
<td>240 cm</td>
<td>6.5 cm</td>
</tr>
<tr>
<td>260 cm</td>
<td>7 cm</td>
</tr>
</tbody>
</table>

Using these measurements one can provide a list of the mean buffer height at several moments during ploughing. Note that only 10 moments during ploughing are measured. The moments in between these measurements are found by simply taking the trend between those two points. One can see in the picture provided below how a representation of $h_b$ and $h_{b-mean}$ looks like.

As one can see in figure 2.16, the $h_b$ is higher and by calculating the loss of sand from the sides by subtracting one yields the $h_{b-mean}$. Which lies a bit under the $h_b$ line. Using the one can now use formula 2.20 in order to calculate the cutting forces with the weight of the buffer contributing.

With all forces calculated one can now subtract the cutting forces and drag forces from the forces measured over the time. This leads to the buffer forces for a particular test. It is now possible to compare two different tests. To see the difference in buffer between a plough session against the stream and a session with the stream these steps must be done. This will provide a graph where the buffer forces are set against the normalised time. With these findings it is possible to draw conclusions on the influence of the current on the buffer process.
Chapter 3

Test set-up

To do research on the plough and the buffer it is already ruled out to do this in situ. These types of experiments would be hard to execute and would be very costly to execute. Here one would have to use the natural circumstances so the parameters that one would like to adapt are fixed and parameters, like the speed of the boat, can only be adapted to the degree the boat allows. The decision to do a small scale research is therefore much more satisfactory. The dredging lab at the TU Delft allows for such a research. In this chapter one will find what how an experiment works and one will find a description of the parts that are important for the research.

In the dredging lab, a large see trough tank is available. Luck have it that this tank is already equipped with an cart that rides on top of the tank. This cart can be set to a certain speed. This allows the researcher to set a speed on the plough and measure the influence of the speed on the buffer. The see trough tank allows the researcher to see the buffer from the side. Here, the principle of plouging is executed in the same manner as in the Waal plough. The small scale plough is pulled by two front wires and is fixed to a precise depth using a vertical wire. Adding load cells to measure the force on the wires allows the researcher to investigate the forces that are present during a plough session. Here, the front pull wires will measure all forces that act in the horizontal direction. Cutting forces, drag forces and buffer forces and the vertical wire will measure the loads perpendicular to that. For instance, the vertical cutting forces and the weight of the sand inside the plough. A simple drawing of how the set-up should look like can be seen below in figure 3.1

![Figure 3.1: Set-up of the plough.](image)

Here, in this figure one can see the plough, number 3, inside the tank cutting sand. It is pulled by the cart, number 1. During the test, the load cells, 2, measure the force. The goal is to start the plough at one side of the tank and let it plough a sand path of a fixed length and at a fixed speed of the cart.
When measuring the force in the pull wires one measures all forces in the horizontal (and partly vertical) direction. The goal is eventually to determine the buffer forces. This is done by subtracting all known forces. The forces known are the cutting forces, current drag forces and the friction forces. The first two can be calculated. The last force is however not easily calculated. The friction between the underside of the plough and the sand is a function of the weight of the plough and the angle of external friction. This can be calculated by determining the weight of the sand inside the plough and assuming a friction factor. Not to cope with this extra devious method it has been decided to hang the plough slightly above the sand bed. This way one rules out the friction between the plough and the sand. One can see a representation of this in 3.2. In order to keep the plough level and straight a frame (number 5) has to be build. This prevents that the plough (6) can roll or tilt. Rolling and tilting is not allowed since this changes the cutting depth. The cutting depth has to be fixed in order to calculate the cutting forces. If the cutting depth is not constant over the complete plough track than the calculated cutting forces will not be equal to the actual cutting forces. In figure 3.3 one can see the cutting depth. This will be set at 6 mm and this will also be the input when calculating the cutting forces. Now, one can calculate the buffer forces in a single experiment. By adding pumps to the water tank one can introduce a current. For this, a simple submersible pump can be used. By pumping out water on one side and pumping it to the other side a current will start. Adding a flow meter and a valve allows to set the flow to a fixed mean speed. This is however in practice never the actual speed. The pumps will have a small outlet so water will never be laminar. This is allowed but noted. By switching the pump from one side to the other one can set a counter or a with-current. (the plough always ploughs in the same direction.) The tank has a depth of 1 meter. However, only a water depth of 10 cm is needed.(the scale factor is set at 1:20 ) By filling the tank with sand up to 80 cm, the height difference is overcome. The type of sand is important in this setup since the behavior of the sand is the most important part of the research. Sand should be picked up by the current easily so it has to be small enough to be transported under a slight current (like in the Waal) but not too small to cause problems with under pressures during cutting. For this, the Hjulstrom curve in 2.5 is used. The Dorsilit nr. 9 sand proved suitable for these experiments. Information on the Dorsilit nr. 9 can be found in Appendix H.

Here a step by step description is given for a single plough test. The first step is to make sure that the sand bed in the water tank is nicely flat and equalized. This is done using a rectangular bar. This bar is connected to a wooden board using threaded ends. Using threaded ends enables
the researcher to set the precise depth of the sand layer. Continuously using the same method will ensure valid experiments. Secondly, the model of the plough is moved into the starting position. When the plough is placed, the computer software can be calibrated and configured as desired. When the plough is in place, the software is started and the desired speed is set for the particular experiment. This speed is set by a potentiometer, the actual speed is not precisely known but can be calculated afterwards. The potentiometer is set to a speed from which is known to lie close to the desired speed. The cart is not yet started. Every run is furthermore filmed with a GoPro camera, especially the so-called buffer developing in front of the buffer. This way the behavior of the buffer can be analyzed later. Before starting the cart, the camera films which experiment is done so every video contains the name of the experiment. The pump is started before the plough starts. The pump is set to a certain flow rate that will create the desired current in the water tank. Now there is a waiting period of a minute or so, to make sure the current in the tank is a reasonably laminar flow and the start-up turbulence is gone.

After that, the plough is ready to start moving. At the moment the button is pressed to start the pulling, the measurements are started (including time registration). The camera starts before the plough starts to record the run. The researcher however needs to operate the tank and the start button so the first centimeters of the track are not filmed. During the pulling process itself no further special actions are needed, aside of recording. Once the plough arrives at the end of the water tank. It now has traveled exactly 260 cm the pulling is stopped automatically via sensors. Immediately the measurements are stopped, followed by the camera and the pump. Pictures are taken from the spillage from the sides of the plough.

Now one person empties the filled plough and equalizes the sand bed for the next run, while the other person saves the data that the computer software measured with the load cells. Now the water tank is ready for the next run. The plough can be moved to the start position again while the measuring software is reset. The current and/or pulling speed parameters can be adjusted where needed, and the next run can commence. This can continue for several runs until the water is too cloudy to film the plough process. Here, the water is replaced by new water from the tap.

3.1 Set up

In the following sketch all the individual parts are indicated. Also the start position, the moving direction and the final position (in dashed lines) are shown.

The main dimensions of the water tank are:

<table>
<thead>
<tr>
<th>Length</th>
<th>Width</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 m</td>
<td>0.5 m</td>
<td>8 m</td>
</tr>
</tbody>
</table>

Here one can see the cart above the test tank and the plough which is attached to the cart. The plough is at sand bed level. In this sketch the plough would be at the end of the plough session. Starting at the right, the plough completes a path of 260 cm. Here, no pumps are seen. In the parts description one will see how these are installed and used.

A detailed description of these items and other components, including the tank and plough, in the set-up can be found in the next paragraph.
3.2 Parts description

The individual items of the set-up are described in more detail below.

**Water tank** The biggest part of the set-up is the water tank, the dimensions of the tank are shown in the previous paragraph. The tank is a rectangular steel frame without a bottom. The side walls consist of thick glass. This tank was already used in other researches where the visual part was of great importance. This visual aspect is in these experiments also of big importance. The front- and back are steel plates, they also have connections for optional piping to other equipment. Since the tank has no bottom and has to be waterproof, special sealing mats are clamped between the floor and the walls. Figure 3.5 shows the water tank in empty state. The floor of the lab is visible, as well as the sealing mats and the glass side walls. At the bottom of the figure three connection pipes are visible, these are the connection points for external piping.
The water tank has a rails installed over the length in order to drive a cart from one side to another. This rails is simply an U profile steel beam in which the wheels of the cart can drive. In the U profile, a chain is tensioned. This chain is needed for the cart to drive from one side to another.

![Figure 3.6: Tank with rails.](image)

In Figure 3.5 one can see the water tank with the chain in the U profile on both sides. In this case, the tank is already filled with sand. On both ends of the tank a big bucket is placed. The buckets have two functions. The first function is placement for the pumps. The pumps used are submersible pumps where the water intake is at the bottom of the pump. Placing the pumps on the sand bed will cause sand to be pumped in. Running experiments for a day will cause the pump to bury itself in. The second function for the buckets is to act as an stilling chamber. This smooths out the turbulent behavior of the pump water. High water speeds at the outlet causes an very erosive situation of this is placed directly on the sand. Placing the end of the hose inside the bucket smooths out the water speed and provides a more uniform flow in the water tank. More on the water pumps further in this chapter.
Pulling cart Riding on four rubber wheels, a pulling cart drives between the rails, pulling itself forward and backwards with the use of the chain. The cart is a very basic concept as one can see in figure 3.7. It consist of an electric motor, a steel plate and eight wheels. Four wheels are mounted on the corners of the steel plate. The four other wheels are oriented so that the cart stays in the rails. The electric motor is oriented in the length of the cart. Using a gear case and an axle, the rotation is translated to forward or backward motion.

On either side of the cart, chainwheels are fitted on the axle. These chainwheels are connected to the tensioned chain on the rails. The electric motor drives the chainwheels and because of the chain being unable to move, the cart runs over the rails. Pulling it self in one direction. It’s direction dependable on the rotation direction of the electric motor. The speed of the cart can be controlled by the user. This will be further discussed in the chapter experiments. Important to know is that the water tank is fitted with sensors which limit the movement of the cart. At both ends of the tank, sensors are in place so when the cart hits the sensors, the cart stops. Thus preventing the cart from self-destruction.

Connected to the pulling cart is a horizontal beam that supports the weight of the plough, a simplified A-frame, as in the real situation. This beam stretches out for 70 cm from the end of the cart. It is positioned in the middle of the width of the water tank. On this beam, the model plough is hanged. Here, the plough is hanged on a load cell in order to measure vertical forces. The load cell has several degrees of freedom. It can translate in horizontal direction (in the direction of the length of the water tank) and rotate since it is hanged in a bearing. The load cell for the pulling forces hangs underneath the pulling cart. More on the load cells will be discussed in the description of the load cells further on in this thesis.
**Model plough** The most important item in the set-up is the scale model of the plough.

It represents the plough used in actual Waal river maintenance. This is a 1:20 replica of the real size plough with bottom plate. The model plough has several adaptations in order to aid the experiments and exclude unwanted effects. A detailed description of the plough will be given below. In figure 3.8 the replica is shown filled with sand after a preliminary run. The model has a cutting blade that can be set to different cutting angles, one of the independent parameters in the experiments.

The plough also has the storage capacity behind the blade, likewise to the closed bottom plough. In the front, next to the blade, the pulling cables are connected on both sides the plough. These cables stretch to the pull load cell under the pulling cart. These wires can be set to a particular length but will be set to a fixed length, scaled to the dimensions of the actual plough setup. The port and stern side of the plough is 2 cm high. The back of the plough is also 2 cm high and 25 cm wide. The height will be adjusted in future experiments. In the middle of the plough, a large ruler is fixed. On this ruler the vertical and horizontal distance can be measured. The ruler is a simple 1x1 cm grid with a length of 20 cm and a height of 7 cm. This ruler stretches out for 12 cm in front of the plough. This is measured from the front of the bottom plate. The ruler is used to visually measure the volume of the buffer in front and inside the plough. The ruler is fixed to the bottom and back of the plough. This ruler also divides the cutting blade in two over the width of the plough since it was otherwise physically impossible to mount the ruler and mount the blade. Previous plans stated that the plough should be hanged on wires to the vertical load cell. Implementing this plough in this mode proved to be impossible. The steel wires in combination with the low weight of the plough resulted to much slack. The wires tended to rest in their ‘natural position’. Instead of a straight line, the wires had a curvature. When executing an experiment, the plough dough in the sand in an irregular manner while the experiments required a straight cutting line and a fixed cutting depth. After numerous failed attempts, the decision has been made build a frame for the plough. To keep the plough straight and on a fixed height, a connection frame is engineered on top of the plough sits a connection frame, see next paragraph for more about this frame.
Plough frame On top of the model is a connection frame has been built. In reality the plough is only vertically supported by a wire from the A-frame. Preliminary test runs showed that this would not work in smaller scale. The combination of the low weight and the steel wires proved to be non-applicable. The vertical gravity component proved not sufficient enough to keep the plough horizontal during cutting. The result was a crooked cutting path with a variable cutting height. Also the steel wires suffered from the lack of tension due to the low weight. So when no vertical load was present, the plough would just float above the sand. To prevent this from happening a connection frame was built. Main functions of the frame are to transfer the vertical forces from the plough to the pulling cart, but under no circumstances should the frame somehow transfer horizontal forces. Key was that the frame could fix the vertical position of the plough and keep the plough straight. The plough is not allowed to tilt or roll. By using four threaded ends in the corners of the plough, the height of the plough can be fixed.

The plough is fitted with a wings on each side of the plough. The wing is attached to the side using rivets. The threaded end are placed so that they do not cause a disturbance in the filling of the plough. The four threads run up to a mounting plate. This plate holds the threads using nuts. Here the length of the thread can be adjusted. In the middle of the plate, a shorter thread mounts the plate to the vertical load cell. This thread can also be adjusted in length. This comes in handy when the whole plough must be lowered or risen. In the starting phase with the plough frame, the vertical load cell above the plough was fixed. It did not allow rotation or translation. The pull wires had a few centimeters slack. The result of the slack was that the connection frame tilted slightly when ploughing began. The result was that the fixed vertical load cell partially transferred horizontal forces. Introducing a sew horizontal load measurement. This problem was solved by using a rolling bearing connected on the vertical load cell. A rolling connection can hold the mass of the plough but can not pull it. Adding the freedom of rotation and translation. At the start of ploughing, the pull wires start to get tense and lengthen a centimeter in comparison to the inactive position. This is the length between the pull load cell and the front of the plough. This lengthening could now be coped with since the vertical load cell should roll the same distance, preventing tilting of the plough and keeping the plough horizontal. In the next paragraph the load cells will be discussed. Here, in figure 3.11 one can see the rolling connection.
Figure 3.9: Plough frame.
Load cells
Also, of great importance for the set-up are the load cells. A load cell is an item that can convert applied forces to an electrical signal. The type load cell applied does this based on a strain gauges, these gauges are applied to the side of the main body of the load cell. These strain gauges can be seen as a sort of spring with changing electrical resistance when the length changes. As a result of the force on the main body, the strain gauges are elongated or compressed. During this process the electrical resistance of the gauges changes. The length change however is very small and is only due to elastic deformation.

Because of the changing electrical resistance the changing load force can be converted to a changing electrical signal. This electrical signal is measured. Using a computer these signals can be read. A load cell however, must firstly be calibrated. The signal conversion must be correct. By using standard weights, the signal conversion is calibrated. Giving a reliable reading. The conversion also allows the researcher to add or subtract a weight.

The decision has been made to subtract the weight of the plough in the output. So before an experiment starts, the reading gives a zero kilogram reading. The load cells where both positioned, as stated before, so that the force acting on it is in the same direction. So the force acting on the load cell has only one component. For the vertical load cell, hanged in the beam, the vertical forces are measured. These forces are the gravitational forces, vertical cutting forces and sand buffer forces. The vertical load cell is hanged in a bearing so that the vertical component is in the direction of the gravity.

Pulling the plough is the pull load cell as one can see in figure 3.10. The pull load cell is actually not horizontal, it is tilted in such a position that the pull wire is aligned. The type of load cells used are the Zimic H3G-C3-50kg-6b. The load cells can measure a load up to 50 kilogram. In the experiments this weight load will be sufficient enough. A smaller load cell could have been used but these types where readily available and proved sufficient.
The key in the experiments is to mimic the original plough situation. At the Waal river there is a steady stream of water. A mean water speed of 4 kilometers an hour is normal. Plouging occurred with or against the current. In the experiments, the influence of the current is tested. Therefore, a current must be present in the water tank. This current is provided by using pumps. The type of pump is a submersible pump. A submersible pump is lowered into the bucket in the water tank, sucking in water at the inlet. The outlet is a 50 mm hose, ending in the bucket on the other side of the water tank. Sucking in water on one side and pumping in water at the other side provides a stream. Depending on experiments, the pump can easily be pulled out of one bucket and be placed in the other. Thus providing a counter current or a with-current situation. A submersible pump has the advantage that they are cheap and reliable. The downside is that this type, in comparison to a bigger centrifugal pump, can not be set to a specific flow rate. It is either off or on. Since other available pumps were too large to use, the decision has been made to use submersible pumps which were easily available. To adjust the water volume, a valve is installed. This allows the researcher to control the flow rate. In the time of the experiments no suitable flow rate meter was available to test the pumps capacity. In the data, a max flow rate is given but this is not reliable so an small experiment had to be done in order to test the capacity of the pump at several valve settings. By utilizing a large bucket available in the dredging lab the flow rate could be calculated. This bucket has a volume of 80 liters. Installing the pump in the water tank and installing the hose in the bucket at a height comparable to the experiments. Measured here was the time it took the pump to fill the bucket in several valve settings. The little experiment proved not to be completely watertight since water sprayed out of the hose at such speeds that it reflected partly out of the bucket wetting the lab partner. Executing multiple experiments with equal valve settings gave an good indication of the flow rate. These experiments where also done with another similar pump. Data on the submersible pumps are available in the Appendix K. In the experiments the pump what first started. After several minutes, a steady stream developed inside the water tank. After the steady stream was present, the experiment could start.
Chapter 4

Experiments

Here, a description will be given on the small scale experiments that will be done. An overview on the different types of experiments is given. The experiments can be divided into four parts. The preliminary experiments, basic experiments, the main experiments and the stability experiments. For this thesis the scope lies in the basic and the main experiments. The basic and the main experiments describe the behavior of the buffer and several of the main experiments are used to execute a force model in order to calculate the plough forces. Not to enlarge this thesis, several of the main experiments and stability experiments are moved to the appendices. These experiments are of lesser importance but can however be helpful for the design of a new plough and can be used for references. One will find the main experiments in Appendix 1 and the stability experiments in Appendix 2. In this chapter one will find what the four different types of experiments are and what parameters will be changed and which adaptions will be made to the plough.

4.1 types of experiments

There are multiple experiments to be executed where there will be a couple deviations to model setup. Here is an overview of the types of experiments that are being executed. The testing starts with the preliminary test. Here the tank is filled with water and buffer tests are executed before other adaption are done to the plough. The preliminary tests will be described here in order to explain how and why some adaptions have been made. The basic experiment has 8 different settings. This basic experiment is the first set of experiments in the research on the buffer and the total plough forces. Following from these are the main experiments. For the main experiments, the plough from the basic experiments is adjusted. These adjustments are done in order to improve the efficiency of the plough process. After the main experiments, several stability experiments are executed. These experiments test adaptions on the plough in order to improve the stability of the ploughing prices.

preliminary test

Before the basic experiments starts, some simple tests are done in order to test the if the set up works as it should. This can also be of use to give a insight on the amount of time one test takes. Before filling the tank with water, experiments are being held to test if everything works as it should. Here the plough is being pulled through the dry sand while measurements are done. Here, the researcher can test if the set-up of the experiments works like it should and can fine tune the pot meter on the control box to get a certain speed. If any abnormalities show up in these experiments, an adjustment can be done easily. This preliminary test is referred as the dry tests. In figure 4.1 one can see a picture of such a dry test taken in action.
After the preliminary tests are done and the set-up has proven sufficient, the basic tests can start. Here, water is added to the towing tank in order to start testing. An overview of all the basic experiments is given in the section list of experiments. Here, tests with water and current are done. The No flow tests are test where no current is yet set so no influence of the current is present. This gives the researcher the advantage to better compare the current tests. The two other types have a current set. Here the plough session occurs against or with the current. Just like in the Waal river.

- no flow experiments
- with flow experiments
- against flow experiments

In the basic experiments, a flat sand bed will mimic the bottom of the Waal. These experiments share similarities to the main experiments. However, the basic test have to be done in order to test the plough process and will be used in order to draw conclusions on the plough process. These are descriptive conclusions. It is not possible to exactly calculate the buffer forces using the standard plough without spokes. Therefore, the experiments will be described but not analyzed further. In the basic experiments one will investigate the filling and build-up of sand in the plough as well as the build-up of sand in front of the plough, the so called buffer. In these experiments a fair amount of tests will be executed. In these test, a number of independent parameters will be adjusted. These independent parameters will be discussed below. In these tests different speeds will be set for the cart. Also test will be executed where there will be a counter current, a with-current and no current. Furthermore, different current speeds will be tested. A change will be made in the water height. Here, the height of the water will decrease with 10 cm. This water height will result in a higher water speed. These experiments are a simplification of the Waal plough session. The plough utilized in these tests is shown below. This is referred as the standard plough. More information on the standard plough is provided in the section Parts descriptions (previous chapter) and pictures can be found in appendix B.
After clearing the basic experiments, adaptations to the plough will be done in order to improve the efficiency of the plough. From here one, the main experiments starts. First, a start is made with a description of the adaptations. Since the main experiments are the basis of the thesis, a broad description is done. The first adaptation made to the plough is to ease measurements, this is using spokes inside the plough. These adaptions are needed in order to calculate the plough buffer forces. These calculations are needed in order give an decisive answer on the research question. Next to that, for the increase of efficiency, several adaptations will be done in the following experiments. To compare the results with the old plough version, similar tests as the main experiments will be executed. Here, speeds of the plough and the current are corresponding to ease the comparison in efficiency and the buffer build up. Here a decision will be made on which tests are worth repeating and which will not be of great importance. With the adaptions to the plough that will help measurements, drawing conclusions and calculations can now be done. Other adaptions to the plough help to better understand the buffer and are used to improve the plough efficiency. These adaptations on the plough will be given here. Not all these experiments are worth to include in this thesis and will therefore be added in the appendices. Also, in the appendices, pictures can be found on the complete plough models and adaptations. A list of experiments will be given in the next chapter. Next one will find all adaptions that will be done to the plough in the main experiments.

**grid ruler** An adaption to the plough in order to better measure the height of the buffer in front and in the plough is a grid ruler. This grid ruler is like a normal ruler but can measure length horizontal and vertical. Using this grid ruler inside the plough. The ruler is fixed in the middle of the plough so that it gives an good measurement. Measurements are only done at one side of the plough since the plough is mirrored on the other side. The buffer on the other side of the grid ruler will be the same. In picture 4.2 one can see the grid ruler installed in the basic plough. The grid ruler helps the researcher to measure the length the buffer stretches in front of the plough and the height of the buffer.

**steel spokes**
The first adaptation on the plough that will be used are steel spokes on the inside of the plough. These spokes will be fixed in a vertical position just behind the cutting blade (The position where the buffer is at it’s highest position) These steel spokes form a row of 10 over the width of the plough. The function of the spokes is to ease the research on the buffer. Each spoke acts as a single ruler. The spokes have one stripe per centimeter. Using the spokes, one can see the behavior of the buffer at the sides of the plough. Sand not only spills at the back of the plough but also at the sides if the plough. The form and height of the buffer can be derived more easily using the spokes. The decision on using the spokes was put forward by dr. Talmon since these spokes are very thin and do not affect the buffer or the filling process. Since dr. Talmon always repairs his own bicycles spokes where readily available. For installing the spokes, an adaptation had to be made to the frame. Installing a plate 20 centimeters above the plough, fixed in the four corners by the threaded ends with nuts made it possible to install the spokes. Putting the spokes with a hole in the plough and a hole in the plate made them stay in the right position. Minimal extension of the spokes under the plough prevented a skew consequence. In Appendix C one can see the adaptation of the plough with the spokes. This is called the basic plough. Figure 4.3 provides a Solid Works render of the plough with the steel spokes. Since the time was available, the decision has been made to re-do most of the tests of the main experiment. Also the most of the following experiments are adaptations of the steel spokes plough unless it is explicitly described. In the next chapter the test matrix will be given.
Figure 4.3: steel spokes installed.
High back

After the experiments using the adjustment of the plough with the spokes, is the usage of a higher back. In the preliminary tests, experiments have shown that spillage of sand occurs at the back of the plough. When the buffer is high enough, the sand rolls over the back slope of the buffer and exits the plough at the back. Leaving small amounts of sand on the freshly cut sand bed. The standard plough, in the basic experiments, has a back of 2 cm high. In the standard experiments, the plough fills up to a certain height before it spills the sand over the back. The sand heap inside the plough forms a natural limit. A certain degree of the slope where the sand starts to roll. When the slope of the buffer exceeds this natural slope, sand will start to roll. When building up the buffer, the boundary of the heap does not extend to the back of the plough, only when the buffer is large enough, the sand will spill. In the new test, the back is raised to 4 cm in order to test if the plough fills more than in the basic plough set-up. Furthermore, raising the back would allow the buffer to reach a bigger height. This can create a more unstable situation, a lower gradient slope. Raising the back of the plough is a quite simple modification. By mounting a higher plate to the original back using rivets, the back is heightened. In the Appendix D one can see the new back mounted on the plough. In the test matrix one can see the used experiments with the 'high back' plough. In the movies, this adaption is also called the high back. In the two pictures provided, 4.4 and 4.5 one can see the Solid Works render from the front and from the back side of the high back plough.
Figure 4.4: High back plough.

Figure 4.5: High back plough back side.
**Side flaps**

Another adjustment to the plough in order to reduce spillage of sand is the usage of side flaps. These side flaps have a multi purpose. Spillage of the sand is already discussed in the previous item on the higher back. Spillage does not only occur at the back of the plough but also at the sides of the plough. The same gradient of the slope causes the sand to roll from the side of the buffer over the wall of the plough. When the buffer builds up, the spillage from the side starts sooner than the spillage from the back. Right after the cutting blade the highest point of the buffer emerges. When the buffer build-up is halfway, sand starts to roll out of the plough at the sides. Half way the build-up is where the height of the buffer is at the half of its maximum height. In order to enhance the efficiency and for experimental reasons, the sides are heightened with 2 cm. The same height as the high back. The natural slope of the buffer is not only at the back, but also at the front. Here, the slope gradient is variable since the cutting process makes the buffer very changeable. If one considers the buffer as a stationary heap of sand, then the middle is right after the cutting blade. The front of the buffer is already a few centimeters in front of the plough. When ploughing, a lot of sand already rolls to the sides of the buffer. This means that the sand does not reach the plough but is already pushed aside, creating a small heap next to the plough. To prevent this, the sides of the plough are not only heightened but are lengthened. Where the sides previously stretched to the cutting blade, they now stretch in front of the cutting blade for 3 centimeters. Thus preventing spillage in front of the plough. In the tests, this version of the plough is referred as the 'side flaps' plough. In the Appendix E one can see the overall dimensions of this plough version. Mounting the flaps is done using rivets on the original side, in the same fashion as the high back. In the next section, an overview is given on the experiments that will be executed. One can see in the pictures provided below how the side flaps are mounted, referring to figure 4.7 and 4.6.

![Figure 4.6: side flaps left.](image1)

![Figure 4.7: side flaps front side.](image2)

The decision has been made to describe the experiments with the side flaps to the Appendices in order to keep a focus on the main subject.
Thesis - Filling process of a river plough

Top flaps
Early experiments had shown that filling the plough turned out to go not as expected. While the expectancy was that the sand would be pushed to the back of the plough, the sand would be pushes more upward. Due to this upward force and not a force that pushes the sand to the back, the ploughing process creates a large buffer in front of the plough. This large buffer introduces a high friction component. In front of the plough, a big sand/sand friction component contributes to the total horizontal force. In the full scale plough, this could cause a rather large factor in the towing forces. Sought after is a method to prevent this buffer in front of the plough. To direct the sand more to the back of the plough, a flat flap above the cutting blade is positioned so that the upward force in the buffer is changed in direction. The change in direction can cause the sand to be forced more to the back of the plough instead of being directed upward. This leads to a quicker filling process and, more important, a smaller buffer in front of the plough. To test this theory, several test have been done with the 'top flap' adaption. An advantage of the top flap that can also be tested is the added stability factor the flaps can induce, this will be discussed in the next bullet. From now on this adaption will be referred as the 'top flaps' plough. In the next section there will be a matrix on what tests have been done with the top flap adaption. In figure 4.8 one can see the top flaps installed in the plough in real and in 4.9 in Solid Works.

Figure 4.8: top flaps adaption.

Figure 4.9: top flaps Solid Works.

For all adaptations a row of experiments is done. These consist of experiments against flow and in the same direction of the flow. Some experiments will deviate from these parameters. Also, several speeds are tested. In the section List of Experiments one will find all the tests done within the main experiments. Also, for these experiments, the decision has been made to describe effects of the top flap addaption in the Appendices in order to keep a focus on the main subject.
The stability experiments are described in Appendix 2
4.2 parameters

In the experiments, multiple parameters are set. These are the independent parameters, set by the researcher. These parameters are adjusted to give a broader view of the plough process. Also to give a usable amount of data on which conclusions can be drawn and hypotheses can be tested. An overview of the independent parameters is given below:

- Speed plough
  The first parameter which is varied is the speed of the plough in the model setup. The speed of the plough determines a lot of effects. First of all, the cutting process. When the speed is higher in a cutting process, the forces needed in the process are higher due to dilatancy effects. Water needs to flow in the pores caused by the change in the particle arrangement. At higher speeds, this water needs to flow faster causing higher horizontal cutting forces. Higher plough speed also gives a higher flow resistance. If the speed doubles, the drag increases quadratic. The effect of the speed in the sand/steel friction is not yet known. However, the vertical forces increase linear with the speed. These are the vertical cutting forces. The pressure between the plough and the sand underneath increases, hence giving a higher friction. Filling of the plough during the cutting process also gives a higher friction. The friction factor is excluded in the model plough by using the plough frame. Important to understand is that a higher speed also gives a more turbulent cutting process, this can cause more effects which are not yet accounted for. This speed can be set to a fixed speed. The speed of the plough can vary between 0.02 \( \frac{m}{s} \) and 0.20 \( \frac{m}{s} \). The original speed of the plough in the Waal was between 1 \( \frac{km}{h} \) and 6 \( \frac{km}{h} \). The speed in cm is respectively 0.28 \( \frac{m}{s} \) and 1.66 \( \frac{m}{s} \). Scaling these values with an scaling factor of 20 gives the following model plough speed: 0.14 \( \frac{m}{s} \) and 0.84 \( \frac{m}{s} \). Since the speed of the cart on the tank can be varied continuously, the decision has been made to vary between 0.01 \( \frac{m}{s} \) and 0.15 \( \frac{m}{s} \). For the overall experiment, test with a higher plough speed will also be executed. The higher quantity of data will give a broader view on the ploughing process. Since it is not possible to give the plough a precise speeds, a small test has to be done in order to establish the representative speeds for the pot meter. These speeds are given below in the following table, table 4.1. As stated before, it is hard to set the potmeter to a precise speed so the speed is always calculated after the experiment:

<table>
<thead>
<tr>
<th>Pot meter</th>
<th>Representative speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.016 ( \frac{m}{s} )</td>
</tr>
<tr>
<td>0.5</td>
<td>0.042 ( \frac{m}{s} )</td>
</tr>
<tr>
<td>0.6</td>
<td>0.060 ( \frac{m}{s} )</td>
</tr>
<tr>
<td>0.7</td>
<td>0.068 ( \frac{m}{s} )</td>
</tr>
<tr>
<td>0.8</td>
<td>0.075 ( \frac{m}{s} )</td>
</tr>
<tr>
<td>0.9</td>
<td>0.088 ( \frac{m}{s} )</td>
</tr>
<tr>
<td>1.0</td>
<td>0.090 ( \frac{m}{s} )</td>
</tr>
<tr>
<td>1.1</td>
<td>0.109 ( \frac{m}{s} )</td>
</tr>
<tr>
<td>1.2</td>
<td>0.119 ( \frac{m}{s} )</td>
</tr>
<tr>
<td>1.3</td>
<td>0.131 ( \frac{m}{s} )</td>
</tr>
<tr>
<td>1.5</td>
<td>0.147 ( \frac{m}{s} )</td>
</tr>
<tr>
<td>1.8</td>
<td>0.152 ( \frac{m}{s} )</td>
</tr>
<tr>
<td>2.0</td>
<td>0.198 ( \frac{m}{s} )</td>
</tr>
</tbody>
</table>

Important to know is that, in the experiments, the name of the experiment is noted with the pot meter setting. This setting is also described in the name of the experiments. In the calculations and the graphs, the speed of the plough is described.
• Water flow
The second parameter which is varied is the flow of water. Since the flow of water in the river Waal can also vary over time and over location, the model must also have a variation in water speed. The direction of the water speed is also varied. In the experiments of van der Lugt, the plough was towed in the downstream and upstream direction. In the downstream direction, the vertical forces in the towlines where higher than in the upstream direction. During the tow in the downstream, the water flow should decrease the horizontal forces. However, this was not the case in the experiments. An explanation for this is the bulldozer effect. The water flow of the Waal prevents the freshly cut sand to overflow the plough (spilling over the back of the plough) and creates a wedge in front of the plough, therefore moving a bigger volume of sand, increasing the horizontal wire forces. In the opposite direction. The water flow against the plough gives a higher drag but creates a higher spillage at the back of the plough. In this case, a smaller or no wedge is created in front of the plough decreasing the horizontal wire forces in respect to the downstream tow. Another possible explanation is that both directions do not give an sand wedge in front of the plough but the sand pack within the plough forms differently. Increasing the water flow in an ‘against stream’ plough session can cause more sand to flow from the front to the back, over the sand buffer, and over the plough, spilling from the back. When comparing two different plough sessions, both with the same plough speed but different water speeds. In the situation with a higher flow velocity one expects more sand to roll over the buffer instead of contributing to the buffer. This gives an lower horizontal pulling force which is positive. However, spillage from the back is not desirable. In the tests, the video footage can show if this process actually occurs and measurements will give a decisive reading if there is a difference in the buffer. The waterflow in the experiments will be set to

• Water Direction
This parameter is dependent on the water flow. In the precious parameter an explanation is given for the filling of the plough and the possibility for a sand wedge. The towing direction is related to the water flow. In the field tests, where upstream and downstream ploughing sessions where done the water, there is a discrepancy in horizontal forces. As described in the previous bullet, the water speed can have an effect on the buffer build up. Here was described what, hypothetically speaking, water speed can cause in an against stream (up stream) ploughing session. In the other case where the ploughing direction is in the same direction as the water, the water can prevent the sand from rolling over the buffer. In the case that the water speed is higher than that of the plough, or in the same amplitude, the rolling of sand stops. This can contribute to a higher or bigger buffer. The contribution of this rolling process will be tested in the model experiments. It is possible that the rolling sand on only a neglectable part in the complete process. For further explanations another possible cause can be describes for the difference in horizontal forces. A possible explanation for the difference in forces can be that, if present, the dune forms affects the filling of the plough. Towing the plough downstream means one is towing it on a slightly increasing dune. On the other side(towing upstream) the plough must cut into a steeper dune. This difference can cause the discrepancy between the forces in the towing lines. In the experiments however, no dune test will be done since these are lengthy experiments and time for these tedious experiments is not available.
Blade angle

The blade angle has multiple influences on the behavior of the plough. First of all, the blade angle is decisive for the cutting forces of the plough. Sharper angles give higher horizontal cutting forces and lower vertical forces. If the blade angle increases, vertical forces increase and horizontal forces decrease. Giving a constant cutting depth. Secondly, the cutting angle influences the upward force for the buffer. The upward force for the buffer is a result of the combination between the horizontal cutting forces and vertical cutting forces. A sharper blade angle will direct the sand in a higher direction (more vertically directed) which will cause a build up of sand in the vertical direction. A decrease in the blade angle will provide a more horizontal directed force on the sand and will push the sand barrier to the back of the plough instead of upward. In figure 4.10 one can see the cutting blade in front of the model plough.

Cutting depth

In the model setup, the cutting depth of the plough can be adjusted. By lowering the plough completely, the depth of the cut increases. In several experiments, a bigger cutting depth is used. The result of using a bigger cutting depth is that more sand will be cut. The buffer will build up more quickly when comparing to a similar speed at a lower cutting depth. The horizontal and vertical cutting forces will be higher when cutting a bigger sand volume. Expected is that the buffer will build up more quickly. This means that the buffer will be at its top height in a shorter distance traveled. Expected is that this height can be compared to the height when ploughing with a smaller cutting depth. The height of the buffer is dependent from its natural slope, so it will spill out of the back and side when it gets to high. The buffer in front of the plough is expected to be bigger. The amount of sand which has to be moved vertically is bigger (pushing the buffer upwards). The weight of the sand above the cutting blade will partially prevent newly cut sand to be pushed further. This induces a bigger buffer in front of the plough. The sand will be pushed upwards due to the cutting at a reasonable distance in front of the blade.

Filled plough

In all experiments the plough cuts a path of 260 cm. In the basic experiments, a reading of the forces proved that the buffer is not yet in a stationary process. The horizontal forces do not reach a permanent value but keep increasing. Expected is that, when filling the plough, a limit will be reached where the buffer does not grow. Here the volume of sand that is cut per second is equal to the amount of sand that spills over the back and to the sides. Trying to reach this process, the plough has been filled in the beginning. The plough starts at the 0 cm start point and completes a normal cutting path of 260 cm. The difference is that the plough is filled with sand in the beginning. Here, the goal is to reach the stationary process where the buffer does not grow anymore. Expected is that the stationary process is reached and that the curve in the horizontal and vertical forces is horizontal in the end of the cutting path. Only few experiments will be done with the plough filled.
4.3 List of Experiments

As said before, the thesis consists of the preliminary tests, the basic experiments and the main experiments. We will start with an overview of the preliminary tests. An important note is that in Appendix M, one will find all the names of the videos and the measurements of the experiments.

**Preliminary experiments**

To test if the load cells work as intended, the decision has been made to dry test the plough. This is the preliminary test. The tank is not yet filled and is tested several times to fine-tune the pot meter and test the complete system. In these experiments, one can try to adjust the speed of the cart using the pot meter to get an incremental speed. Low speeds have shown very difficult to adjust since only small adjustments to the pot meter make big differences in speed of the electric motor. Low speeds for the plough proved to be too low for the electric motor which powers the cart and therefore the low speed of 0.014 m/s which comes from down scaling the Waal speed can not be used. Speeds lower than 0.05 m/s proved to be difficult to set so only few experiments are with a speed lower than 0.05 m/s. The first dry tests give the researcher an insight on which position on the pot meter gives which speed. These pot meter stances and representative speeds are already given in the previous section at the parameter plough speed. Also the values from the load cells could be read in order to establish proper speed measurements. The following tests that have been done in a dry environment can be seen in table 4.2.

<table>
<thead>
<tr>
<th>0.4-nowater-45</th>
<th>0.5-nowater-45</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6-nowater-45</td>
<td>0.7-nowater-45</td>
</tr>
<tr>
<td>0.8-nowater-45</td>
<td>0.9-nowater-45</td>
</tr>
<tr>
<td>1.0-nowater-45</td>
<td>1.1-nowater-45</td>
</tr>
</tbody>
</table>

The name of the test represents several parameters. Taking the first test, 0.4-nowater-45. The first numbers stand for the pot meter position. nowater stands for the state of the tank. In this case the tank is not yet filled so only dry sand is present. The last number stands for the blade angle in degrees.

**Basic Experiments**

Hereafter, the tank is filled with water and the basic experiments will be done. For ease, these basic experiments are split up into three parts. The following parts are:

- no flow experiments
- with flow experiments
- against flow experiments

An overview of these experiments can be seen in table 4.3.

As one can see, several parameters are changed in these experiments. One should see this as a test matrix. Each cell that contains an X stands for a experiment that has been executed. Some of these tests are with a flow in the tank. This flow is made possible by adding a pump to the tank. The flow will vary in speed and direction as one can see in the matrix. It is very hard, if not impossible to change the ploughing direction of the cart. Therefore, the direction of the waterfowl is changed. The result for this is that all measurements with the parameter flow direction have to be done in one time. After doing all the measurements in the -with flow- conditions, the pump system is switched and the flow direction will be set to -against flow-. The pump installed can provide a flow rate of Q = 150 m³/min giving a flow rate of 2.5 l/s. This gives a maximum mean flow velocity in the tank of 0.025 m/s given a width of 50 cm and a water height of 20 cm. The flow rate will be controlled by an butterfly valve. This gives the researcher the possibility to throttle the flow. It is also possible to increase the flow by adding another pump. The flow rates used in the preliminary
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Table 4.3: Basic experiments

<table>
<thead>
<tr>
<th>Water depth</th>
<th>20 cm</th>
<th>10 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>with</td>
<td>against</td>
</tr>
<tr>
<td>Water speed $\frac{m}{s}$</td>
<td>0.025</td>
<td>0.01</td>
</tr>
<tr>
<td>0.4-(0.016)</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>0.5-(0.042)</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>0.6-(0.06)</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>0.7-(0.067)</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>0.8-(0.079)</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>0.9-(0.088)</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>1.0-(0.090)</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>1.1-(0.11)</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>1.2-(0.12)</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>1.3-(0.13)</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>1.5-(0.147)</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>1.8-(0.152)</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2.0-(0.198)</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Tests are 50% and 100%, where 50% is a flow rate of 0.01 $\frac{m}{s}$. In the names of the experiments, the 100% is used instead of the speed of the water. In the experiments described and used for calculations the speed of the current is calculated. The current here is the sum of the speed of the plough and the current installed. One can see that the slow speeds used in the no flow condition are not tested. These proved to be not of importance since no difference in measurements as well visual was observed.

After a large part of the basic experiments, the water depth is decreased to 10 cm. In the main experiments the water depth is kept at a height of 10 cm. This was instructed in order to increase the water speed and to more mimic the water depth at the Waal river. These tests can be seen in the column of 10 cm water depth. After the basic tests, the plough is adapted but the water depth is kept at 10 cm.

**List of main experiments**

In the main experiment the plough is fitted with spokes in order to measure the size of the buffer over the width. More on these adaptations can be found in the section above and here below is a picture provided.

![Figure 4.11: adapted plough with spokes](image)

The first three experiments in this chapter are experiments similar to the experiments in the basic tests with the water depth kept at 10 cm. These are called the comparison experiments. In the main experiments the water depth is constantly kept at a height of 10 cm.

One can divide all the measurements in this chapter into several sub-parts or plough adoptions.
Here, a list of all types is given.

- Comparison experiments
- High back
- High Back 200%
- 8 mm cutting depth
- Frontflaps
- Frontflaps, blade angle 30 degrees
- Frontflaps Filled
- Topflaps

For each of these plough versions, an array of tests is done. This is found further on in this section. The decision has been made to place the last three rows of experiments to the appendix. Descriptions of these tests can be found in Appendix 1.
Table 4.5: main experiments

<table>
<thead>
<tr>
<th>Water depth</th>
<th>10 cm</th>
<th>Current</th>
<th>with</th>
<th>against</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water speed (m/s)</td>
<td>0.05</td>
<td>0.09</td>
<td>0.05</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>High back plough</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High back 200 %</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 mm cutting depth</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side flaps</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side flap filled</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side flaps, 30 degree blade angle</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Topflaps</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Starting with the comparison experiments. These are done in order to determine whether the set up works properly after adjusting the plough. Beginning with the with flow experiments, only a few speeds are used to compare the plough process of the adapted plough with the standard plough. Here, the goal was to set up the experiment in order to gain similar results as in the preliminary tests. One can see which speeds have been tested in table 4.4.

Table 4.4: Experiments with flow 100% (0.05\text{ m/s}) 10 cm water depth, 6 mm cutting depth and adapted plough

- 0.8-with-100%-10cm-adapted
- 0.9-with-100%-10cm-adapted
- 1.0-with-100%-10cm-adapted

After setting up the experiment (adjusting the height of the plough installation and zero out the added weight of the adjustment) the efficiency enhancing experiments can begin.

If we first take a look at the experiments that are being executed one can see that every plough adaption executes several experiments. Almost every plough has experiments in the with-current situation and the against-current situation as one can see in 4.5.

One can read this table in the same manner as it is in the section basic experiments. However, here every X stands for a total sequence of experiments. This sequence is the different speeds at which the plough is tested. The speeds that are used are 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.5, 1.8 and 2.0. These are the pot meter positions. The representative speeds can be seen in the previous section. So every plough version follows 2·9 experiments. If one looks at the measurement data one will see names as 0.8-with-100%-10cm-frontflaps-Filled. Here the first number stands for the pot meter position. This is deliberately chosen because one must know that a speed can vary and can only be determined during the experiment or from the video footage. Therefore no representation of the speed is given in the experiment name. The with and 100% stand for the direction of the current and the flow. 100% stands for the 0.05\text{ m/s} current. The 10 cm is the depth of the water inside the tank. The last words are the plough version.
Chapter 5

Results

In this chapter a broad overview of the results will be showed. An extensive explanation on the physics of the different plough adaptions, the different settings of the parameters and the effects of the parameters on the plough sessions. Different plough adaptions will be discussed in the main experiments. Also the preliminary experiments will be viewed. Several main experiments and the stability experiments are discussed in Appendices 1 and 2. Firstly, a start will be made with the results of the preliminary experiments.
5.1 Results Preliminary tests

Preliminary to the basic tests, the dry test have been done. This is to test whether the plough works as intended and if the methods used by the researchers is sufficient. The dry test give an overview of the time used in one experiment and to see if the set up works as intended. The first problem that occurred was the decision to copy the design of the plough used in the Waal. In this design, the plough is vertically hanged by an steel chain which can be varied in length to vary the depth of the plough. The first design of the plough mimics this principle by using a steel wire.

This vertical wire is fixed to the plough in the middle and fitted with a load cell to measure the vertical force. This steel wires proved to have several disadvantages which arises in the preliminary tests. The vertical suspension using one steel wire is seen in figure 5.1. A function to achieve for the plough is to maintain a fixed cutting depth. With a fixed cutting depth the cutting forces can be calculated. Using the current drag and the other drag components, one can calculate the force used to move the buffer in front of the plough. With a cutting depth unknown or variable, the contribution of the horizontal cutting forces can not be calculated and therefor, the buffer force can not be calculated. The wire which should keep the plough just above the sand bed proved to have a big slack when not experiencing load. When starting a plough session, the plough would float above the sand bed at 1 cm height. This prevented the plough from cutting the sand. Is the vertical wire was lengthened, the plough would start cutting sand but would dig itself in under the influence of the vertical cutting forces or the increasing weight of filling. The crooked cutting depth would not be sufficient to calculate the buffer forces.

Another disadvantage of the single vertical steel wire was that the plough had the freedom to make a roll motion. When starting a plough session, the plough tended to roll to one side, never was the plough stationary horizontal. This caused the plough to start cutting sand at one side. This proved to be an unstable situation. Cutting on one side would cause the plough to roll, cutting deeper on one side whilst cutting less on another side. This unstable roll would continue until the researcher stopped the cart. In figure 5.2 one can see such an unstable situation where the left side of the plough would fill more and the right side of the plough would lift up from the sand bed, unable to cut sand. In this figure one can see that two wires where installed to prevent a crooked cutting depth. This was only done as a trial but did not prove suitable. Also proven to be inadequate was the smaller grid ruler used in the dry sand experiments. The grid ruler turned out to be short. The vertical growth of the buffer could not be measured with this plastic ruler. An complementary problem was that this ruler tended to bend. The decision was soon made to use another ruler which could cope with the growth of the buffer and would be more resilient to bending. Since these grid rulers are not available it was necessary had to build one from scratch. A see though ruler would be most suited but a see through material was either to thick or to easy to bend so the grid ruler was build from the same material as the plough, aluminum.
As one can see in figure 5.3 and figure 5.4 the smaller grid ruler is replaced by the bigger ruler. Here, the frame adaption is present in the picture. This adaption was needed to ensure a fixed cutting height and a stable cutting path. The slack in the vertical suspension wires would only disappear when the weight of the plough was sufficient. The possibility to weighten the plough would mean that a total rebuild was needed so the decision had to be made to make a frame for the plough. This proved to be sufficient in order to keep the plough level. In the chapter set-up a broad description of the frame is given and what further problems had to be overcome. In this chapter, findings on the buffer will be explained.

In the dry tests, the bigger grid ruler is not yet installed in the plough. Therefore, thorough quantitative results can not be given. In the first tests, very low speeds are used. These speeds where at the limit of the electrical motor. At the lowest position of the pot meter, the plough could stall during ploughing when the friction became to high. This speeds are given in the chapter on the experiments. The lowest speed here was with a pot meter position of 0.4. This gave a plough speed of $0.015 \frac{m}{s}$. Lower speeds resulted in a stall of the electrical motor. The conclusion here has been drawn that if the tank was filled, the cutting forces in the saturated sand would become much larger and the electrical engine would stall at speeds where, in the dry situation, the motor power would be sufficient.

An important conclusion in this stage of the experiments was that the buffer would start build-up above the cutting blade. The expectancy was that the buffer would be pushed more to the inside of the plough rather than being pushed upwards. Since these where at low speeds and in the dry situation, the expectancy was that water would contribute to the force pushing the sand inside the plough since water has a momentum in the direction of the plough when the water has a current. Also, higher speeds could force the sand more inside the plough due to inertia forces. Sand in a stationary position would get pushed upwards, but would remain at the starting horizontal position. With the plough shoving under the sand layer, the sand would fill the plough to the back. However, sand is pushed upward and would be given a horizontal velocity relative to the stationary bed. This velocity would be in the same magnitude as the velocity of the plough. A drawback of the sand not being pushed inside the plough is that spillage occurs instantly. While building up the buffer above the plough, sand is spilled to the sides as one can see in picture 5.6.

This spillage is due to the rolling of sand from the top of the buffer to the front and to the sides. This rolling starts at the moment where the slope of the buffer is steeper then the natural slope. Here sand starts rolling downward. The result is an heap of sand next to the cutting path of the plough. In figure 5.3 one can also observe a rather large heap after the plough has passed. In figure 5.6 one can observe the aftermath of a plough session, heaps of sand rise above the sand bed. This
is an undesired effect of ploughing and is not desirable in the Waal where the goal is to lower the sand bed instead of heightening.

An other deduction of the dry tests was that ploughing at higher speeds would cause the front limit of the buffer to have a lower distance from the plough. This is relative to the low speed plough sessions. Note that in all experiments the cutting height is equal. Therefore, the amount of sand which is fed to the plough is equal, independent of the speed of the plough. In the low speed plough session, the buffer is build-up in a more stationary process. The overall shape of the buffer remains constant but grows continuously. The front side of the buffer has a lower gradient than the back of the buffer. This gradient reduces when the plough speed increases. This results, in the high speed plough sessions, that the undisturbed sand is closer to the plough than in a low speed session. To demonstrate this, two pictures are provided. In these figures one will see a low speed plough session and a high speed plough session. The low speed is a speed of \(0.06 \text{ m/s}\) and the high speed is \(0.10 \text{ m/s}\). Here, the plough has traveled 200 cm in both figures. The cutting depth and the blade angle is constant.

As one can see in figure 5.7 the screen shot has been taken at 200 cm. This is measured from the back of the plough. The buffer reaches to the ruler at grid number 18. Note that this is not the distance in cm from the front of the plough. The height of the buffer is not yet determined since the small grid ruler is insufficient. Where in figure 5.8 the screen shot is taken at the same traveled distance of 200 meter, yet the speed is higher in this plough session. One can see that the buffer reaches up to grid number 15. Increasing speed has the result that the buffer has a steeper angle at the front. A decisive conclusion on the height of the buffer can not be drawn here. A steeper slope could indicate a higher buffer but spillage also has to be taken in to account. A steeper slope could cause higher loss of sand due to spillage since this sand will roll down and spill from the front side. The load cells indicate that the load in these cases is not similar. The load at 200 cm for the high speed is 0.57 kg. The load for the low speed is 15 kg.
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Figure 5.9: flattening device

Other smaller details in the dry tests where that flattening the sand bed would be the most time consuming activity. A test would only last as long as the plough did over the 260 cm distance. Emptying the plough and straightening the sanded would take a lot more time and proved to be an activity where some skill was needed. Using the flattening device, specially developed for this experiment, the path could be straitened. The flattening device consisted of a wooden board which could slide over the rails on top of the water tank. Under two long threaded ends an aluminum profile was bolted. This profile ensured a straight horizontal sand bed and a fixed height. After flattening, the plough would be positioned at the starting position and the next experiment could start.
5.2 Results basic experiments

In the basic experiments, the water tank is filled with water. In these experiments, the water height is 20 cm. The width of the water tank is 50 cm. In these experiments several parameters have been varied as independent parameters. Here, the water speed, the current direction and the speed of the plough have been adjusted. In these experiments the plough is fitted with a bigger grid ruler in order to deduce a quantitative volume of the collected sand from the video. At the start of these experiments, the water tank was filled with water. An unexpected effect was that the water turned out to be very milky. It was not possible to see the plough in the tank. From the sides and from the top, the plough was not visible. An experiment turned out to be a non visual one. Researchers could start the test and monitor the load cell measurements but where not able to film the buffer or even see the buffer. By emptying and filling it with clear water experimenting could continue. The first experiments where done with no water flow, so stationary water of a depth of 20 cm was present. In these first experiments, low speeds have been used. Further on these low speeds have been skipped since these did not contribute to the research on the buffer. In the first experiments, the water had to be flushed right after one plough session. Disturbing the sand would result in a new milky cloud which made it impossible to see anything in the experiment after that. So, in order to get decent video, the water was flushed right after every experiment. This resulted in a single experiment of one hour and 15 minutes.

The first deduction taken from the wet experiments is that the sand behaves in the same manner as in the dry situations. Where, in the dry state, the sand would form a natural slope of about 35 degrees, the wet slope would be similar. Also, the dynamic behavior is similar. Sand is being pushed upwards above the cutting blade and would than roll to the front or to the back when the natural slope angle is reached. Rolling of sand from the top of the buffer down to the front or back is not constant at low speeds. Initially, the buffer bulges upward. This causes that the slope is larger than the 35 degrees natural slope. Sand will roll downward and the slope will decrease. Rolling stops and the buffer will grow in height until the natural slope is reached and the process will start again. The limit in this situation is that sand will start rolling over the back plate. When this starts, the buffer will not increase in height. At slow speeds, the growth of the buffer is slow so the period between two sand rolling processes is long. At higher speeds, this period is smaller, where, at a certain cutting speed, the process is constant. Note that at only very low speeds, the shape of the buffer in front of the plough is mirrored with the back of the plough. At higher speeds, the front of the buffer will not behave as an slope where sand rolls. The shape of the buffer here is varying. A slope can transform to a slight concave and to a convex shape. This is due to the shear stress created by the sand-sand friction. The very low speeds where the transformations do not occur were not of great interest. More on the transformations will follow. To illustrate the rolling of sand figures have been provided.
In the figures 5.10 and 5.11 one can see the film footage where rolling of sand has occurred. Both images are captured from the same experiment with 1.4 seconds in between. Here the plough has a speed of $0.06 \frac{m}{s}$ and a current of $0.025 \frac{m}{s}$ in the same direction as the plough. The screen shots have been taken at 70 cm and 80 cm of the plough track. One can see in the first figure, figure 5.10 that a buffer height of 3.1 cm at the zero vertical grid line is present. The back limit of the buffer is at -6 cm. This is 6 cm from the back. The slope starts at this point to point (-1, 3). The top of the buffer is not shaped as a sharp point but is rounded. In this screen shot, the slope of the sand is at a maximum. In the next screen shot, seconds later, the sand has rolled from the top to the back of the buffer. This moment, the slope of the buffer is a smaller gradient. At this point, the height of the buffer is similar as the previous situation since the sand rolled down to the back and the sand underneath the top is pushed upward. This process repeats until the height of the back plate is reached. The buffer will then grow, roll, grow and roll. The amount of sand that will rise above the top will also roll off at the back. In the previously described figures one can also see that the sand spills from the sides at the front of the plough. This is similar to the dry situations. Different in the wet circumstances is that the front of the buffer behaves in an other matter. Where, in the dry sand, the shape of the buffer would be somewhat mirrored, the shape of the buffer in the wet situation is not mirrored. Only at very low speeds, the shape of the buffer is a simple sand heap. The limit of these speeds are around $0.04 \frac{m}{s}$. Above this speed, the buffer shape is not like a normal sand heap. Investigations on the low speeds and the influence of the water are not performed. A finding worth investigating here is the influence of the speed of the plough on the shape of the buffer at the front. As stated, speeds higher than $0.04 \frac{m}{s}$ give a dynamic shape to the buffer where the buffer forms can vary from a slope to a convex to a slightly concave shape. This will be discussed next.
First, the influence of the speed of the plough on the shape and build-up of the plough will be given, further on, the influence of the current on this shape will be given. In the first descriptions on the shape of the buffer one will refer to the experiments where no current is present. These are the NOFlo experiments. Here, a water height of 20 cm is present but the pumps installed will be shut off. As mentioned, higher speeds give other shapes to the buffer. This other shapes will give other sand-sand friction forces and other buffer volumes.

Starting with a low speed, a speed of $0.075 \text{ m s}^{-1}$, the buffer builds up like described in the low speeds in the beginning, with a straight slope in front. When the buffer reaches 3 cm high, the shape of the front side changes. The straight slope starts to form a bellow shaped form. This bellow shaped form is caused by the sand that is not able to be pushed upwards more. This causes that the front limit of the buffer moves more toward the plough. As one can see in figure ?? In this situation the rolling of the sand is considered constant. Sand rolls here to the front and to the sides. While the height of the buffer increases, the front limit of the buffer increases in distance from the plough. This is linear dependent.

If the height increases, the sand spills and the front side of the buffer increases in distance. Finishing the cutting path, the height has increased to 7 cm and the front side of the buffer stretches out for 11 cm in front of the plough. The slope gradient of the buffer next to the top is similar to the natural slope. The rounded shape at the front is not present, only a slight bulge in the slope is visible as one can see in figure 5.13. Increasing the speed of the plough to $0.109 \text{ m s}^{-1}$ initiates a new regime. Here the rolling of sand is not continuously anymore. Also, the shape of the buffer is influenced by the water hitting the buffer. This is in the early state of the build-up. The sand that wants to roll to the front of the plough is not allowed by the water hitting this sand. Although the water is stationary, the buffer moves with $0.109 \text{ m s}^{-1}$. The induced momentum prevents the sand from rolling down to the front of the plough constantly. Instead, packs of sand fall down from the top to the bottom at the front side. The natural slope is not present, the front of the buffer is more a steep wall from which sand falls down.
In the figures 5.14 and 5.15 one can see the front of the buffer where sand falls from the top like an avalanche. As the buffer grows, the front side of the buffer gradually evolves to the shape described in the 0.075 m/s situation. A linear slope forms and the buffer reaches a height of 7 cm and stretches in front of the plough for 11 cm. The buffer does, in this case, not grow bigger than the buffer at the lower described speed.

Also, the plough is not filled more visually in the case where of the 0.109 m/s speed compared to the lower 0.075 m/s speed. Where the plough at lower speed begins to spill sand from the side walls at around 180 cm, the faster plough only starts to spill at the end of the track. However, the plough is full at the end of the track in both cases. Looking at the load forces in figure ??, for these two speeds than one can see that the vertical loads are practically similar. However, note that the vertical cutting forces also contribute. With high speeds come higher vertical cutting forces in these cases since this is not in the cavitation cutting regime. More one the influence of the cutting forces will follow. To compare multiple experiments one needs to normalize the time of all experiments. A slow experiment will have a longer time period. By dividing each time step by the total time of the measurement $T_{total}$ one will get a time domain between 0 and 1 on the X axe. With all measurements normalized it is possible to compare two experiments though they have a different time. The X axe can also be considered as the track length where the number 1 is the end of the track at 260 cm.

If one now takes a higher speed cutting experiment. Here, still with water that stands still, a mean speed of 0.147 m/s is reached at position of the pot meter of 1.5. Similar to the previous described test of 0.10 m/s, the buffer in the beginning has a slope higher than the natural slope at the front side. In this buffer, the sand does not roll continuously at the front side but falls of in bigger chunks.

At 120 cm, the height of the buffer is 4 cm above the cutting blade. The growth of the buffer from 1 to 120 cm is very rapid. It grows continuously since spillage from the front side is low and spillage from the side walls and spillage from the back does not yet occur. At the height of 4.5 cm above the plough, the shape of the buffer in the front changes. Quite rapid changes the steep slope of 45 degrees to a less steep slope. Here the slope is about 25 degrees which has a shape of a radius at the front limit. One can see the shape of the buffer in front of the plough at 160 cm in figure 5.18. Note that here, the height is still 4.5 cm. From the point where the slope of the buffer changes, the growth rate of the buffer decreases. While the first half of the track, the buffer grows to a height of 4.5 cm. The second half of the track, the buffer only grows to a height of 6 cm. This is reached at the end, about 260 cm track length. Where the buffer, in the first half grew in height, the buffer grows in length at the second half. One can compare figure 5.18 to figure 5.19.
the height of the buffer is almost similar. The front limit of the buffer at 130 cm reaches to 6 cm in front of the plough with the slope of the buffer quite steep. Here, the slope is almost straight. If this is compared to figure 5.18 the buffer is stretched to 9 cm in front of the plough and has a slope of 23 degrees from the top to 6 cm in front of the plough, from there the front of the buffer forms a radius where the buffer at the end reached to 9 cm in front of the plough. A higher speed in this case does not result in a higher buffer. This can be caused by the water hitting the buffer at a higher speed, preventing the buffer from building up higher. Note that the plough just starts to spill from the side walls and the back of the plough at the end of the plough track. This is also the case in the plough session of 0.109 m/s. However, here, the buffer reached a height of 7 cm. In both of these cases, the load readings are compared as one can see in the picture below.

![Figure 5.17: load readings at different speeds](image)

Note that at higher speeds, higher cutting forces are present. For example, two different speeds be similar in force. Here, the lower speed will have a higher friction force due to the buffer than the higher speed while the higher speed has higher cutting forces. For the highest speed, the reading of 0.149 m/s. The pulling forces are a fraction lower than the 0.109 m/s plough session. This can be explained by the buffer in front of the plough. In the lower speed, the buffer in front of the plough is of a larger volume than the higher speed. A bigger volume of the buffer in front of the plough gives a higher sand-sand friction force. This contributes to a higher pulling force. As one can see in figure 5.17 the pull forces for the 0.109 m/s plough session are overall a fraction higher than the pull forces at the highest speed. Only at the end of the track, the pull forces of the highest speed start to catch up with the lower speed loads. This is where the buffer in front of the plough starts to grow. If one takes a look at the load forces, one can see that the load forces for the higher 0.149 m/s plough session tend to be much higher than the 0.109 m/s plough session.

![Figure 5.18: front buffer 0.147 m/s at 160 cm](image)

![Figure 5.19: front buffer 0.147 m/s at 130 cm](image)

Load forces are measured by the vertical load cell. This does not measure the buffer in front of the plough but measures the vertical force. This is the weight of the plough and the vertical cutting forces. The last contribution explains the higher loads. While the plough fills comparable
for both sessions, the cutting forces are higher for the high speed session. Hence the higher loads for the vertical load cell at higher speeds.
5.3 Results Main experiments

In this section one will treat the main experiments. Here, the observations during the experiments for the different plough versions will be discussed. Starting with the standard plough equipped with the spokes. The spoke adaption was done in order to better measure the size of the buffer inside the plough. With the spoke assembly, the height of the buffer over the width of the plough could be determined. In the previous chapter, the list of experiments, one starts with the comparison experiments. This is due to set the plough and the installation in order to have a proper working set-up. This experiments will not be discussed. The discussion will start with the experiment with the high back.

**High back experiments**

The adaption of the high back was installed to prevent spillage from the back of the plough. This spillage already occurred in the basic plough at 200 cm. The decision has been made to firstly heighten the back of the plough. If we take experiment 1.5-withflow-100%-10cm-high back we have an current in the same direction of the plough. Expected was that the plough would fill more and a higher buffer was reached. This was in fact reached. However, while the first part of the buffer builds up quickly, the buffer loses its growth momentum after it has cut a path of 100 cm. In the first 100 cm, the buffer grows up to 6 cm inside the plough. From here on the buffer only grows 1 cm higher the next 50 cm of the cutting path. This is caused by two phenomenons. The first reason that the buffer fails to grow quicker is that spillage from the side of the plough already occurs. So here, a lot of sand that is fed to the plough spills from the sides and in front of the plough. Since sand that rolls down in front of the plough, most of the newly cut sand layer is spilled at the front. Sand that rolls down in the middle of the plough will stay in the buffer but sand that rolls from the side will end up next to the plough.

![Figure 5.20: spillage from High back plough with-current, exp: 1.5-withflow-100%-10cm-high back](image)

In figure 5.20 one can see the spillage from the plough at the front. Here, it is seen that sand also spills over the side walls before the plough reaches its full capacity. The limit of the high back is not yet reached. The second reason that the height of the buffer increases slowly is that for an
increase in the height of the buffer a larger volume of sand is needed. If one considered the buffer as a triangle, the increase in height means an increase in all sides of the triangle, so an increase in height gradually slows down since a larger volume is needed in order to grow a centimeter higher if the buffer is already at 6 cm. Combining this with the spillage of the sand in the front, the increase in height is only small. The buffer managed to stretch 10 cm in front of the plough. This is at a speed of 0.135 m/s. With a current of 0.05 m/s in the same direction as the plough path, this translates to a counter current of 0.085 m/s. The maximum height of the buffer is around 7.5 cm. Increasing the speed of the current by adding another pump gives the comparison experiment 1.3-withflow-200%-10cm-high back. Here, the current has a maximum velocity of 0.09 m/s. This gives a smaller counter current. This translates in a buffer which stretches more forward. Here, the plough only has an resulting current of 0.045 m/s. This allows the buffer to stretch forward.

As one can see in figure 5.21, the buffer stretches out to the limit of 12 cm of the grid ruler while the height of the buffer remains equal. This is not directly a result of the change in current. This can be explained due to the higher speed of the plough. With the higher speed, the shape of the front of the buffer is constantly changing. Here, sand is being pushed upward inside the buffer, in front of the plough, causing the plough to bulge. This can be seen in figure 5.22.
If one now takes a look at the print screen taken a second later at 230 cm of the plough path. Here the bulge collapses and stretches the volume of sand to the front of the buffer. This can be seen in 5.23. This process is seen at higher speeds of the plough where sand fails to roll down quick enough. This transition from normal rolling to collapsing is at a speed of $0.10 \frac{m}{s}$ but is dependant on the speed of the current. This can explain that the buffer in 1.3-with-flow-200%-10cm-high back stretches more to the front of the grid ruler but this can be a coincidence at this moment.

If one now takes a look at the situation where the current is set in opposite direction of the plough direction but the same plough speed. This gives the test 1.3-againstflow-100%-10cm-high back. Here, we have a difference in speed between the plough and the current of $0.185 \frac{m}{s}$. Here, the buffer builds up in the same manner as in the with-current situation. Sand is being pushed upward and starts to roll down front the top to the back and sides of the plough. There is a difference however at the front of the buffer: where, in the with-current situation sand would roll down nicely, here sand is being washed away by the current at the front sides of the plough. Normally, this sand would leave a small heap at the sides but this heap is now more scattered. At the front of the buffer, in the middle sand will not roll down easily. Rolling is influenced by the current and rolls only slightly. This is more a wave of sand that rolls down the buffer instead of an area of sand that rolls continuously from the top to the bottom. A small section of the sand in this wave is sometimes washed away by the current.
In figure 5.24 one can see two smaller waves of sand traveling downward where the upper wave loses some sand. The sand that is inside these waves which is washed away is however a very small proportion. This is neglectable compared to the spillage from the sides. In the counter current situation, the buffer grows higher. This is due to the influence of the counter current. Here sand from the top does not roll down as easily as it does in the with-current situation. This allows the buffer to grow to just above 8 cm. If one would decrease the speed of the plough, the buffer would not grow above this height. For instance, in the 0.9-againstflow-100%-10cm-high back experiment, the buffer also grows to 8 cm. However, here the buffer in front of the plough is much bigger. So although the plough is filled equally. The power lost due to the buffer is higher in the slower experiment. If one does increase the speed of the plough, the buffer reaches the same height. However, sand washes away a lot from all sides of the buffer. The buffer stretches in almost all cases to the limit of the grid ruler, 12 cm in front of the blade. If we start to take a look at the spillage of the sand that leaves the plough during ploughing. This spillage leaves small heaps of sand next to the freshly cut plough path. We use 0.9-withflow-100%-10cm-high back to gain insight on the spillage since this is a slow experiment where sand does not wash away.

One can see in figure 5.25 the height of the heap left by the plough. Though this figure one can not read the width of the heap. Other photos show a heap with a width of 6 cm. This is measured with the first, white ruler. The height of the heap is measured with the second small grid ruler. Here, one stripe is set flush to the freshly cut sand bed. This gives a height of 1.5 cm above the freshly cut bed. The heap lies however on the original bed. Considering the heap a triangle with equal sides gives a spillage area of sand of \((1.5 - 0.6) \times 6 \times 0.5 = 2.7 \text{ cm}^2\). Here, sand that rolls into the cutting path is not considered so spillage is slightly more than this. The cutting depth here was 6 mm. With the width of the plough on this side being 12.5 cm gives a area of sand that had been cut of 7.2 cm. This gives a spillage of 40% and this is positive educated guess. This is however at the end of the plough path. Spillage here is already high. In the beginning spillage is lower so this number does not indicate the efficiency of the whole process. If one now takes a look at spillage of higher speed sessions one yields the following figure 5.26. This is the 1.3-withflow-100%-10cm-high back experiment. Here, the width of the area is larger, about 10 cm. The height however is lower. This is 1.2 cm. So 0.6 cm above the original bed. This gives an area of 3 cm\(^2\). This is close to the spillage in the lower speed experiment proving that spillage is reasonably equal but in the higher
speed test, sand will be more dispersed.

Figure 5.25: Spillage of sand by 0.9-against-flow-100%-10cm-high back

Figure 5.26: Spillage of sand by 1.3-with-flow-100%-10cm-high back
High Back 200%

In order to test whether the current has a big influence on the buffer, the decision has been made to add an extra pump to the experimental setup. As stated before, this pump did not have the same quality as the first pump did. The current with the two pumps is maxed out at 0.09 m/s. This can however give the researcher the opportunity to test the influence of the current in the with-current and against-current situation. Using a larger with-current might cause a bigger buffer and a larger buffer force while the high counter current at low speeds might prevent rolling of sand at the front and reduce the size of the buffer and thus reduce the buffer force. We start with the same plough as seen in Appendix D. We start comparing the slow experiment from the previous section with the slow experiment in the 200 % with flow section. Taking experiment 0.8-withflow-200%-10cm-high back and 0.8-withflow-100%-10cm-high back. The difference between these two experiments is the speed of the current. The plough speed is in both experiments around 0.07 m/s. The current flow is around 0.09 m/s. This gives, at low speeds, a current faster than the speed of the plough in the 'with' experiments. If one compares the buffer between the two experiments one will see that the buffer in the 0.09 m/s current is similar in height. The height is somewhat around 7 cm. If one calculates the resulting flow with the speed of the plough of 0.07 m/s and the speed of the current of 0.09 m/s, we get a flow of 0.02 m/s over the top of the buffer in positive direction. This is in the same direction of the plough direction. Since this resulting current is only small, no influence of the current is being detected visually. On the top of the buffer, the flow is similar in magnitude only different in direction. However, if one takes a look at the front of the buffer, the buffer in the 200 % case is larger than the 100% flow. This can be caused by the current, since no drag force prevents the sand from rolling downward at the front in the 0.09 m/s current flow case. In the figures provided below, figure 5.28 and 5.27 one can see the difference in the size of the buffer.

Figure 5.27: buffer with 200 % current
Figure 5.28: buffer with 200 % current

If one now compares the higher speed experiments in the 'with' flow situations the buffer size and build up is practically similar. No big visual difference is being detected other than that rolling off sand of the buffer in the 200 % situation is smoother. The sand rolls more than in the lower current situation. Here, sand is slightly affected by the current but not enough to change the shape the buffer. Comparing the force measurements in these cases gives similar results. The lines of the load force and pull force are in the same magnitude. In both cases, sand starts spilling from the back of the plough. This was not the case when the plough had a lower speed. The higher speed of the speed of the plough affects the filling of the plough. Higher speeds fills the plough more in these experiments. This is seen by the fact that at high speeds, sand is being spilled from the back earlier on in the plough session.

Looking at the counter current situations will give an insight in the influence of the current. Expected is that the current influences the size of the buffer highly and spillage due to the current will be high. In the case with the 200% against-current, expected is that the front limit of the buffer will not reach as far as in the 100% experiment and spillage due to washing will be larger. If we take experiment 1.5-againstflow-200%-10cm-high back and look at the video footage it is clear that the current highly effects the spillage. Sand that would roll is picked up at the sides and at the top and is washed away. This start earlier from the sides than it does at the top. As soon as
the buffer reached the height of the side walls sand that would normally roll to the front and spill at the sides is now picked up and washed away. This is not all the sand. A part still forms heaps next to the plough. As the size of the buffer increases, the spillage increases. A large part of the sand that would normally roll to the sides, or partly to the sides (more in front-side direction) is picked up and washed away as seen in figure 5.29.

As the buffer continues to grow, the spillage area increases. But this sand would normally also roll from the sides thus would normally also spill. The only difference is at the front of the buffer. The current prevents the sand from rolling down and creates the wave-like patterns described earlier as one can see in 5.30. The current also prevents the buffer from stretching more forward. But if one compares this to the 100 % against-current experiment, this is only affected by a cm so the difference in 0.04 in current does not have a very big influence other than affecting the rolling of the sand. It does not push the buffer more in the plough. Also, the washing of the sand also occurs at the lower current situation. Although the buffer is only slightly bigger, the pull forces in the 100 % against-current are higher than in the situation with the 200 % against-current. Here, the relative speeds of the current to the plough are respectively 0.175 and 0.215. There is a 10 % difference in the pull forces although the load forces are similar. This gives a distorted image since the pull forces are not horizontal and affect the load forces slightly. In the graph below one will find the measurements for both cases and will see that although the 100 % experiment has lower pull forces, the plough load forces are higher. Figure 5.31 shows this scenario.
This experiment gives us insight on how the current affects the buffer. Although the size of the buffer is only partially affected, the size of the buffer affects the total forces highly. The current does not cause the buffer to fill the plough more but affects the total forces strongly. In the chapter "forces on the plough" one will find a more elaborate comparison between two experiments to further explain this phenomenon.

8 mm cutting depth

Although the water tank is 400 cm long, the cutting path of the plough was 260 cm long.

Increasing the cutting depth would result in spillage more quickly. Where the plough would normally start to spill sand from the front sides after ploughing 60 cm, the plough now starts spilling at 40 cm and continues to spill sand further. The limit of the height of the buffer at low speeds is reached when sand starts to spill from the back of the plough. The buffer does not grow higher since all sand that is being pushed...
upwards rolls down to the back, to the sides and to the front. In the front of the buffer the shape is irregular. Where, in the beginning of the plough track, the sand would roll to the front if the slope reached the natural gradient. When the plough is filled, the shape of the buffer in front of the plough is more like a bulge as seen in figure 5.32. This shape is created by the sand that is being pushed upward inside the buffer. Normally sand is being pushed upward at the blade. However, due to the fact that there is so much sand being fed, the sand already inside the buffer hits the sand that is being pushed upwards by the blade. This can be considered as a wedge. This wedge pushes the sand upward 5 cm in front of the blade. This creates the bulge in the front of the buffer. This bulge is common when the plough is already very full. The wedge can be explained by the fact that the weight of the sand above the cutting blade is too high to overcome and only moves partially. With more sand being fed to the plough without the ability to push it upward creates the wedge and therefore the bulge. This bulge is also seen at lower speeds in other experiments. Lower speeds are more affected by the gravity while the higher speeds are affected by the inertia of the sand that is being cut. This explains why the plough tends to fill quicker at higher speeds. At higher speeds, the front limit of the buffer lies closer to the plough than at lower speeds. This is caused by the inertia of the sand bed. The influence of the current on the buffer is small in comparison to the influence of the speed of the plough on the buffer. The direction of the current influences the front limit of the buffer and the shape of the buffer. Although expected, a limit in pull or load forces is not found since the buffer grows continuously. The constant supply of fresh sand, and the inability of the buffer itself to transport this sand causes the buffer to grow constantly. The volume of spillage is never as high as the supply of the sand and therefore no maximum buffer is ever reached. As one can see in figure 5.33 the pull forces are still increasing. Although the plough is full and thus the load forces are to reach a maximum.

![Pull forces graph](image)

Figure 5.33: Pull forces for the 8 mm cutting depth experiments.
Chapter 6

Analysis

This chapter contains the construction of the plough model. The investigated force balance of the plough and the investigated cutting theory are combined into a useful ploughing model. One can see a representation of the plough in figure 6.1. Goal of this model is to enlarge the insight in the ploughing process, and the principles around the process like the build up of the buffer. Also can this insight give an answer to the question why a downstream plough session gives a larger pulling force than an upstream plough session. In this chapter all forces will be given which are present during the ploughing process and the main parameters which are decisive for the process are described.

Figure 6.1: plough model
6.1 plough process forces

To investigate the forces during the ploughing one must understand all the different forces acting on the plough. These forces are investigated within a larger perspective; the force balance of the plough. First part is to give a broad view of all the acting forces on the plough. Secondly is to add all forces together into a force balance. In the picture below, figure 6.2 one can see the forces acting on the model plough. After a broad overview of the acting forces, a model will be created for the plough process. Starting first with the acting forces for the plough process.

![Diagram of plough forces](image.png)

Figure 6.2: acting forces on plough model

6.1.1 Acting forces

To investigate the horizontal forces and the vertical forces during ploughing it is necessary to look at the fundamentals of the plough process. In this chapter the forces acting on the plough are mentioned and thereafter, the force balance of the plough is constructed. In this paragraph the fundamentals of the acting forces are treated. Take note that some forces can be calculated, i.e. cutting forces and drag forces. Other forces can only be calculated using the measurements. The horizontal buffer force is one of those values.
• vertical frame \((F_v)\)

The vertical frame accounts for the vertical forces. This frame translates all vertical forces acting on the plough to the vertical load cell. This force is the vertical resulting force of the plough process, and depends mostly on the cutting and filling forces acting on the plough. As stated before, the frame is hanged up in a bearing, preventing skew measurements. So during the experiments this vertical force is measured in an accurate way. The vertical force will be given as \(F_v\). In all measurements, the weight of the vertical frame and the plough are removed. The value of \(F_v\) is zero for all measurements at \(t=0\) sec.

• wire force \((F_w)\)

The wire force is the second resulting force of the ploughing process. The wire force is not a horizontal force but is a force under an angle. The wires account for the pulling of the plough. The wire force is the only force which pulls in the direction of the plough path. Derived from this wire force can be the horizontal force component and the vertical force component. The angle of the pull wires with the horizontal plane is indicated with the angle \(\alpha\). The two components, the horizontal and vertical will be referred as, respectively, \((F_{wH})\) and \((F_{wV})\).

• cutting forces \((F_c)\)

Cutting forces are the most fundamental forces of the ploughing process. Cutting sand gives a vertical and a horizontal forces component. Miedema (1987) has investigated the fundamentals of saturated sand cutting intensively. Since the cutting forces are an important component in the plough process, they will be discussed to a bigger extend in the next paragraph. The horizontal and vertical cutting forces will be referred as, respectively, as \((F_{ch})\) and \((F_{cv})\).

• Current drag \((F_{current})\)

In the experiments, the current can be changed in direction and can be changed in flow rate. Expected is that the flow rate has an influence on the buffer. Not yet described is the influence of the flow on the total plough model. The plough itself has a certain surface area which produces drag. The vertical frame which hoists the plough also induced drag. When cutting the sand, the buffer builds up. This buffer also contributes to the drag of the plough. At the end of the plough process, the drag contribution of the buffer will probably be the biggest component. Calculations on the drag will be given further in this chapter. The current drag force will be referred as \(F_{current}\).

• Friction forces \((F_{friction})\)

In the design of the model plough the decision has been made to exclude the friction component between the plough and the sand. By using the vertical frame, the plough is kept at an fixed height. When cutting, a void between the bottom of the plough and the sand bed arises. This void is constant. The only friction between the sand and the plough is during the plough process where the plough spills sand from the sides. Here sand is pushes side wards and creates heaps of sand at the side of the cutting path. These heaps interact with the plough, This causes friction. Expected is that this is a small component to the total friction. The big component to the friction is the buffer in front of the plough. Here a large volume of sand in front of the plough is pushed forward. This is a rather large vertical force. One can easily derive the friction force from a vertical force. In formula 6.1 one can derive the friction force.

\[
F_{ss} = \mu \cdot N \tag{6.1}
\]
Here, the weight of the buffer in front of the plough is $N$, the normal force acting on the sand bed. The friction angle $\mu$ is high in this case. Sand-sand friction gives a high angle of friction. Result is that the friction component contributed by the buffer is quite large. Further in this chapter the friction components will be calculated.

- **mass plough (G)**

  The mass $G$ is the underwater weight of the empty plough and the underwater weight of the collected sand inside the plough. This is the part of the buffer that is inside the plough. The part of the buffer that is in front of the cutting blade is considered to be outside of the plough and has therefore no influence on the mass of the filled plough. The total mass of the plough increases while ploughing since it keeps on filling during the run.

- **buffer force**

  The buffer force is caused by the movement of sand which is in front of the plough. This sand moves over the sand bed and causes an extra force. This forces is called the buffer force. The buffer force can originate from a sand-sand friction force. The buffer is pushed by the movement of the plough and the dynamic sand (buffer) moves over the stationary sand (sand bed). The angle of internal friction is high for sand so this movement gives a high friction force. As the buffer grows, the friction force grows along. However, a clean straight boundary between the buffer and the bed is not likely. More likely is that sand follows a circular motion. It is pushed upwards after being cut, rolls down the buffer to the front and is then carried to the plough once again. This clockwise motion is then repeated. This also gives an friction force but not along a straight path. The horizontal buffer force is not easily calculated with a friction factor and a mass since the mass is continually changing and the motion is dynamic. The buffer force is therefore calculated by subtracting all horizontal forces from the measurement.
6.2 plough process forces

A more elaborate calculation is needed for several force components acting on the plough. Stated before, these need a more extensive calculation. Below one will find these forces.

6.2.1 Current drag force

The current drag is dependant on a couple of factors. Some factors are constant during one plough session. The plough has a constant speed during the session and the current is considered constant. The shape of the horizontal frame is this case a constant factor. Also the plough and the pull wires are considered constant during one plough session. A note to take is that when the buffer builds up, the spokes in the plough are being buried. This changes the drag force of the horizontal frame. Since the spokes are such a small contribution to the total drag, the change in drag area is neglected. To calculate the drag, the speed of the current in respect to the plough must be established. In the experiments, one has the current speed $U_{\text{current}}$ and the plough speed $U_{\text{plough}}$. Taking the direction of the plough positive and the counter current positive, the total current $U_{\text{total}}$ can be calculated as one can see in formula 6.2.

$$U_{\text{total}} = U_{\text{plough}} + U_{\text{current}}$$  (6.2)

In the case where the current is in the same direction as the plough the formula will be as formula 6.3.

$$U_{\text{total}} = U_{\text{plough}} - U_{\text{current}}$$  (6.3)

Using the next formula to calculate the drag force for the plough. This is the standard drag force calculation as seen in formula 6.4.

$$F_{\text{drag}} = \frac{1}{2} \cdot C_d \cdot A \cdot \rho \cdot U^2$$  (6.4)

Here $U$ stands for the $U_{\text{total}}$ used in the total current formula 6.3 and 6.2. A stands for the total front surface area. In this case, the submerged part of the frame, the plough, the wires and the buffer. The $C_d$ stands for the drag coefficient. The drag coefficient is dependant on the shape of the area. This coefficient is thus different for the before stated, drag inducing items. The plough is considered a flat area while the frame with spokes and the pull wires are considered cylindrical and the buffer is also considered rounded. In 6.4 the $\rho$ stands for the density of the water hitting the plough with the speed $U_{\text{total}}$.

In the experiments several different water speeds have been used. Also, a large variation in the speed of the plough was utilized. Varying between 0.07 and 0.20 m/s. The current has a variation between -0.05 and 0.05 m/s and has a maximum current of 0.09 m/s in some experiments where a second pump is installed. In this calculation, the current of 0.05 m/s is chosen with the plough speed of 0.20 m/s since this current is the most used maximum flow and the speed of the plough is the maximum speed used. The reason for using these speeds is that this calculation will give the highest current induced drag force. The calculations will show that this drag forces is only a small contribution to the total horizontal forces and can therfor be taken as a constant in stead of a variable force since the drag current speed is variable. Taking these speeds, the total current speed $U_{\text{total}}$ is easily calculated.

$$U_{\text{total}} = U_{\text{maxplough}} + U_{\text{maxcurrent}}$$  (6.5)

$$U_{\text{total}} = 0.020 \frac{m}{s} + 0.05 \frac{m}{s}$$  (6.6)

Even a garbage man will tell you that this gives an $U_{\text{total}}$ of 0.25 m/s.

Next in the calculation is the total area $A$. firstly, the plough. When seen from the front, the plough is a simple rectangular shape. Small wings at the sides and the grid ruler are neglected since
these only have a thickness of 1 mm. With a width of 25 cm and a height of 2 cm the frontal area of the plough is 50 cm$^2$. The frame holding up the plough consists of four threaded ends. These threaded end have a diameter of 6 mm and are submerged for 9.5 cm. Spokes are submerged for 10 cm and have a diameter of 1 mm. In total, there are 9 spokes. Both the threaded ends and the spokes are round, giving a constant drag coefficient for both parts, $C_d$. For a cylinder, the drag coefficient is 0.5. Since the pull wires are also cylindrical, the ease has been taken to add these to the calculation. Two wires, having a diameter of 1 mm and are submerged for 10 cm. The 10 cm is the height of the frontal area. The wires have a similar drag coefficient. Different is the $C_d$ for the plough: around 1.2 for a flat surface. Total cylindrical surface is easily calculated:

$$A_{cylindrical} = A_{spokes} + A_{threaded-ends} + A_{frontwires}$$

$$A_{cylindrical} = 9 \cdot 0.1 \cdot 10 + 4 \cdot 0.6 \cdot 9.5 + 2 \cdot 0.1 \cdot 10 (cm^2)$$

This calculation gives a surface area of: $A_{cylindrical} = 33.8cm^2$ Using the drag formula 6.4 one can calculate the drag induced by the frame.

$$F_{drag-frame+wires} = \frac{1}{2} \cdot C_d \cdot A \cdot \rho \cdot U^2$$

$$F_{dragframewires} = \frac{1}{2} \cdot 0.5 \cdot 33.8cm^2 \cdot 1000 \frac{kg}{m^3} \cdot 0.25 \frac{m^2}{s^2} \cdot 10^{-4} \frac{m^2}{cm^2}$$

Resulting in a drag force, induced by the frame of $F_{drag-frame+wires} = 0.053 N$. Next is the drag force induced by the plough. A note to take is that the plough only creates drag when it is empty. When the plough fills, the buffer of sand is in front of the back plate. Thus replacing this component. However, as stated before. The total drag component will be of such a small factor in the total force balance that this effect is negligible. A calculation is still needed to prove the statement. Using the Drag force calculation 6.4 for the plough:

$$F_{drag-plough} = \frac{1}{2} \cdot C_d \cdot A \cdot \rho \cdot U^2$$

$$F_{drag-plough} = \frac{1}{2} \cdot 1.2 \cdot 50cm^2 \cdot 1000 \frac{kg}{m^3} \cdot 0.25 \frac{m^2}{s^2} \cdot 10^{-4} \frac{m^2}{cm^2}$$

Drag force induced by the plough follows from 6.12 $F_{drag-plough} = 0.19 N$. In several experiments, the back plate of the plough is heightened, doubling the surface area and thus, doubling the drag induced. Hence, $F_{drag-plough-highback} = 0.38 N$.
The drag induced by the buffer is not a constant since the buffer starts with zero volume and builds up during the plough session. Also, build-up of the buffer can not be considered constant. Fed to the buffer is a constant volume of sand but this sand is pushed to the side and upwards so the growth in height is not linear. To calculate the drag, the buffer is considered to grow linear. Here the frontal area is considered to be growing linear. The effect of an increasing current due to the build-up of the buffer is neglected.

Firstly the total frontal area is calculated. In the previous chapter, the statement has been made that the height of the buffer depends on the height of the back plate and the height of the side plates. When the natural slope of the sand is reached, the sand will spill over the back and over the side. The basic plough has a back and side height of 2 cm. Here the buffer reaches a height of 8 cm as one can see in picture 6.3

Experiments have shown that a maximum height of 8 cm is reached in the basic plough configuration. Here the buffer inside fills the complete plough so sand spills from the back and from the sides. A frontal picture has been taken to explain the shape of the plough at the maximum volume. As seen in picture 6.4 one can see the height and width of the buffer when the plough is filled to the max. The width of the plough is 25 cm. The buffer how ever is somewhat wider. Sand in front of the buffer is spilled to the right and left, giving the base of the buffer an extra 4 cm width. At the maximum height of 8 cm, the width of the buffer is 15 cm. The picture only shows the starboard side of the plough, the grid ruler is placed in the middle of the plough. The port side can be considered as a mirrored starboard side. With the height and width of the buffer known, the resistance can be calculated. The buffer will be considered as a trapezoid where the port side and starboard side corner have an equal angle. The width of the underside of the trapezoid is the width of the buffer, 29 cm. The height has been discussed, 8 cm. The total frontal area of the trapezoid is calculated with the following calculation:

\[ A_{\text{trapezoid}} = \frac{1}{2} \cdot (W_{\text{lower}} + W_{\text{upper}}) \cdot H \] (6.13)

In formula 6.13 the \( W_{\text{lower}} \) stands for the width of the lower horizontal side of the trapezoid and \( W_{\text{upper}} \) stands for the upper horizontal side. The H represents the height. The total area is calculated using the before stated values.

\[ A_{\text{trapezoid}} = \frac{1}{2} \cdot (29 + 15) \cdot 8 (cm^2) \] (6.14)

The total area resulting from the calculation 6.14 equals 176 cm\(^2\). Using a \( C_d \) value of 0.5. Note here that the buffer is a rounded area and therefor represents a cylinder more than a flat plate, hence the lower \( C_d \) value. The formula that follows is already known. Using 6.4:

\[ F_{\text{buffer}} = \frac{1}{2} \cdot C_d \cdot A \cdot \rho \cdot U^2 \] (6.15)

\[ F_{\text{buffer}} = \frac{1}{2} \cdot 0.5 \cdot 176 cm^2 \cdot 1000 \frac{kg}{m^3} \cdot 0.25 \cdot \frac{m^2}{s^2} \cdot 10^{-4} \frac{m^2}{cm^2} \] (6.16)
Following from equation 6.16 is a drag force of $F_{buffer} = 0.27$ N. The total, current induced, drag is now known. Calculating the maximum drag during ploughing gives the total drag is $F_{total} = F_{buffer} + F_{frame}$. The $F_{plough}$ is not added since the buffer replaces the plough area. Note that this calculation is for the basis plough hence $F_{totalbasicplough} = 0.32$ N.

Since several adaptions of the plough has been made, more calculations on the current drag have to be done. As described before, placing a higher back on the plough is one of the adaptations. The higher back results in some cases to a higher buffer. The combination with the normal, 2 cm, high side walls and the higher back gives, in these cases, a higher trapeziod with a smaller top. The natural slope at the sides causes the higher build-up of the buffer to roll over the sides. In the case where the side walls are heightened to 4 cm high. The trapeziod has a similar height but a wider top deck. And thus a bigger, drag inducing, total frontal area. Video footage have shown that the build-up of the buffer in side the plough is bigger. A larger velocity results in a higher trapeziod shape. In other adaptions, the build-up of the buffer is described. Note that the suspension frame is not present in all plough adaptions. Here follows the calculation of the drag for all plough versions. Only the maximum drag is calculated, where the buffer is at a maximum.

In the high back plough, the plate at the back is heightened to 4 cm, 2 cm higher than the basic plough. The angle of natural slope is constant for all cases. The natural slope is heightened with 2 cm. At low velocities, loss of the sand is not influenced by the high back. The buffer is not high enough to cause the sand to roll over the back as one can see in picture 6.5. Here the speed is $0.075 \text{ m/s}$.

|Figure 6.5: High back low speed buffer|

|Figure 6.6: High back high speed buffer|

The sand here spills from the sides of the plough and in front of the plough. In the case of the higher plough speeds, the buffer is heightened more. As one can see in picture 6.6. The speed here is approximately $0.13 \text{ m/s}$. In these cases, the build-up of the buffer is to such an extend that sand also spills from the back. In this calculation one looks at the buffer at the maximum height, here is where the most current drag is caused. In the total drag calculations this maximum is used where in real life, the drag forces can be smaller for the high back plough. Taking the case where the buffer is biggest, seen in 6.6. Note here that the buffer also spills at the sides of the plough, giving the trapeziod a bigger base width. The buffer is spilling over the side wall and over the frame mounting brackets. The trapeziod base is widened with 4 cm. The height is 9 cm high. The width at the top is smaller due to the natural slope. The natural slope of the dynamic buffer is about 45 degrees. In figure 6.3 one can see the slope at the back of the plough. With the height one cm higher, the top width yields 1 cm. Giving a top width of about 13 cm. Using the area calculation for a trapeziod 6.13 one end up with:

$$A_{trapeziod} = \frac{1}{2} \cdot (29 + 13) \cdot 9 \text{ (cm$^2$)}$$

(6.17)

The total frontal area for the high back buffer at the maximum is $A = 189 \text{ cm}^2$. This can then
be used for the drag calculation. Using an already known equation, 6.4 with the calculated frontal area in 6.17 it yields:

$$F_{\text{buffer high back}} = \frac{1}{2} \cdot 0.5 \cdot 189 \text{cm}^2 \cdot 1000 \frac{kg}{m^3} \cdot 0.25^2 \frac{m^2}{s^2} \cdot 10^{-4} \frac{m^2}{cm^2}$$ (6.18)

This yields a maximum drag force, for the high back plough of $F_{\text{buffer high back}} = 0.29 \text{N}$. This is the drag calculated for the maximum buffer in a counter current situation. The maximum buffer occurs at the highest speed. Remember that all calculations are done with the maximum current. The maximum current is always at the highest speed.

In the next calculation, one looks in to detail to the drag induced by the buffer using the side flaps adaptation. The side flaps, as mentioned before are an extension of the side walls of the plough. The original side of the plough is heightened with 2 cm, the same height as the high back. Since experiments have shown that the most sand spills from the sides in front of the plough, the adaption has been made to extend the side walls. The original walls begin at the cutting blade but in the adaption, the side walls are stretched forward. Beginning with an offset of 3 cm in front of the cutting blade. The intended effect is to prevent spillage at the beginning of the plough session and results in an higher yield since more sand is pushed in side the plough. When the plough is filled to a larger extend, spillage in front of the plough will still occur but this will only be in a later moment in the plough session. In the side flap adaption spillage occurs from all sides when the buffer is at a maximum. The higher walls cause a higher build-up of the buffer. The extension of the flaps in front of the plough result in a quicker build-up of the buffer. Where spillage in front of the plough occurred immediately in the basic configuration, here spillage only commences when the buffer is big enough to reach the front of the plough. In this stadium the buffer is still growing. At a maximum, the buffer reaches a higher vertical maximum and a similar vertical top (compared to the high back). This is because the plough fills completely as one can see in the following picture.

![Figure 6.7: side flaps buffer](image)

The reason for the similar top is that the build up on the sides is now limited by the vertical side wall. Previously, it was limited by the horizontal side mounting brackets. With the naturals slope, the spillage from the sides occurs at a similar height. The spillage from the sides in the side flaps configuration only starts earlier on in the plough session. Feeding more sand to the plough gives the opportunity to build up higher until spillage from the back occurs. Since this is a dynamic
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process, sand can get higher than the natural slope allows it to. The buffer bulges upward a few times only to let sand roll to all sides. (refer to a video for this process). In the next calculation, one deduces the current drag from such a situation since this creates the maximum drag. The shape of the buffer here is more bulge like, instead of an straight edged trapezoid it is a trapezoid with curves. It will however be considered as an straight edged trapezoid. In picture 6.7 one can see the height of the buffer reach up to 11 cm above the plough. The height of the grid ruler is 9 cm, one can see the sand being pushed up higher than the ruler. The sand here already spills over the side walls and spills in front of the plough. Taking the before used trapezoid area calculation, formula 6.13 with a height $H = 11$ cm, a base width of 29 cm and a top width of 13 cm the total frontal area can be calculated:

$$A_{\text{trapezoid side flaps}} = \frac{1}{2} \cdot (29 + 13) \cdot 11 \text{(cm}^2)$$ (6.19)

And filling this area $A_{\text{trapezoid side flaps}}$ in using the drag formula 6.4 one yields the following equation:

$$F_{\text{bufferside flaps}} = \frac{1}{2} \cdot 5 \cdot 231 \text{cm}^2 \cdot 1000 \frac{kg}{m^3} \cdot 0.25 \frac{m^2}{s^2} \cdot 10^{-4} \frac{m^2}{cm^2}$$ (6.20)

Here, one will experience a maximum, buffer induced, current drag of $F_{\text{bufferside flaps}} = 0.36 \text{N}$. The drag of the frame will be added to this calculation to give a total drag of $F_{\text{totalside flaps}} = 0.41 \text{N}$. A little reminder is that the calculated drag by the high back is almost equal to this drag force. Although a bigger area, the shape of the buffer is much more efficient in the current then the flat plate at the back of the plough.

In the next item, the top flap addition is described. The top flap is a wing like horizontal plate fixed above the cutting blade. The reason for the top flap is duplex. The first function of the top flap is to limit the growth of the buffer. The buffer will build up to the top flap and is stopped. Than the second function of the top flap is used. The sand that is pushed upwards has to be directed to the back of the plough. Since the top flap is horizontally fixed, the forward momentum should push the sand more to the back of the plough than to the front of the plough. However, sand will partly be pushed to the front of the plough since a large volume of sand is fed and this will will not all be transferred to the back. The physical top flap will not induce a lot of drag. It is horizontal oriented which gives it an total frontal area of 25 cm times 1 mm. This small area is neglectable compared to the frontal area of the buffer and will not be taken into account. The buffer in the top flap adaption will not grow as high as in the precious plough versions, the height of the top flap will be the height of the buffer. Some sand will reach higher due to the constant delivery of sand. Here sand that is compressed in a horizontal direction will bulge upwards.

![Figure 6.8: Top flap low speed topview](image)

![Figure 6.9: Top flap low speed side view](image)

Seen in the experiments and seen in a figure 6.9 one can see the bulge of sand in front of the top flap. If one considers a sand wedge under the horizontal flap, sand will partially be transported to the back of the plough an to the front of the plough. When the sand inside the plough reaches a
maximum (this is not the maximum volume of the plough but the situation where the momentum limits the growth) the sand will be directed to the front. One can see in figure 6.8 a situation where the plough is not completely filled but the sand starts to bulge in front of the plough. Here, the upward pushing and the horizontal frontal movement will cause it to bulge above higher than the top flap in front of the flap. Here, a maximum height of 8 cm is reached in the experiments that have been done with the top flap. The top flaps sits at a height of 4.5 cm. Maximum height of the buffer is reached with the higher plough speeds. In figure 6.9 an experiment is shown with a low plough speed and thus a lower buffer in front of the plough. One can still see that sand is present inside the plough, right behind the top flap.

\[ A_{\text{trapezioptopflaps}} = \frac{1}{2} \cdot (29 + 8) \cdot 9(\text{cm}^2) \]  

(6.21)

Following directly is the current drag calculation with the calculated frontal area of 121.5 cm². Using formula 6.4:

\[ F_{\text{buffertopflaps}} = \frac{1}{2} \cdot 5 \cdot 121.5 \text{cm}^2 \cdot 1000 \frac{kg}{m^3} \cdot 0.25 \frac{m^2}{s^2} \cdot 10^{-4} \frac{m^2}{cm^2} \]  

(6.22)

This gives a maximum, current induced, drag force for the top flap plough of \( F_{\text{buffertopflaps}} = 0.19N \) With all current drag forces known, the next step is to take a look at the cutting forces. Mentioned before, cutting forces will be of bigger magnitude. Compared to the cutting forces the drag forces can be considered very small.

### 6.2.2 cutting forces

Several unknown parameters are present in the calculation of the cutting forces for the plough. We have an 45 degree blade angle, with this blade angle we will be starting with the shear angle \( \beta \). One can see the shear angle \( \beta \) in figure 2.8 This is the angle in which the sand shears under load relative the cutting direction. Assumed is that the shear plane is straight. To calculate \( \beta \) one needs the parameters \( \varphi \) and \( \delta \), relatively speaking, the angle of internal friction and angle of external friction. The internal friction is the friction between the sand-sand at the shear plane. The external
friction is the friction between the sand and the steel blade. Not much is known about the external friction angle. This can vary under different densities of sand and can have a different value at different cutting speeds. To ease calculations this value is taken as a constant. A value mostly used is 30 degrees. For the calculations of the cutting forces for the plough, the value of 30 will be used for further calculations. So $\delta$ is 30. The angle of internal friction can normally be derived from measurements in the sand pack. Such measurements have not been executed in the water tank so the angle of internal friction has to be derived from somewhere else. Normally, one can calculate the angle of internal friction from cutting tests. However, since in the plough process one also copes with the buffer forces it is not possible to derive the horizontal cutting forces from the measurements. (In this case, the buffer forces are calculated by subtracting the cutting forces from the measured forces. Which is the other way around). A value mostly used as the angle of internal friction is 38. This value will be taken in the calculations of the plough cutting forces as well as the horizontal friction forces due to the buffer in front of the plough. With the friction angles one can derive the angle of the shear plane $\beta$. Using the method of Coulomb, one can derive the shear angle. This is where the cutting force is at a minimum. Taking the derivative $\frac{\delta F}{\delta \beta}$, one can derive the minimal force at which the sand will shear. This is at a certain shear angle $\beta$. Somewhere between 10 and 30 degrees. In Appendix A one will find the determination of the shear angle $\beta$. This proved to be 20 degrees.

Other parameters needed for the calculation of the forces are the water sub-pressures and the permeability values. The average water sub pressures $P_{1m}$ and $P_{2m}$, are resp. the water sub-pressure in the shear zone and the water sub-pressure on the blade. Miedema provided the dimensionless sub pressures for several blade angles and shear angles. The pore pressures are dependant on several parameters. $\alpha$ and $\beta$ are already stated. other parameters are the ratio between the blade height and the cutting height $H_b/H_i$ and the ratio between the permeability of the sand in situ $k_i$ and the sand that has been cut $k_{max}$. All parameters are known for the plough except for the permeability ratio. The permeability has also not been calculated or tested in the model setup. As one can recall on step through for an experiment, sand is removed from the plough and is put back in the sand bed. Between two experiments, the sand layer does not get the chance to get tightly packed. Between two experiments, there is a time span of maximal one hour. It is safe to say that the permeability in the sand bed is similar to the permeability of the sand that has been cut. Both situations lack a nicely arranged sand structure. If both $k_i$ and $k_{max}$ are equal, the ratio between the permeability’s is 1. Using this ratio, one can use table 2.01 to find the water sub-pressures on the blade and in the shear zone. Using the following parameters for the interpolation; $\beta = 20$, $\alpha = 45$, $H_b/H_i = 3$ and $k_i/k_{max} = 1$ gives the following sub pressures. $P_{1m} = 0.187$ and $P_{2m} = 0.076$ . Respectively, the dimensionless pore sub pressure in the shear zone and on the blade surface. In order to use the dimensionless pore pressures one needs to replace the initial permeability and the maximum permeability with the weighed average permeability. The following equation shows how the weighed average permeability can be calculated.

$$K_m = K_i \cdot a_1 + K_{max} \cdot a_2$$  \hspace{1cm} (6.23)

For the equation 6.23 average permeability applies that $A_1 + A_2$ is equal to 1. With the permeability in the sand bed and in the plough equal, the mean permeability is the initial permeability. Here, $K_{max} = K_i$ So $K_{max} = K_i = K_m$ The permeability is however not yet known and also not tested in the water tank. In order to calculate the permeability one needs to refer to Den Adel (1986). Den Adel provided an equation based on the relationship between the sand diameter 15, porosity $n$ and the kinematic viscosity. The equation for permeability is as follows:

$$a = 160 \frac{v \cdot (1-n)^2}{g n^3 \cdot d_{15}^2}$$ \hspace{1cm} (6.24)

Where $a$ is the inverse permeability (in $\frac{m}{g}$). Permeability is given with $k = \frac{1}{a}$. As stated $n$ is the porosity and $d_{15}$ is the 15th percentile of the particle diameter spectrum. With the porosity taken at 40% and the $d_{15}$ of the sand composition known, the permeability can be calculated. Taking the 15th percentile diameter of the Dorslit nr. 9 batch, the particle diameter in the sand bed for
which 15 percent of the particles is finer than \( d_{15} \). The permeability can be calculated. The mean diameter is taken from the data sheet provided by Dorslit. Here, \( d_{15} \) is 0.238 mm. The porosity of the sand is high. This is a normal porosity for sand after it has been cut. Note that the sand does not get the chance to sink in after an experiment and the sand bed is therefore not packed. Porosity before cutting and after cutting are therefore almost equal. The porosity before cutting will be taken at 40 %. Since sand will not have the opportunity to get packed, the volume strain will be very low, due to the unchanged porosity. The volume strain or void ratio will be taken 0.003.

Filling in equation 6.24 gives:

\[
a = 160 \cdot \frac{10^{-6}}{9.81} \cdot \frac{(1 - 0.4)^2}{0.4^3 \cdot 0.000238^2}
\]  

(6.25)

This gives a permeability \( k \) of \( 6.17 \cdot 10^{-4} \text{ m/s} \). This value is the permeability of the sand used in the test tank. This is a reasonable value for the permeability. Higher permeability’s relate to low cutting forces since water sub pressures become less dominant. Now all parameters for calculating the cutting forces are known and the horizontal and vertical forces can be calculated. The process starts by using equation 2.13 but firstly, an overview of the parameters will be provided.

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</table>

In the Appendix one will find an example on how the cutting forces are calculated. A total overview of the cutting forces at different speeds is given below in figure 2.8
As one can see in figure 2.8 the speed of the plough barely has an influence on the cutting force. This is caused by the void ratio being very high. The sub pressures almost have no influence on the forces what so ever. The dominant force in this calculation is the weight of the sand $G$ above the blade. In our case, as already discussed in the chapter theory, we need to account for the sand that builds up above this blade. To account for the weight of the buffer above the blade, one can replace the constant $h_b$ for a variable $h_{b\text{-mean}}$. This $h_{b\text{-mean}}$ is the mean height of the sand taken from the underside of the blade. This has been widely discussed in the chapter theory, section Plough forces 2.6. By using this method, the blade height is virtually increased and thus accounting for the constant increase in the gravitational factor. Where the gravitation in D.2 (In the Appendix on the cutting forces calculations) resulted in a constant of 1.69 N the new gravitation factor constantly increases during ploughing. The new formula is now:

$$G = (\rho_s - \rho_w) \cdot g \cdot h_i \cdot b \cdot \frac{\sin(\alpha + \beta)}{\sin \beta} \cdot \left( \frac{h_{b\text{-mean}} + h_i \sin \alpha}{\sin \alpha} + \frac{h_i \cos(\alpha + \beta)}{2 \sin \beta} \right)$$  \hspace{1cm} (6.26)

Already known is that the height increase of the buffer is not constant over time. While the increase in the beginning of the plough session is high, sand starts to spil after a few seconds and the height of the buffer grows slower. Also, the height of the buffer is not constant over the width of the blade. The buffer is always at a maximum in the middle of the plough while spillage from the sides creates a lower height. The next figure can help explain that phenomenon.

Figure 6.11: cutting forces 0.05 - 0.21 m/s

![ Cutting forces graph ]
One can see in figure 6.12 that the buffer in the middle of the plough is at a height of 8 cm (the height of the grid ruler) while, at the sides the height is much lower. To use the adaptation of blade height $h_b$ in the gravitation formula we must use the mean buffer height $h_{b\text{-mean}}$. This will give an more suitable and convenient approach in calculating the buffer forces. As one can recall in the first part, where the drag forces are calculated, the shape of the buffer represents a trapezoid (when seen from the front). Using the trapezoid shape, one can calculate the mean height of the buffer.

Using the same experiment as before, one can use the video material to measure the height of the buffer. This measurement is done every 30 cm. This provides a list of heights at several moments in the ploughing process. Here, the researcher takes the height of the buffer at the grid ruler.
Figure 6.13: heigh measurement at 90 cm

As one can see in figure 6.13 a print screen of the video material is provided. Here, at a path of 90 cm the height of the buffer is 3.8 cm. As one can see in figure 6.13 sand already spills from the sides, meaning that the height of the buffer at the sides is not equal to the height of the buffer in the middle of the cutting blade. At the blade, the spillage starts when the buffer reaches the height of the side walls. In this case the side walls are 2 cm high. In the plough models where the side walls are 2 cm high one can assume that the height of the buffer is constant over the width of the blade (this is only true up to a buffer height of 2 cm). Using the trapezoid shape one can calculate the mean buffer height as is discussed in the Theory. Firstly, the assumption of the 2 to 1 slope angle is measured.
Figure 6.14: slope buffer sides

Here in figure 6.14 one can derive the slope from the sides. Using the spokes provided a measurement can be taken. Both spokes are 2.6 cm apart measuring the height of the buffer at two spokes at the sides gives a height of 4.6 and 6 cm. This gives a rough 2 to 1 slope. At the sides of the plough, the slope increases and the slope decreases more inward. For the ease of calculation, a slope gradient of 2 to 1 is chosen. Continuing with the measurements $h_b$ from the video footage every 30 cm one will result in a list.

<table>
<thead>
<tr>
<th>path traveled</th>
<th>$h_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 cm</td>
<td>0 cm</td>
</tr>
<tr>
<td>30 cm</td>
<td>2 cm</td>
</tr>
<tr>
<td>60 cm</td>
<td>3 cm</td>
</tr>
<tr>
<td>90 cm</td>
<td>4 cm</td>
</tr>
<tr>
<td>120 cm</td>
<td>4.5 cm</td>
</tr>
<tr>
<td>150 cm</td>
<td>5 cm</td>
</tr>
<tr>
<td>180 cm</td>
<td>6 cm</td>
</tr>
<tr>
<td>210 cm</td>
<td>6.5 cm</td>
</tr>
<tr>
<td>240 cm</td>
<td>6.5 cm</td>
</tr>
<tr>
<td>260 cm</td>
<td>6.5 cm</td>
</tr>
</tbody>
</table>

Using these measurements one can provide a list of the mean buffer height at several moments during ploughing. Note that only 10 moments during ploughing are measured. The moments in between these measurements are found by simply taking the trend between those two points. One can see in the picture provided below how a representation of $h_b$ and $h_{b-mean}$ looks like.
As one can see in figure 6.15, the $h_b$ is higher and by calculating the loss in frontal area by subtracting one yields the $h_b - \text{mean}$. Which lies a bit under the $h_b$ line. Using the one can now use formula 6.26 in order to calculate the cutting forces with the weight of the buffer contributing. If one contributes the weight of the buffer to the gravitation factor one yields the following graph:

Figure 6.16: cutting forces with weight buffer

In figure 6.16 one can see a considerably higher cutting forces in vertical component and double cutting forces for the horizontal component.

6.2.3 Buffer forces

The buffer in front of the plough causes a lot of force in the total plough process. Calculations on the cutting forces and the drag forces have shown that the biggest factor in the process is the movement of the buffer. The model plough has been designed to hover just above the sand bed. So when a layer of 6 mm has been cut, the plough does not touch the sand bed underneath. So no sand / aluminum friction will occur at this place. Only small areas of the plough experience friction. This is due to sand that spills from the sides and touch the plough on the port- and starboard side. As mentioned before, the buffer of sand is a dynamic process where sand that is cut gets pushed upwards to the top of the buffer, rolls downward to the front of the buffer and then gets pushed towards the plough again. In this clockwise motion sand can travel this course multiple times if it does not get pushed inside the plough. One should see this motion as a breaking wave or as snow
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being pushed by a snow plough. In the buffer however, the motion is slower. Sand positioned more on the inside the buffer also make this clockwise motion but in a smaller radius. Sand which escapes this motion can only travel inside the plough and to the sides of the buffer. Continuing with cutting sand only feeds the buffer and causes the buffer to grow in height and in length. The buffer loses most of the sand by spillage from the sides and by feeding sand to the plough. When the buffer is big, the plough is practically full so most of almost all the sand that is cut will end up in the buffer or will spill. The buffer force is considered to be caused by sand / sand friction. The buffer in motion and the stationary sand have a friction forces. This force is determined by the friction angle and the mass of the sand in motion. With no clear boundary between the stationary sand and the sand in motion it is hard to give an estimate of the mass of the sand in the buffer which is in motion. However, Since all horizontal forces on the plough can be calculated, the horizontal buffer force can be calculated by subtracting all forces from the measurement value. The result is the buffer force. In this part a calculation on the buffer force will be done for one measurement. For convenience, a measurement with the speed of 0.10 m/s will be used as was the case in the previous part where the cutting forces have been calculated. Firstly, we start with a picture where the forces on the plough act.

![Figure 6.17: acting forces on plough model](image)

One can see in figure 6.17 that multiple forces act in horizontal direction. Cutting forces, drag forces and loading forces. Also, minor friction forces are present but these are quite small and therefore not taken into account for the overall view. As one can see that the wire forces is not in horizontal direction. In the figure this is denoted as $F_{\text{pull}}$. The model setup did not allow a straight horizontal pull wire since the load cells where not able to be submerged. To account for this skew horizontal pull wire, equilibrium equations have to be used to find the horizontal buffer force $F_b$.

Starting with acting forces in horizontal direction as seen in picture 6.17 we have three forces acting in negative x direction. (Positive direction is in cutting direction). These forces are the horizontal cutting force; $F_{\text{cutting, hor}}$, the current induced drag; $F_{\text{current}}$ and the buffer induced force on the plough; $F_b$. Only the wire force is directed in positive x direction. Although the plough has two wires, for calculations one wire is considered. Also, only one pull load cell is installed. This forces yield an equilibrium:

$$\sum F_{\text{horizontal}} = 0$$
Since the pull wire is under an angle, we do not have a nice straight horizontal pull force. The pull wire was set under an angle of \(25^\circ\). This angle prevented the load cell from hitting the water. A smaller angle would have been possible for the model set up but this would have the disadvantage that the plough would hang on a very long beam. A long beam could have bend under pressure, introducing a skew cutting path. Also, a long beam would have the downside that the total length of the cutting path would be shortened. The pull wire angle will be referred to as \(\omega\). Using this angle equation 6.27 can be rewritten:

\[
F_{\text{pull, horizontal}} \cdot \cos(\omega) = F_{\text{cutting, hor}} + F_{\text{current}} + F_{\text{buffer}}
\] (6.28)

For the calculation of the buffer force we now take a simple experiment. For the calculation convenience, a speed of 0.10 \(\frac{m}{s}\) is taken since this is also used in the calculations for the cutting forces. A suitable experiment is 1.1-100%-against-10cm. This experiment is the basic plough in 10 cm water height with a 100 % flow against and a speed of 0.11 \(\frac{m}{s}\). The water speed is here 0.05 \(\frac{m}{s}\). Which gives a total counter current of 0.16 \(\frac{m}{s}\). If we now provide the measurements for this experiment in the following picture

![Figure 6.18: Pull measurement 0.10 \(\frac{m}{s}\) against flow](image1)

![Figure 6.19: Horizontal pull force 0.11 \(\frac{m}{s}\) against flow](image2)

In picture 6.18 one can see the measurements of the load cell for the pull wire. This load cell is known to measure kilos. Converting this to Newton and using the \(\cos \omega\) to get the horizontal pull force in Newton one yields the following graph seen in figure 6.19. If one now removes the horizontal cutting force that is calculated and the current induced drag force one ends up with the buffer force. Take into account that the drag force calculated for the basic plough assumed to have a counter current of 0.25 \(\frac{m}{s}\). This is calculated in equation 6.12 and gives a total drag force of 0.32 N. To account for the slower speed of the plough and the lower drag contribution, a small calculation have to be done.

In the experiment used, a total drag induced water flow of 0.16 \(\frac{m}{s}\) is considered. In equation 6.12 one uses a flow of 0.25 \(\frac{m}{s}\). Drag force is dependant on the flow speed \(U\) with \(U^2\). So it is not possible to simply multiply the 0.32 N with the factor \(\frac{16}{25}\). To get a proper drag force one needs to multiply by the factor \(\frac{16^2}{25^2}\). This yields the following equation:

\[
F_{\text{drag} - 0.10\frac{m}{s}} = 0.32 \cdot \frac{15^2}{25^2}
\] (6.29)

This yields a drag force of \(F_{\text{drag}} = 0.13N\). This is calculated, as one could see in the chapter on the current drag calculations, for a maximal height of the buffer. In the normal situation, the buffer starts from zero height to the maximum height and so does the drag. In this situation however, the current drag is considered constant over the whole path since it is such a small factor to the total
force equilibrium. If one now subtracts the cutting force $F_{c,h}$ and the drag force calculated above. The following graph will show:

![Graph showing horizontal forces](image)

Figure 6.20: Horizontal pull force 0.11 m/s relative flow 0.16 m/s

This graph shows the forces which remain after all other forces have been subtracted. The cutting forces shown in red are also visible in the graph. As one can see, these are not constant over time but grow due to the constant increase in the gravitational factor $G$. The same trick can be done for the vertical forces. In figure 6.17 one can see that the pull force $F_{pull}$ is under an angle. In calculation 6.28 the horizontal component is already calculated. By using a similar equation, we can calculate the load inside the plough. This is $F_{load}$. The weight of the sand inside the plough and the vertical internal friction.

$$F_{pull} \cdot \sin(\omega) + F_{cutting, vertical} = F_{load}$$

(6.30)

Note that here one does not have the influence of the current, which is perpendicular. The load force $F_{load}$ consists of the weight of the sand and the internal friction of the sand created by the movement of the buffer. This internal friction is not easily calculated. However, for this thesis, the vertical induced buffer force is of lesser importance. Not that in the calculation the weight of the plough is not present. During testing the vertical load cell was always set to zero kilograms. So the weight of the plough was already subtracted leaving the vertical load. Starting with the measurement of the vertical load cell one can see in picture 6.21. Here, the measurement is already converted to newton. By adding the vertical Pull force component one yields the vertical load as calculated in 6.30.
With the total vertical load known we can now subtract the vertical cutting forces which already have been calculated in the previous section.

As one can see in Figure 6.23 the cutting forces are considerably higher in vertical orientation than in the horizontal orientation. Subtracting these cutting forces (blue line) from the measured load forces (Green line) yield the actual load force (in red). Note that the actual load force is a combination of the weight of the sand in the plough and the internal friction of the sand in motion in vertical orientation.

If one now take another test. We can compare the two tests with each other. By using a test with similar circumstances we can prove the influence of parameters. The most easy test would be where the speed is similar and the only difference is the current. If we now take 1.2-100%-with-10cm as a comparison. The test here has a pot meter setting of 1.1 but calculations after measurements shown that this test had a speed of 0.115 m/s. The previous test had a speed of 0.11 m/s. As is already shown on the previous chapter in figure 2.8 the cutting speed barely has an influence on the horizontal
cutting forces which allows us to compare the both speeds. The speed of the water is 0.05 \( \frac{m}{s} \). This gives a relative speed (in opposite direction of the plough) of, 0.065 \( \frac{m}{s} \) After the video footage has been examined a graph of the mean \( h_{b-mean} \) can be constructed which gives the following graph seen in figure 6.24

![Graph of \( h_{b-mean} \) with flow](image.png)

Figure 6.24: \( h_{b-mean} \) with flow

From video footage it has been seen that the buffer in this case grows higher than in the counter current situation. With a higher \( h_{b-mean} \) one will see that the cutting forces will end up higher. Following is a graph of the cutting forces for the test 1.2-100%-with-10cm. This can be seen in figure 6.25.

![Graph of cutting forces](image.png)

Figure 6.25: Cutting forces with flow

With the cutting forces known over the whole plough track one can now subtract these cutting forces from the measurements and end up with the buffer forces. Also the current induced drag must be subtracted but with a speed of 0.115 \( \frac{m}{s} \) and a current in the same direction the result is that we have a speed difference between the plough and the current of 0.65 \( \frac{m}{s} \) giving a negative drag force of:

\[
F_{\text{drag-0.10}} = 0.32 \cdot \frac{6.5^2}{25^2} \quad (6.31)
\]

This yields 0.021 N. So this can be neglected in the further calculations since the cutting forces are much bigger in magnitude. Subtracting the cutting forces from the measurements gives the following graph seen in 6.26.
If we now take a look at the vertical forces, the following graph shows in figure 6.27.

If we now compare the horizontal forces in the 'against-current and 'with-current' situation one arrives with the following graph seen in 6.28:
Here we can see a obvious difference in the horizontal buffer forces. As expected, in the situation where the current is against the plough, the cutting forces are considerably lower. If we take the trend in the both lines, a difference of 20% in force can be seen. While, in vertical direction, a small difference in load can be seen as one can see in figure 6.29:

Here one can see that the load forces are slightly lower for the case where the plough direction is in opposite of the current. Video footage proves this also. The buffer inside the plough is slightly smaller than the buffer in the test with the current in the same direction.

The influence of the current on the size of the buffer can be considered small. From the video screen shots one can see that the buffer only decreases in size with max two cm. In both scenarios we have a relative current in the opposite direction of the plough. In the Waal river this is comparable. Here, several test have been executed in the with-current situation. The plough has a minimal speed of $1 \frac{m}{s}$ with the current having the same magnitude of $1 \frac{m}{s}$. Here, there is no relative
velocity between the plough and the current. In the thesis of T. van der Light, the discrepancy between the pulling forces is in the higher speeds. With higher speeds there is no actual -with-current situation. The plough is still moving faster than the current so there is an counter current situation. If we now start to translate the small scale experiments to the actual size plough. We have demonstrated that a difference in current of 0.10 \( \frac{\text{m}}{\text{s}} \) can have a 20 % difference in the horizontal buffer force. This is while the plough in both cases is filled completely as seen in the video footage. (both ploughs are full in the scenario). The filling is not equal over the length of the path and the heap in not equal in height. This explains the small difference in the graphs in 6.29. If one takes a look at the video footage from both experiments, 6.30 and 6.31 here below.

![Figure 6.30: Buffer 0.11 \( \frac{\text{m}}{\text{s}} \), relative flow 0.16 \( \frac{\text{m}}{\text{s}} \) at 230cm](image1)

![Figure 6.31: Buffer 0.115 \( \frac{\text{m}}{\text{s}} \), relative flow 0.065 \( \frac{\text{m}}{\text{s}} \) at 230cm](image2)

If one takes a look at the against-current situation, where the relative current is 0.16 \( \frac{\text{m}}{\text{s}} \) on 230 cm (figure 6.30). One can see that the height of the buffer is slightly smaller than the buffer in the other picture. This is due to the higher current situation. Most important is the difference in the buffer at the front of the plough. In the high relative current, the buffer stretches up to 10 cm in front of the plough. While in the other situation seen in figure 6.31, the buffer stretches up to 12 cm in front of the plough. The buffer forces consists of sand/sand friction force and is dependant on the weight of the sand and not the sand /sand friction area. Higher forces in the with-current situation are the result of a larger weight of sand in front of the buffer. The buffer is also bigger in volume in front of the plough in the 0.065 \( \frac{\text{m}}{\text{s}} \) current situation. As stated before, the dominant force in the plough process are the buffer forces. In the Waal plough, experiments with an open bottom have been executed. Here, the sand/sand friction component is much larger. All the weight of the sand creates friction and therefor buffer forces. If we look at figure 6.31, the part of the buffer inside the plough is slightly larger than in front of the plough. Lets say that the volume of sand in front of the plough is roughly 40% of the total. With no bottom plate, the weight of the 60% part also contributes to the buffer force. In the experiments of T. van der lugt, a open bottom plough was used, where, in these experiments a closed bottom plough was utilized. As one can see in the figures, the buffer in the 0.065 \( \frac{\text{m}}{\text{s}} \) is higher and stretches more to the front. The volume of sand is larger here. The volume of sand that is on top of the buffer does not contribute to the buffer force in the small scale but does however in the large experiments. If we compare the two buffer sizes with each other in the following figures. See figure 6.33 and 6.32.
If we look at the buffer in the high counter current we can see that the sand in front is smaller, giving a smaller buffer force. In the small counter current situation, the sand stretches more forward. This gives a higher buffer force. The sand inside the plough is also of larger volume. Since there is an open bottom, this also contributes to the buffer force. In this scenario one can understand that the difference in a with and counter current can go up to 30 %. In the calculation if the buffer forces, experiments have been chosen that are comparable in plough speed. If one would start to investigate in other speeds, especially comparing a low plough speed in the direction of the current and a higher plough speed in counter current direction than the difference of 50 % in the wire forces can be explained with the buffer as the cause.
Chapter 7

Conclusions

Several conclusions can be drawn from the experiments executed. First of all is that the buffer in front of the plough is a complex phenomenon which is hard to describe using words. As one has seen in this thesis, the buffer is a large force factor in the cutting of sand to be reckoned with.

- Instantly after cutting, a buffer builds up above the blade as a symmetrical head of sand growing in height and in width. This is all actuated by sand that is being pushed upwards from the cutting blade perpendicular to the sand bed.

- The buffer has its top above the cutting blade where the sand is being pushed upwards. This upward grow is limited by the size of the plough. Spillage occurs from all sides when the buffer grows high enough.

- Spillage occurs firstly, and almost directly from the start of the plough session from the front-sides of the plough. This leaves heaps in the sand bed where the plough has passed and are in definition higher than the original soil.

- Growing further in height, the buffer starts spilling over the port side and starboard side when the buffer is at a height of 4 cm in the middle of the plough. Here the shape of the buffer is determined by the natural slope of the sand. This slope is between 30 and 40 degrees.

- This slope of the buffer is barely influenced by low water speeds and if it is influenced, it is from the front. When the buffer grows, it does so pulsating. A volume of sand is being pushed upwards, this heightens the buffer. The result is that the natural slope is exceeded and sand rolls downward from all sides. Sand that rolls down the buffer to the front can stay in the buffer or rolls from the sides, out of the buffer so spills at the front sides of the plough.

- Sand that rolls in the direction of the plough path stays in the buffer and is once again directed to the blade and being pushed upwards. This is a roll motion of sand in front of the plough. Sand that rolls down from the sides and the back fills the plough up to the limit where the height of the side or back is reached and sand starts spilling from these places.

- In the basic plough configuration, spillage from the back is the last place where spillage occurs. At this state, most of the sand that is being cut is spilling from the side of the plough. Although the plough is full at this state, the buffer in front of the plough grows continuously. In the experiments executed, no limit is reached for the size of the buffer. In this state, the buffer can reach up to 12 cm in front of the plough and is the dominant force in the plough process.

- In experiments with a speed higher than 0.010 m/s one can see that the inertia of the sand bed plays a roll in the shape of the buffer. Here sand is being pushed upward by the blade. The sand is not able to roll down anymore and the buffer is now a dynamic process.

- Here, sand falls down the buffer in a wave like pattern and is here affected by the current. Although the current influences the motion of the sand, it only partly influences the size of the buffer. The size of the buffer is the most dominant force in the plough process.

- Readings have shown that higher speeds have lower buffer forces due to the smaller buffer size. The buffer forces have shown to decrease with 20 % when the direction of the current is in counter direction of the plough motion.
Although the influence of the current is small on the buffer size, the influence of the buffer on the pull forces are large. So a small difference in buffer size can therefore not be ignored.

The influence of the current on the buffer proved to be considerable. Video footage proved that the buffer in front of the plough is different in volume under the influence of the current. Here all circumstances are equal except for the current direction. Examining the video footage shows that during counter current plough sessions, the front limit of the buffer lies closer to the cutting blade than in the with-current situations. The shape is also different. Where the counter current buffer has a steep hill, the with-current buffer has a smooth slope.

A considerable difference in buffer size is seen between different directions of the current. In the scenario where the buffer is bigger and stretches more in front of the plough, the total forces are higher. This is due to the size of the buffer.

The buffer force is the dominant force in the total force equation. This explains why a counter current plough session has lower horizontal forces than a with-current plough session.

Spillage however is in the counter current situation higher. Where the buffer in front of the plough would contain a large volume of sand, the buffer in the counter current situations spills more sand to the sides.

The shifting of the front limit of the buffer under influence of speed of the current is equal. If the counter current decreases, than the front limit of the buffer moves forward, further away from the cutting blade.

It is shown that the total buffer force for the counter current situation is lower than the with-current situation. Here one can see that a counter current plough session results in 20% lower buffer forces. Buffer forces are accounted for 50% of the total plough forces.
Chapter 8

Recommendations

Starting with the first goal of this thesis, improving the plough process in the Waal river. In the research of T. van der Lugt the plough process was considered of low efficiency. The plough did not have the yield one had hoped for and energy was wasted during ploughing. The hypothesis was that this was due to the presence of a buffer in front of the plough. Also, a discrepancy was discovered in the plough process. When the tugboat pulled the plough against the current in the Waal river, the total pulling forces were lower than in the sessions were the tugboat was pulling in the same direction as the current. Although the plough current around the plough was higher in the against-current situation, the total pulling forces were lower. The explanation for this was the existence of a so called buffer. In this thesis, research was done after this buffer on a small scale and was proven to be existent. Although the plough in the original setting had an open bottom, and the buffer would be pushed to the back instantly, the principle stays the same in both cases. If the sand fills the large plough the buffer than also positions itself to the front of the plough. The buffer in the small scale was in front of the plough from the very beginning of the plough session. Here, sand is being pushed upward by the cutting blade and creates the height of the buffer. The original hypothesis was that sand would be washed away from the buffer under the influence of the counter current. This would then result in a smaller buffer and thus lower pulling forces. In the small scale experiments sand was washed away but not in the magnitude that this would cause a smaller buffer. Spillage did occur but was neglectable. It was however proven by comparing two experiments that a plough session against the current has got lower total forces compared to the session in the same direction of the current. By subtracting all known forces from the total horizontal force one yields the buffer force. This is the forces created by the friction/interaction of the buffer in front of the plough with the sand bed. Calculations have shown that the buffer force in the against-current situation is 20 % lower. Video footage have also shown that the buffer is visibly smaller in this scenario, further strengthen the buffer hypothesis. The influence of the current on the buffer is however not dominant. The most dominant parameter in the research is the speed of the plough. At higher speeds, the inertia of the sand starts playing a roll. In lower speeds, sand is able to roll downward to the front of the buffer and can create a large buffer. This large buffer has to be kept in motion. This translates to higher buffer forces. Although cutting forces are lower in these low speed scenarios, the buffer forces are higher and buffer forces are the most dominant forces in the plough process. The total forces in low speeds, tend to lie relatively high. In the high speed scenarios, cutting forces are higher and the buffer forces are lower due to a smaller buffer. This has a catch however. The buffer grows continuously under the constant feeding of new sand. At a certain point, the buffer collapses and starts to stretch forward so at this point, buffer forces also start to increase. The total forces in the high speed experiments therefor will be higher than the low speed forces eventually. So the higher speed of the plough only has a partly advantage. However, in the Waal river, the goal is to work efficient. In both cases, low and high speeds, sand is being transported. At high speeds this will cost more energy in the long run. Since one would get the higher buffer forces above the higher cutting forces. The advantage that can be taken is by ploughing in the direction against the current since this influences the size of the buffer. This
can reduce the buffer forces by 20%. As said before, the buffer forces are the most dominant force present in the plough process. These forces take up to 80% of the total horizontal forces. These forces can not be eliminated but can be lowered. In the Waal plough, the bottom is open. This means that inside the plough, sand sand friction occurs. This is considered a buffer force. By fixing a bottom inside the plough, these forces can be reduced drastically. The friction force is dependant of the weight of the sand. Most weight is present at the position of the blade since the buffer is highest here. In the small scenarios, the buffer stretches up to 10 cm in front of the plough. When adding a bottom plate inside the plough the buffer forces can be largely reduced. (If the plough is designed as the small scale plough that slightly floats above the surface). This implies that a method has to be found on how the plough is emptied. Spillage is a big problem in the plough process. The spillage causes two problems, the first problem is that it creates a less efficient process. Power is wasted on sand that does not end up inside the plough. Calculated is that, when the plough is filled, at least 40% of the sand that is being cut spills. The other disadvantage from spillage is that heaps are created. These heaps are higher than the original sand bed. This is not desirable since the goal is to reduce the height of the sand bed. Adding the side flaps have greatly solved this spillage. This is up to the point where the plough was too full to contain all the sand and spillage would still start. In the Waal plough spillage is also present. If the decision will be made to add an steel bottom plate, the buffer will shift forward. This will induce more spillage. By increasing the height and the length of the side walls, the spillage will drastically decrease. Also rolling sand is more easily picked up by the current. In the side flaps experiments sand does not roll as much as in the other experiments. For the Waal plough it is important to design the plough with the power of the tugboat as a decisive parameter. A buffer will always be present and it is key to design the plough to where the buffer is not yet spilled and the tugboat has enough power to pull the buffer. Heaps as big as in the small scale experiments (relevant to the size of the plough) will not be present in the Waal since the cutting depth is lower. However, the track length can be larger so a buffer can grow high enough to spill from the sides and front. It is recommended to lengthen the side of the plough and heighten the side walls. Creating a longer plough has no further efficiency with a closed bottom since no force is present to push the sand to the back of the plough. Only widening the plough will be more efficient but this can create stability problems. An adaptation that can enhance the roll stability is the top flap. It has proven that the top flap can stop a roll motion and can straighten the plough when the blades are still in the sand. This is suitable when the plough hits more sand on one side than the other and the suspension of the plough allows the plough to roll. This is only when the plough is suspended on wires. The other advantage from the top flap is that this adaption makes the plough stop cutting sand. When the buffer hits the top flap, the buffer pushes on the underside of the top flap and the plough rises up, the cutting depth decreases and no new sand is being cut. This can limit the size of the buffer inside the plough and in front of the plough. If one can design the height of the top flap to be adjustable one can attain a maximum size of the buffer and a maximum pulling force. Using this adaption requires that the plough can rise or tilt. In the small scale design a frame was build in order to keep the plough steady and fixed at a certain cutting depth. This could be possible for a prototype but takes out the simplicity that was the key property of the plough. Still a lot of thought has to be done in order to translate this information to a workable prototype of the plough. Still a lot of information on the buffer lies in the measurements and the video footage. The method used to compare two experiments in this thesis is very elaborate and therefor not suited for the vast amount of information that is present. Another method has to be used in order to really compare all experiments and the buffer forces. In this thesis a lot of information is taken out of the video footage and by providing hard numbers one can assure the principles of the buffer. By using all the information that is provided one can predict the size of the buffer by using the speed of the plough and the speed of the current as an input parameter. With this information, a translation can be done to the design of a large scale prototype.
Appendix A

main experiments

A.1 Results of main experiments

Here one will find the results of the main experiments where the plough has been fitted with side flaps and a top flap. These findings are beyond the scope of the thesis but can be helpful in designing a new plough or increasing the efficiency of the plough process.

**Side flaps** Even without the high back yet installed, it was clear that the plough would spill sand mostly front the sides and the front of the plough and not at the back. The sequence of spillage was the fronts, the side and when the plough was full, the back. In order to enhance the effectiveness of the plough, the spillage from the front and the sides is being affected by adding a front flap. This flap stretches the side walls of the plough to 4 cm in front of the blade. Normally, the wall would start at the place where the blade is installed. As soon as a buffer would build up, spillage would start. Lengthen the sides prevents this. Since spillage over the sides was also an issue the walls are also heightened with 2 cm. This is the same height of the High back. With this adaption, the volume of sand that fits inside the plough increases. This has an influence on the effectiveness of the plough process. Although the plough has an higher effectiveness, the flaps can cause the buffer to further stretch forward. Since the buffer force is the most dominant force this can have a negative influence on the pull forces and therefore the power invested. If one takes a look at the low speed experiment, 0.9-withflow-100%-10cm-high back-frontflaps, on can see that the buffer builds up nicely symmetrical. Sand is not able to spill from the sides and roll to the front of the buffer. When the buffer is at a height of 5 cm, sand starts spilling over the sides. This is at the same moment as the front limit of the buffer starts spilling to the sides. The adaption of the side flaps have the positive effect that the buffer grows higher than normally. The height of the buffer reaches 9 cm. This was not seen before. The front limit stretches to the end of the grid ruler, 12 cm in front of the plough. If we look at the same speed but with the current pushing against the plough direction we observe an unexpected behavior. The behavior we would expect is that the buffer is slightly pushed on the front side towards the plough. This is normal for all experiments before where the current is in the opposite direction of the plough. However, figure A.2 shows the behavior of the buffer in the 1.0-againstflow-100%-10cm-high back-frontflaps experiment.
This behavior is not as expected and is hard to explain. This is only seen at the against-current situations and would normally not occur. A logical explanation for this behavior can be that the blade somehow changed in angle and has interrupted the experiments. If the blade angle increases, the horizontal cutting forces increase and the vertical cutting forces decrease. With the blade angle changed, the motion of sand will be changed in direction, instead of being pushed upward, it is being pushed forward. This creates the wedge as described earlier. It is possible that the angle of internal friction changes $\beta$ this causes that the shear line lengthens. The sand pack breaks over this shear line, causing sand to being pushed upward more in front of the blade. As one can see in figure A.3 the shear angle $\beta$ is decisive for where the shear line meets the boundary of the sand bed-water. Increasing the blade angle decreases the shear angle. The result is a bigger shear plane. This means that sand starts shearing more to the front. It is however not determined how the blade angle has changed and it is therefor not possible to determine the blade angle. A important note to take is that the shear angle $\beta$ is determined by minimizing the derivative $\frac{\delta F}{\delta \beta}$. In our plough model, the cutting force is not a constant but increases during ploughing as an result of the added weight of the sand above the blade. In Appendix A one will find that when the gravity factor $G$ increases, the shear angle will only slightly decrease. It is therefor not likely that, according to the cutting theory of Miedema that the shear angle will decrease. This could however explain that sand will be pushed upward in front of the plough as a result of the decrease in the shear angle $\beta$ can decrease causing the shear plane to increase. In the theory of Miedema it is assumed that the sand stays packed (Miedema calls this the flow type) and will not roll down to the front of the shear line. The weight of the sand in front can cause that the shear angle is influenced. The result of this is. Where the boundary of the shear plane can lie close to the cutting blade in the beginning, it can lie more to the front. Most likely is that in front of the shear boundary the sand moves horizontally over the sand bed. This friction might cause
small deformations in the sand bed which can cause irregular shapes. Another explanation is that
the shear plane is not straight but a curve. This can also cause that the shear boundary is more to
the front than the theory claims. This lies however far beyond the scope of this thesis.
**frontflaps, blade angle 30 degrees** With another blade angle, it is possible to see whether sand is more pushed inside the plough. With a smaller blade angle of 30 degrees instead of 45 degrees the sand is more pushed towards the plough instead of upward. In these experiments, the blade angle is changed with the cutting depth kept at a constant 6 mm. The cutting depth is kept at a constant in order to keep the volume of sand that is being cut in these experiments equal to the previous experiments. This meant that the plough is lowered a little bit in order to maintain the cutting depth of 6 mm. While expected was that the top of the buffer would shift a little bit to the back of the plough, the top of the buffer remained above the blade. Spillage in these experiments is also comparable to the experiments with the side flaps. At low speeds, when the buffer is at a height of 5 cm, spillage starts in front of the plough and from the sides at the same time. For the against-current experiments, this is seen in the experiments with pot meter settings 0.8, 0.9 and 1.0. In the experiment with the pot meter setting of 1.2 at a speed of 0.0115 m/s spillage starts first from the side walls and than from the front. This is also seen in previous experiments with the frontflaps. Higher speeds tend to spill sand later in the track at this side of the plough. This is partly due to the current but more due to the speed of the plough and therefore the inertia of the sand bed.

In the with-current situations, rolling of sand is still possible. This is not the case in the against-current situations. Sand is not able to roll down the buffer in the front and is washed away from the sides. This is in combination with the wedge that pushes up the sand in front of the plough as seen in figure A.4. This wedge type is seen in slow experiments. 0.9-againstflow-100%-10cm-high back-frontflaps-30degree blade is a video where this wedge type buffer is seen. Where the inertia of the sand bed would start to dominate, the wedge type buffer disappears. This transition is around the 0.10 m/s for the against flow experiments. Footage from the with-flow experiments indicate that this is around the same speed for the opposite current direction. Increasing the speed of the plough would decrease the distance of the front buffer border to the cutting blade. However, the buffer is a dynamic process and the distance from the blade to the front of the buffer can therefore not be calculated beforehand. As said before, the buffer has a more wave like motion at higher speeds of the plough. This means that in a matter of seconds, the front limit of the buffer can move by centimeters. This is seen in 1.3-againstflow-100%-10cm-high back-frontflaps-30degree blade as seen in A.5 and A.6 where the plough has created 15 more on the plough path.
It is clear that by increasing the speed of the plough, the mean distance from the cutting blade to the front limit of the buffer decreases. Since the buffer force is the most dominant force the overall force balance, the difference in pull forces do not change much. If one takes a look at the pull forces for these experiments.

In figure A.7 one can see that the pull forces lie relatively close to each other. This is explained by the fact that a faster track (with higher cutting forces) have lower buffer forces and slow experiments are more dominated by the buffer force than the horizontal cutting forces.

Frontflaps Filled
This experiment was called for in order to gain information on the maximum size of the buffer. However, with the 8 mm cutting depth experiments it has shown that there is no maximum buffer size bug the buffer just grows slowly. In this experiments, the same conclusion is drawn. By filling the plough with sand from the beginning still no maximum buffer is reached. It is however helpful to see the effect of a partially filled plough on the buffer. The buffer behaves normally in the beginning. Here, it is not affected by the sand already in the plough. When the buffer is affected by the sand that is inside the plough, the buffer grows fast and starts to react in the same manner as it did in the 8 mm cutting depth experiments. Here, to much sand is being fed to the already overfull plough and the buffer stretches a large distance to the front where a lot of sand spills. The buffer stills grows slowly but does not reach a maximum size.

Top Flaps
The top flap adaption is made up because of the continuous growth of the buffer. The thought was to limit the growth of the buffer in height and direct the buffer more to the inside of the plough by adding a horizontal flap above the cutting blades at 4 cm. By adding the flap, the vertical movement of sand that was being pushed upwards by the blade would be directed to the back of the plough. The thought wast that the horizontal pushing of the sand on the front would direct the sand to the back of the plough. It would, however be more suitable to place the topflap under an angle but that was not tried since the time in the dredging lab was running out.

After the first experiment the researchers thought a fault was being made. Normally the buffer would increase in front of the plough to the front of the grid ruler. However, in the topflap adaption, the buffer did not grow as expected and the plough frame was being pushed out of the place. This meant that there was a large upward force, causing the plough to lift up from the sand bed.
buffer can be seen in figure A.8. In all experiments, the size of the buffer is limited to the size seen in this picture.

The principle behind the size of the buffer is simple. Where the sand is being pushed upwards by the cutting blade, it hits the topflap. This motion is then stopped and the force of the sand pushes to the topflap.

Normally, the blade would be pushed downward and the topflap would be pushed upward in the same magnitude. However, the sand that hits the topflap forms a wedge. This wedge is causing that sand in the buffer pushes to the topflap. This creates an upward force, causing the cutting depth to decrease. Now the volume of sand that is being cut is only slightly larger than the volume of sand that spills. The upward motion of plough is very small but causes the plough to lift up. The result is that the weight of the plough plus the frame is being compensated. The result is that the load cell starts to hang free. The load cell was normally supported by the beam attached to the cart. This construction can be seen in 3.9. due to the upward force, the roll bearings are pushed out of the beam it is supported in and the plough tilts backward. This is seen in figure A.9. Although this looks like an undesired phenomenon, this can still be used in a good manner. By adding the topflap as an limiter, the size of the buffer can be controlled. If the power of a tugboat is considered the limit than the topflap can prevent a buffer from growing to large. In the experiments, another conclusion could be drawn. If the speed was faster, the plough would be pushed out of the beam more quicker. This is supported by the fact that the inertia of the sand bed plays a larger role in the faster experiments.
A.2 conclusions main experiments

Adding a higher back and side flaps prevent spillage from the sides and back early on. The most spillage is prevented by lengthening the sides 4 cm in front of the cutting blade. Where spillage started practically immediately in the front sides of the plough, the side flaps now prevent this spillage. The higher side walls allow the buffer to grow higher than the buffer in the basic plough configuration. Here, the plough can grow up to a height of 8 cm. Also in this situation, sand spills from all sides where most spillage occurs in front of the plough. Here the sand that rolls from the top down to the front of the buffer can spill or stay inside the buffer where it can stay continually in motion. Here sand rolls downward to the front, gets directed to the blade due to the internal friction of the sand in motion and the stationary sand bed and is being pushed once again upward. In this configuration, the buffer grows higher and wider. The buffer only stretches out slightly more than in the basic plough configuration. In the beginning of a plough session, the buffer in front of the plough has the shape which follows the natural slope. Continuing ploughing will create a bulge of sand. This bulge is created by a sand wedge inside the buffer. Where normally the sand is being pushed upwards by the blade, the sand in the already larger buffer hits this sand in motion. This is horizontally speaking from a distance from the blade. If one considers the sand that is being pushed upward as a wedge, sand hitting this wedge will be also pushed upward. This creates the bulge in the front side of the buffer. This bulge occurs in low cutting speeds where the influence of the current on the shape of the buffer is small. Although most of the sand is not being pushed in the plough, the buffer in front of the plough still removes sand and pushes the sand forward. However, since buffer forces are dominant, a lot of energy is dissipated through the buffer where still a lot of sand spills from the sides.
Appendix B

Stability experiments

B.1 List of stability experiments

In the end of the experiment period some time was left to get more insight in the stability of the plough. In the very beginning, the model plough was designed to be hanged on wires like the Waal river plough. However, wires turned out to cause side effects that where gladly eliminated. Wires became slack and had to much play which caused crooked cutting depths and crooked paths. Also, the plough could easily become unstable if the roll motion was not limited. These early design flaws lighted the idea of testing several, wire based, plough suspensions. Testing which plough suspensions could give a stable cutting process and which design proved to be unstable, hence the stability experiments. Since the build up of the buffer was of lesser importance not all tests have been measured. If a test is measured, one will find that in the description of the test. In some cases, measurements could not have been done, for instance when no vertical suspension was installed. In the chapter Experiments one will find a broader description of the test executed. A small list of tests that have been measured is supplied.

1. No vertical suspension, No flow
2. Against flow, vertical wires
3. Against flow, vertical wires, topflaps

A list of tests where there has been no measurement, only visual information stored is also given:

1. No flow dune test
2. No flow dune test topflaps
3. No flow, topflaps, vertical front wires and back wire
4. No flow, topflaps, middle front wire and back wire.
5. Unstable, No flow, vertical front wires, back wire, topflaps
6. Unstable, No flow, vertical front wires, back wire
7. No flow, back wire, middle front wire
8. Unstable, No flow, no vertical wires
9. Unstable, No flow, back wire, middle front wire, topflaps
10. Unstable, No flow, back wire, middle front wire, topflaps, side flap
In all the experiments where no measurement has been taken the pot meter was set to a low speed. This was the 0.8 pot meter position. This is roughly equal to 0.075 m/s. The measured experiments have different speeds. The plough is stripped of the suspension frame and spokes and is left with the high back and front flaps. In some cases the top flap is installed. Here, the list of stability experiments is provided:

**No vertical suspension, No flow** In the first stability test there is no suspension to limit the depth of the cutting path or the pitch and roll motions of the plough. Only the horizontal pulling wires are installed to pull the plough forward. In the last test, the top flap is installed in order to determine if the depth of the cutting path is limited by the top flaps and if this causes an more stable cutting path. The list of these experiments can be found below in table ??.

![Table B.1: Experiments No flow, No vertical suspension](https://example.com/table1)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8-noflo-10cm-against-frontflaps-topflaps-novertical</td>
<td></td>
</tr>
<tr>
<td>0.9-noflo-10cm-against-frontflaps-topflaps-novertical</td>
<td></td>
</tr>
<tr>
<td>1.3-noflo-10cm-against-frontflaps-topflaps-novertical</td>
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</tr>
<tr>
<td>1.3-noflo-10cm-against-frontflaps-No topflaps-novertical</td>
<td></td>
</tr>
</tbody>
</table>

**Against flow, vertical wires** Here, the plough is fitted with two wires at the front of the plough, above the blade at port- and starboard side. This partially limits the roll motion of the plough but gives freedom in pitch motion. To be tested is the effect of the front wires on the cutting depth and the stability. And, with no backfire, if the plough decreases the cutting depth when it is tilted backwards. The list is provided in table B.2.

![Table B.2: Experiments Against flow, Vertical wires](https://example.com/table2)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9-100%-10cm-against-frontflaps-verticalwires</td>
<td></td>
</tr>
<tr>
<td>1.0-100%-10cm-against-frontflaps-verticalwires</td>
<td></td>
</tr>
<tr>
<td>1.1-100%-10cm-against-frontflaps-verticalwires</td>
<td></td>
</tr>
<tr>
<td>1.3-100%-10cm-against-frontflaps-verticalwires</td>
<td></td>
</tr>
<tr>
<td>1.5-100%-10cm-against-frontflaps-verticalwires</td>
<td></td>
</tr>
<tr>
<td>2.0-100%-10cm-against-frontflaps-verticalwires</td>
<td></td>
</tr>
</tbody>
</table>

**Against flow, vertical wires, topflaps** In these tests, an 100% flow against is set with a vertical suspended plough as one can see in the beginning of this chapter, seen in picture B.1 but with the top flaps installed. The top flaps are installed to limit the growth of the buffer and push the buffer more to the back of the plough. Thus achieving a filled plough quicker. With no back wire installed, the plough can tilt backward and limiting the cutting depth. The list is provided in table B.3.

![Table B.3: Experiments Against flow, Vertical wires, Topflaps](https://example.com/table3)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8-100%-10cm-against-frontflaps-verticalwires-topflaps</td>
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<td>1.0-100%-10cm-against-frontflaps-verticalwires-topflaps</td>
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</tr>
<tr>
<td>1.2-100%-10cm-against-frontflaps-verticalwires-topflaps</td>
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<tr>
<td>1.5-100%-10cm-against-frontflaps-verticalwires-topflaps</td>
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</tr>
<tr>
<td>2.0-100%-10cm-against-frontflaps-verticalwires-topflaps</td>
<td></td>
</tr>
</tbody>
</table>

With the measurement test done, only the visual experiments are left. These tests are only done once with no change in speed. Here speeds are 7.5 m/s. Starting with the dune test.
No flow dune test. Here a small dune is created at the bottom of the test tank. Here, the aim is to see if the plough can cope with an irregular cutting depth and an unstable situation. E.g. a situation where the plough only cuts at one side. Here vertical front wires are installed to limit rolling and a back wire is installed to stabilize the plough.

No flow, topflaps, vertical front wires and back wire. While in the previous test an irregular cutting path was set up, in this test a clean straight cutting path is created. To be tested is if the topflap limits the buffer and raises the plough at the front. Raising the plough at the front reduces the cutting depth.

No flow, topflaps, middle front wire and back wire. The two vertical front wires on each side are removed and replaced by a front wire in the middle of the plough. The middle front wire gives the plough freedom in the roll motion. With the topflaps installed the test here is of the topflaps stabilize the plough during cutting.

Unstable, No flow, vertical front wires, back wire, topflaps. Since no unstable cutting was seen in the test with the two vertical front wires, the plough is deliberately made unstable. By fitting a screw and a lag bolt at one side, the center of gravity is changed. This is similar to a plough session where sand is more present at one side of the plough. To be tested is the effect of the topflaps to the instability of the plough. In picture B.3 one can see the plough doing what he likes most.

Unstable, No flow, vertical front wires, back wire. This is a test to compare the previous test. With all parameters equal to the previous test except for the topflaps. The researcher can now see if the plough is actually unstable. With the results of this test one can
describe the positive effect of the topflap on the stability of the plough.

**No flow, back wire, middle front wire** Here, the plough is once again fitted with a middle vertical wire instead of the two vertical front wires. With this suspension one can compare the effect of the two vertical front wires with the single front wire. Single wire fitted, being a more unstable plough. With the results of this test one can describe the positive effect of the two front wires.

**Unstable, No flow, no vertical wires** With the large bolt on the stern side of the plough, an unstable plough equilibrium is to be expected. With no vertical suspension the train of thought is that rather than a crooked cutting depth, the plough just cuts in the sand very deep and the effect of the weight of the bolt is soon after negligible. One can see in picture ?? how such a test looks like from top view.

**Unstable, No flow, back wire, middle front wire, topflaps** With the topflaps installed once again, the suspension is in the front and back of the plough in the middle. Thus creating an unstable plough which has the freedom to roll. To initiate the roll motion, the large bolt is installed to provide the weight. Here, the topflaps are installed to counter act the roll motion. To be tested is if the topflaps can balance the plough once again, limit the roll motion of slow down the roll motion.

**Unstable, No flow, back wire, middle front wire, topflaps, side flap** With the previous experiment proving that the topflaps do not counter act the roll motion but only limit the roll motion another form of stability enhancing appendix is sought. While skis normally have a negative impact on the stability humans it is somehow tested on a plough to prove that it can stabilize an unstable situation. With the side flap installed as one can see in picture B.5 the test is to observe whether the side flap only limits the roll motion on the unstable plough or can actually counter act the roll motion and stabilize the plough once again. With the plough stabilized again, the cutting depth is constant over the width of the plough.

Provided below is a list of the tests done with the proper names. This is table B.4.
Table B.4: Visual stability experiments

<table>
<thead>
<tr>
<th>No Flow Dune Test</th>
<th>No Flow Dune Test-Topflaps-Backwire</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Flow Dune Test-Topflaps-Backwire</td>
<td>Topview-No Flow Dune Test-Topflaps-Backwire</td>
</tr>
<tr>
<td>No Flow Dune Test-Topflaps-Backwire-Topflaps</td>
<td>Topview-No Flow Dune Test-Topflaps-Backwire-Topflaps</td>
</tr>
<tr>
<td>Topview-Unstable-0.8-Flow Vertical Front Wires-Backwire</td>
<td>Topview-Unstable-0.8-Flow Vertical Front Wires-Backwire-Middle Frontwire-2</td>
</tr>
<tr>
<td>Topview-Unstable-0.8-Flow Backwire-Middle Frontwire-2</td>
<td>Topview-Unstable-0.8-Flow Backwire-Middle Frontwire-Middle Frontwire-2</td>
</tr>
<tr>
<td>Topview-Unstable-1.0-Flow Vertical Wires</td>
<td>Topview-Unstable-1.0-Flow Backwire-Middle Frontwire-Middle Frontwire-2</td>
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<tr>
<td>Topview-Unstable-1.0-Flow Backwire-Middle Frontwire-Middle Frontwire-2</td>
<td>Topview-Unstable-1.0-Flow Backwire-Middle Frontwire-Topflaps</td>
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<tr>
<td>Topview-Unstable-1.0-Flow Backwire-Middle Frontwire-Middle Frontwire-Middle Frontwire-Sideflap</td>
<td>Topview-Unstable-1.0-Flow Backwire-Middle Frontwire-Middle Frontwire-Topflaps-Sideflap</td>
</tr>
</tbody>
</table>

B.2 Results

Stability experiments

Several stability experiments have been executed in order to better understand the stability in the plough process. Sought after here is the possibility to stabilize the plough in the real world. As one knows, the plough used in the basic experiments and in the main experiments is fixed. Using a steel frame, the plough has no freedom to pitch or roll. The decision to fix these freedoms was based on the fact that the fixed plough would provide trustworthy information on the buffer principle. Since the plough movement was fixed, the influence of these movements on the buffer is neglectable. This way, experiments could be compared. While, with a non fixed plough, the plough would behave differently each test and could not provide the necessary information it should have. In the stability experiments, the buffer is not important, the movement of the plough is. This can provide vital information for the design or improvement of a plough. Here one will find the finding of the several stability adaptions of the plough. starting with the no flow dune test.

No flow Dune test

In the no flow dune test the vertical frame is removed in order to investigate the behavior of the plough when exposed to an irregular sand bottom. In this test the bottom is not flattened but is provided with small dunes and irregularities. These irregularities are set so that the plough might encounter sand at one side, while no sand is encountered at the other. The plough is here hanged from two vertical front wires at the sides and one back wire in the middle as one can see in figure B.6 The two vertical front wires can provide some free play or slack. This gives the plough the ability to roll. The slack in the back line gives the plough the ability to pitch.
Figure B.6: No flow Dune test

The overall stability of the plough is good. Expected was that the plough would start to roll when cutting on one side but this did not happen. The plough however continued with a slight roll angle due to the fact that it was filled up more on one side than the other. This is not a desirable position and this continued further on. Since one side was lower than the other, more sand was being cut at this side. Cutting more sand would fill up the plough more rapidly on that side. Spillage occurred firstly on that side while the other side fills more slowly. The roll angle decreases slightly when the other side if filled more but the plough does not end up horizontally. The added effect of the pull wires can be seen as negative since the plough does not stabilize itself but rolls when it encounters more sand on one side. This also causes that less sand is being cut at the other side. The effect of the back wire can be seen as positive. The plough has the ability to pitch. When the plough is full at the end of the track, the back of the plough is slightly lower. This lower back prevents a large buffer from existing. The blade depth decreases and the cutting height decreases. This can have a positive effect on the plough process since the plough is already full and does not take in any more sand. All sand is being spilled from the sides. Comparing this to the fixed frame plough, the buffer in front of the plough is much smaller inducing less sand-sand friction.
No flow dune test Topflaps
In the no flow dune test with topflaps the goal is to see whether the addition of the topflaps gives a positive effect on the roll motion experienced in the previous test. Here the plough fills more rapidly on one side which causes the plough to roll to that side. With the vertical wires in the same manner as the previous experiment, the difference the topflap can make can now be tested. In the main experiment, the advantage from the topflap was that the plough would not fill up completely and would rise it self above the sand bottom, therefor limiting the size of the buffer. In this scenario, the possibility of self stabilizing is experimented. If one side fills up more quicker, the top flap will counter act the roll motion and the plough would become horizontal again.

Figure B.7: No flow Dunetest Topflaps
As one can see in the picture above, figure B.7 the plough is filling on one side more rapidly than on the other side. This is due to the irregular bottom. The plough starts rolling to this side. The tendency to roll is than limited by the topflap. The topflap here only stops the roll motion. It does not initiate a roll motion towards the other side directly. Following the rest of the path, the plough very slowly rolls back to a horizontal state. This is however not due to the fact that the topflap is installed but more because the sand on the other side fills the plough and counteracts. The topflap can however stop the roll motion from happening and limit the degree of roll. It does not reverse the roll motion. This however was expected.
No flow, topflaps, vertical front wires and back wire

A desired effect for the top flap was that it would limit the cutting depth of the plough at the moment that the plough would fill up. In previous experiments, video footage showed that the top flap would create an upward force. When still installed in the plough frame, the topflaps would push the plough upward. This upward force counteracted the weight of the plough frame and plough itself. Thus creating a total negative vertical force. The affect was that the load cell would be pushed out of its position. Now that the plough is hanged by wires, it is not limited in movement by the frame and can follow the path it desires more easily. In this experiment the sandy bottom is flat so no roll instability is expected. However, pitching can occur. During the test, the plough fills like expected. The back wire and the front wire have some slack in the beginning but are tensioning during ploughing. Due to the slack, the cutting depth can increase. This can be compared to a tugboat. In the real world, the plough hangs on the tugboat at the back. When a plough cuts sand vertical cutting forces pull the plough downward. In the case of the tugboat, the stern is pulled deeper thus creating a larger cutting depth. The same principle is present here.

Figure B.8: Pitching during cutting due to topflaps

After filling to the height of the top flap, the cutting depth decreases since the topflaps push the plough upward. While, in the situation where the frame is installed, the whole plough is pushed upward, in this case only the front is pushed upward. This is a negative pitch. As one can see in figure B.8, the side flap rose above the sand surface while it is normally just touching the bottom. The top flap in this situation limits the cutting depth. The buffer is however still 8 cm in front of the cutting blade so sand-sand friction is still present. Since this is a flat sand bed it is not known what the behavior of the plough will be if a dune would now be presented. Likely is that the plough would only follow the shape of the dune if the gradient is low.

No flow, topflaps, middle front wire and back wire

In the previous experiment, the roll movement was very limited due to the two vertical front wires. The front wires are attached to the port side and starboard side. Replacing these two vertical wires with one middle wire, the plough can roll freely. The experiment here is to test whether the top flap can stabilize the plough when an unstable situation starts. The unstable plough will tend to roll when cutting more sand on one side. In the very beginning of the experiments, the first ploughs where fitted with wires. These proved always unstable. However, this experiment, where the goal was to have an unstable plough, proved neglectable. The plough remained stable and did not roll to one side. The effect of the top flap on the stability is therefore not tested.
Unstable, No flow, vertical front wires, back wire, topflaps

Since the previous experiment was neglectable, due to a stabilize plough, the next step was to purposely make the plough unstable. An unstable plough would start a roll motion ant eh effect of the topflaps on the stability could therefore be tested. Adding a weight to one side of the plough would cause the plough to cut deeper on this side. Cutting deeper would mean that it would fill quicker and start to roll to this side. With two vertical front wires installed, the plough would be able to roll to one side. With one middle cable installed, the plough would be to unstable. Adding a large bolt as a weight to one side would be sufficient to destabilize the plough from the beginning.

In the experiment, the added weight did destabilize the plough. The sand would start filling the plough more on the side of the bolt as one can see in B.9. This would result in a small roll toward that side. The topflap did stop this roll motion. However, the topflap did not stabilize the plough further, a small roll angle would always be present further down the track. Also, as one can see in B.9, the buffer in front of the blade at the port side is bigger than that on the other side. This is due to the fact that more sand in present inside the plough at that side. Since the plough is already full, the topflaps cause a decrease in the cutting depth and no new sand is being cut. The buffer on one side stays bigger than the other side. This proves that the topflap does not stabilize the plough entirely but stops the destabilizing action.
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Unstable, No flow, vertical front wires, back wire
Removing the topflaps gives the researcher the opportunity to see if the plough is in fact unstable without the topflaps. The experiment here is to see whether the roll motion of the plough continues or stops. With the heavy bolt still installed, the plough initially starts to roll to that side. Rolling initiates quicker filling of the plough on that side while the other side of the plough stays behind. The roll motion is now limited by the wire in that side. Since the plough is under an angle, the buffer on one side is much bigger than the other side but he other side is still filling. During the rest of the plough track, the plough is full and spills on one side while the other side (visibly higher up in the air) is still filling very slowly.

No flow, back wire, unstable, middle front wire
With the two vertical front wires replaced by the middle front wire, roll can occur easily. With no topflaps, expected is that the plough will roll to the side with the added weight. The goal is to see whether the plough stops rolling or if it continues to roll and maybe flip over.

As one can see in figure B.10, the plough fills on one side (the side where the added weight is). Here, a large buffer starts is created in front of the plough. Since the middle wire allows to plough to roll, the starboard side rises from the sand bed, preventing cutting and thus preventing a counter acting roll motion. This plough design is very unstable and does not stabilize itself.

Unstable, No flow, no vertical wires
To test if the plough is still unstable with no wires installed, all vertical hanging wires are removed from the plough. With the weight added, expected is that the plough will firstly start cutting more sand on the adds weight side and stabilize further down the track. However, the effect of the weight is neglectable. The plough immediately starts to burrow itself in the sand bed and fills up directly. The weight of the sand in the back of the plough stops the digging and directs the plough upward. This happens all within the first meter. When the plough stops cutting and is pulled above the sand no more sand is being cut. The front of the plough is higher than the back and no new sand is filling the plough. Also no new sand is being cut. spillage from the back does not occur further on in the track, only small amounts of sand leave the buffer from the side.

Unstable, No flow, back wire, middle front wire, topflaps
Comparing the effect of the topflaps with the experiment [No flow, back wire, unstable, middle front wire] which proved to be very unstable. Adding the topflaps might have a stabilizing effect on the plough. The behavior of the plough is similar to the comparing experiment until the sand hits the topflap. The topflap stops the roll motion but does not stabilize the plough. Continuing with this situation does not stabilize the plough. With one side partially above the sand bed, no new sand will be cut and the plough will stay under a roll angle. The conclusion that can be drawn on the topflap is that it has a positive effect on the cutting height if the plough is already stable. The topflap stops the growth of the buffer. The plough tilts backwards due to the sand that pushes to the underside of the topflap. The topflap has no stabilizing effect whatsoever on the roll motion of the plough. The topflap can however be of positive influence on the plough process. instead of growing a bigger buffer in front of the plough, the plough rises slightly above the sand bed. This prevents that new sand is being cut (Which only spills from the plough) The buffer is much smaller so friction is also smaller. Less energy is dissipated through the buffer.
No flow, back wire, middle front wire, topflaps, side flap Due to the fact that the topflap did not provide the necessary stability sought after, a search for a more stabilizing adaption commenced. Although I consider myself not very stable on skies, the train of thought could reason why a ski would have a positive effect on the stability of the plough. Installing a side ski would prevent the plough from rolling to far and could stabilize the plough once it was already under an angle. Here one starts with the plough from the previous experiment. This plough is proven to be unstable. Adding the side ski prevents the plough to roll to much. However, the plough is capable of rolling. The ski is, when the plough is horizontal, a centimeter above the sand bed. Commencing with the experiment, the plough initially starts to roll as predicted. Here, the side ski starts to touch the sand bed and prevent the plough to roll further as one can see in figure B.11. At this moment, the buffer does not touch the topflaps yet. While the side ski still touches the sand bed, the buffer starts to touch the underside of the topflaps. At this point the plough starts to stabilize while the side ski stops touching the sand bed. The plough now fills nicely even over the width of the plough. Since the plough in this case could only roll slightly, the port side could not rise above the sand bed. This principle prevented that the plough would stop filling on this side. The combination of the side ski and the topflap thus has a positive effect on the stability of the plough. Conclusion of this experiment is that the roll motion of the plough is allowed but only slightly. If the plough rolls to much than the topflaps can not stabilize the plough any further. The topflaps can counteract the roll motion and stabilize the plough once again.

stability experiments Before all experiments began the reason of thought was to copy the original plough as it is used in the Waal river. In the design of the model plough, the decision has been made to alter the plough lay-out. Where the plough was originally hanged on steel cables, the plough is hanged in a frame on the model setup. For the less fanatic reader, the frame was engineered in order to prevent a crooked cutting path, and depth. In the real situation, the plough is able to make a roll and pitch motion. This gives the plough more freedom to move. To examine the motions of the plough in the model set-up there have been a couple of adaptions to the plough. In these test, the attention is focused on the visual part of the experiments. How does the plough behave and what is the influence of minor adjustments. Here the focus is not on the buffer or the forces when ploughing. To mimic a more matching plough, the first adaption is to replace the frame with steel wires. So the vertical force is pulled by the wires. In these experiments, there have been several different versions for the vertical wires and in order to hang the plough. Also adaptions to the plough have been made to enhance stability. note that these tests are done without the steel spokes assembly or the vertical frame since the buffer build-up is of lesser importance in these tests.
Further, an overview of the different versions of the test plough is given:

**TWO FRONT WIRES**
In the front of the plough, two vertical wires are mounted which account for the vertical forces. These two wires stretch out to the original load cell above the water. In figure B.14 one can see this wire set up. Here, there is no back wire to lift the back of the sand bed so the back will lower during ploughing since the weight of the sand pushes on the back when filling, making the plough pitch. Allowing pitch motion gives a more variable cutting path. When the plough leans more on the back, the cutting blade will have a smaller cutting depth or no cutting depth at all. The reason for the experiment is to test whether this could work and whether this is a stable principle. In the beginning of the tests, an Unstable plough process occurred. The plough would roll due to cutting on one side, inducing a even bigger cutting height at that side while the other side would rise above the sand bed. Withholding a wire that holds up the back should prevent this from happening since this can act as an pivot point. In picture B.12 one can see the plough with the front wires.

![Figure B.12: front wire adaption.](image-url)
NO VERTICAL WIRES
In the tests with wires there have been several moments where the plough showed an unstable situation. While cutting on one side, the other side rose from the sand bed. This is an unwanted situation since this gives an undesirable cutting path. To test the instability of the plough several runs have been done where the plough is not hanged vertically. Since the suspect in inducing the unstable situation was the vertical suspension. Testing for instability with a 'no vertical' suspension can exclude or prove that the steel wires are at fault. Here the plough is pulled through the sand, cutting the sand in 260 cm. Since there is no fixed cutting depth, expected is that the plough firstly cuts deeper and deeper before rising again when the pull wires pull it upward when the plough is filled. Expected here is that the weight of the sand in the back pitches the plough upwards. A balance situation arises where the plough is slightly pitched backward where the cutting blade is not cutting anymore. Here the back of the plough shoves over the sand inducing friction. No further sand is being cut. In these tests, a visual inspection is done in order to determine a stable cutting situation.

There will be a few adjustments to the plough done in these 'no vertical' tests. Adjustments are designed for adding stability to the plough. In order to test the new stability, the plough must first be unstable. By adding a little weight on one side, an unstable ploughing process can be induced. Now the adjustments can be tested.

Figure B.13: no vertical suspension.

VERTICAL WIRES WITH TOPFLAPS
In the unstable situation, the top flap is once more installed. The function of the top flap firstly was to limit the height of the buffer and push it more backwards. In the 'no vertical' vertical situation the top flap can limit the cutting depth and can therefore stabilize the unstable cutting process. To be tested is if the topflaps stop the unstable situation, i.e. stop the roll motion but keep the plough under an angle or create a counteracting moment which stabilizes the plough again.
VERTICAL WIRES SIDE FLAP
Using the unstable plough with no vertical wires gives a rolling motion to the side where the plough is weighted. The added weight is a nut on the side flap of the plough. By adding a side flap to the same side on the plough, expected is that the rolling motion is stopped. Here, the side flap can be seen as a ski who slides on the sand bed, limiting the depth of the plough on this side. Expected is that the plough stabilizes using the side flap. The cutting depth is limited to such a degree that the non-weighted side will not rise above the sand bed. If this side can still cut sand, the plough is expected to stabilize again. In picture B.14 one can see the side flap which is installed at the left side of the plough.

Figure B.14: side flap

B.3 conclusions
Adding a top flap will limit the height of the buffer during ploughing. This top flap will also redirect the sand more to the back of the plough instead of upward. The top flap however will create the sand wedge early. The result of this sand wedge is that the buffer in front of the plough starts growing earlier on. Creating a large buffer in front of the plough. A side effect of the top flap is that the plough is being pushed upwards. This force can tilt the plough under an angle preventing new sand from being cut. This can be considered as an advantage since no new sand is fed to the buffer and the buffer will decrease in size. The top flap can also have a stabilizing effect on the plough process. If a plough tends to roll to one side, the top flap can counteract this roll moment. This counteracting force by the topflaps is only enough when the roll motion is small. If the plough rolls, the cutting blade on one side will go deeper while, on the other side, the cutting blade will rise above the soil surface. If the cutting blade is above the surface, the top flaps will have enough influence to counteract the roll motion and will only stop the roll motion but will not stabilize the plough. The adaption of the side ski will prevent the roll motion from exceeding this situation. In combination with the topflaps, the plough will become horizontal again.

M.P.J. Wildenberg
Appendix C

determination of shear angle $\beta$ in the cutting process

Using the method of Coulomb, one can derive the shear angle. Here the cutting force is at a minimum. Taking the derivative $\frac{\delta F}{\delta \beta}$, one can derive the minimal force at which the sand will shear. This is at a certain shear angle $\beta$. Somewhere between 20 and 30 degrees. Using the calculations done in part two and varying the shear angle $\beta$ one can derive the shear angle at which the forces are at a minimum. Here, the parameters are all equal to the parameters used in the calculations of the cutting forces, see chapter cutting forces. Varying the shear angle between 10 and 30 degrees gives the following graph.

Figure C.1: Varying Beta 15 - 30 degrees

If one takes a look at C.1 and takes a look at the lowest point of the vertical cutting forces. A $\beta$ of 20 degrees is found. For the horizontal cutting forces a lower value of $\beta$ is found. However, looking at both vertical and horizontal forces, the vertical force component is more dependant on the change in shear angle than the horizontal cutting forces are so a $\beta$ of 20 degrees is chosen for further calculations. In the determination of the shear angle there is no influence of the gravitation factor G. Due to the gravitation factor, the cutting forces will be higher of the plough is filled and the shear angle will increase. However, the shear angle used in further calculations will be constant. Below one can see a graph where the gravitation factor is higher. Here, a buffer is present.
Figure C.2: High Gravitation factor varying Beta 15 - 30 degrees
Here, one can see that the shear angle increases slightly when the buffer is present. The buffer induces higher cutting forces and therefore a different shear angle. Since the increase in $\beta$ is only small, it will be taken as a constant at 20 degrees. One can safely assume that the angle of $\beta$ does not change much and a change of a few degrees has only a small influence on the total cutting force.
Appendix D

cutting forces

Here one will find the step by step calculation for the current forces.

<table>
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<tr>
<th>Symbol</th>
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<th>quantity</th>
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<td>Gravity</td>
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<tr>
<td>$\rho_{sand}$</td>
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<tr>
<td>$\rho_{water}$</td>
<td>Density water</td>
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<td>$\frac{kg}{m^3}$</td>
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<td>$\frac{kg}{m^3}$</td>
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To start with the Gravitation factor, $G$. One needs to refer to equation 2.13

\[
G = (\rho_s - \rho_w) \cdot g \cdot h_i \cdot b \cdot \frac{\sin(\alpha + \beta)}{\sin \beta} \cdot \left(\frac{h_b + h_i \sin \alpha}{\sin \alpha} + \frac{h_i \cdot \cos(\alpha + \beta)}{2 \sin \beta}\right) \quad (D.1)
\]

Filling in yields the following equation:

\[
G = (2650 - 1000) \cdot 9.81 \cdot 0.006 \cdot 0.25 \cdot \frac{\sin(45 + 20)}{\sin 20} \cdot \left(\frac{0.014 + 0.006 \sin(45)}{\sin(45)} + \frac{0.006 \cdot \cos(45 + 20)}{2 \sin(20)}\right) \quad (D.2)
\]
Equation D.2 yield a gravitation force of $G = 1.69 \text{ N}$. Note that this is the gravitation factor of the sand in front of the blade. The sand above this blade, so above the 14 mm blade height is not accounted for. More on this will follow.

Next up is the Inertia factor $T$. Here we need to fill in a speed. A speed of $0.10 \text{ m/s}$ is used for this example, a graph will be used to give an overview of the inertia forces at different speeds. One needs to refer to equation 2.12:

$$T = \rho g \cdot v_c \cdot b \cdot \frac{\sin \alpha}{\sin(\alpha + \beta)}$$ \hspace{1cm} (D.3)

Filling in the inertia formula yields:

$$T = 1990 \cdot 0.1^2 \cdot 0.006 \cdot 0.25 \cdot \frac{\sin 45}{\sin(45 + 20)}$$ \hspace{1cm} (D.4)

For a speed of $0.1 \text{ m/s}$ the inertia force yields: $T = 0.023 \text{ N}$. At double the speed, this force is four times higher since the inertia is quadratic dependant on the speed. The graph of the inertia part on the cutting forces is given below.

As one can see in figure D.1 the force increases quadratic as the speed increases.

Now, the water pressure forces $W_1$ and $W_2$ can be calculated using the parameters provided. In equation 2.9 and 2.10 the following parts are replaced: $(a_1 k_i + a_2 k_{max})$ is replaced for $k_i$. This is due to the fact that the permeability of the sand in the sand bed is practically equal to the permeability in the sand pack that has been cut. The permeability $k_i$ has been calculated in 6.25. Equation 2.9 than becomes:

$$W_1 = \frac{P_{1m} \cdot \rho_w \cdot g \cdot V_c \cdot e \cdot h_i^2 \cdot b}{k_i \cdot \sin \beta}$$ \hspace{1cm} (D.5)
And 2.10 becomes:

\[ W_2 = \frac{P_{2m} \cdot \rho_w \cdot g \cdot V_c \cdot e \cdot h_i \cdot h_b \cdot b}{k_i \cdot \sin \alpha} \] (D.6)

Both equations can be filled in. Starting with the water pressure force component \( W_1 \), equation D.5 yields:

\[ W_1 = \frac{0.187 \cdot 1000 \cdot 9.81 \cdot 0.1 \cdot 0.003 \cdot 0.006^2 \cdot 0.25}{6.17 \cdot 10^{-4} \cdot \sin 20} \] (D.7)

Note that again the velocity of 0.1 m/s is used. For this velocity, the water pressure component yields:

\[ W_1 = 0.023 \text{ N} \]

When the speed increases, the water pressure force \( W_1 \) increases in quadratic magnitude. However, \( W_1 \) is quite low so will be of lesser influence on the total cutting force.

For \( W_2 \) in equation D.6 one can find, after filling in the parameters:

\[ W_2 = \frac{0.076 \cdot 1000 \cdot 9.81 \cdot 0.1 \cdot 0.003 \cdot 0.006 \cdot 0.014 \cdot 0.25}{6.17 \cdot 10^{-4} \cdot \sin 45} \] (D.8)

Here, \( W_2 = 0.0107 \text{ N} \). This force increases in equal magnitude to the velocity.

\( W_3 \) is easily calculated. At a blade angle of 45 the \( \cot \alpha \) equals one. Therefore:

\[ W_3 = 0.3 \cdot W_2 \]

\( W_3 \) is therefor 0.003 N .

With the water pressure forces known, the grain forces can be calculated. The equations for the grain forces \( K_{21} \) and \( K_{22} \) can be filled in using the water pressure forces and the friction angles \( \varphi \) and \( \delta \). Starting with \( K_{21} \), we refer to equation 2.5:

\[ K_{21} = \frac{W_2 \sin(\alpha + \beta + \varphi) + W_1 \sin \varphi}{\sin(\alpha + \beta + \varphi + \delta)} \] (D.9)

Filling in the parameters yields:

\[ K_{21} = \frac{0.0107 \sin(45 + 20 + 38) + 0.023 \sin(38)}{\sin(45 + 20 + 38 + 30)} \] (D.10)

This yields grain force \( K_{21} = 0.033 \text{ N} \). To continue with \( K_{22} \). The equation provided by Miedema is equation 2.6. This equation goes on a diet since we do not have to cope with cohesion, adhesion or current drag. With leaves us with this slimmed-down beauty:

\[ K_{22} = \frac{G \sin(\beta + \varphi) + T \cos \varphi}{\sin(\alpha + \beta + \varphi + \delta)} \] (D.11)

Filling in provides the one who still cares with this:

\[ K_{22} = \frac{1.69 \sin(20 + 38) + 0.023 \cos(38)}{\sin(45 + 20 + 30 + 30)} \] (D.12)

This yields, still for a speed of 0.1 m/s, \( K_{22} = 1.99 \text{ N} \). This gives \( K_2 \) a value of 2.02 N since \( K_2 = K_{21} + K_{22} \). Using these values, cutting forces can finally be calculated. Starting with the horizontal force at a speed of 0.1 m/s , one uses the known equation from 2.7 \( F_{ch} \) yields:

\[ F_{ch} = -W_2 \sin \alpha + K_2 \cos(\alpha + \delta) + W_3 \sin \alpha \] (D.13)

This gives:

\[ F_{ch} = -0.0107 \sin 45 + 1.64 \cos(45 + 30) + 0.23 \sin 45 \] (D.14)
This gives a horizontal cutting force of 0.52 N at the speed of 0.1 m/s. This force increases with the increase of the speed since the inertia component goes up. Furthermore, the vertical cutting forces can be calculated. Using equation 2.8 one can find $F_{cv}$:

$$ F_{cv} = -W_2 \cos \alpha + K_2 \sin(\alpha + \delta) + W_3 \cos \alpha \quad (D.15) $$

$$ F_{cv} = -0.0107 \cos 45 + 1.64 \sin(45 + 30) + 0.023 \cos 45 \quad (D.16) $$

This yields a vertical cutting force of: $F_{cv} = 1.95N$. 
Appendix E

basic plough
plough frame

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TU Delft
Industrial Design Engineering

Schaal: 1:2
Datum: 12-7-2016
Onderwerp: Standard plough without spokes
Gewicht: 1.4 kg
Gebrekend: M. Wildenberg

Benaming: basic plough

Formaat: A3
Tekeningnummer: 1
Appendix F

standard plough
Thesis - Filling process of a river plough
Standard plough with spokes

SOLIDWORKS Student Edition.
For Academic Use Only.
Appendix G

High Back plough
Thesis - Filling process of a river plough
High Back Plough

1.4 kg weight

High Back
Cutting blade
Grid ruler

250
40
123
14.1
210
100

maatverhouding: 1:2

12-7-2016

M. Wildenberg

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Appendix H

side flaps plough
Appendix I

Top flaps plough
Top flaps Plough

1.4 kg
Appendix J

Side ski plough
Cutting blade Grid rulerside ski

250
40
123
13.5
210
100
40

schaal
maateenheid
getekend groep
benaming
datum
opmerkingen
formaat tekeningnummer

1:2

side ski plough

12-7-2016 side ski plough

1.4 kg

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TU Delft
Industrial Design Engineering

A3

1
Thesis - Filling process of a river plough
Appendix K

Specifications Dorsilit 9 sand

**PRODUKTDATENBLATT**

**DORSILIT® Nr. 9**

hierher kommt ein Sackfoto

0.1 - 0.5 mm

DORSILIT® Kristallquarzsande und -kiese zeichnen sich durch einen SiO₂-Gehalt > 97 MA.-% sowie durch kantengerundete Kornform, helle, einheitliche Farbe, monokristalline Struktur, und Reinheit (frei von organischen Verunreinigungen) aus.

Durch Einsatz moderner Aufbereitungstechnologie und modernem Qualitäts- und Umweltmanagement wird eine hohe gleichbleibende Qualität bei bestmöglicher Rücksichtnahme auf unsere Umwelt gewährleistet.

**Einsatzbereich**
- Böden / Estriche hydraulisch gebunden
- Böden / Estriche kunstharz gebunden
- Polymerbeton / Verbundwerkstoffe
- Kalksandstein, Beton
- Dachziegel, Dachbahnen
- Baustoffhandel, Innen- und Außenputze
- Bauchemie, Trockenmörtel, Faserzement

**Lieferform**
lose im Silo-LKW, im BigBag (1250 kg), im PE- oder Papiersack (25 kg)

**Produktdaten**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Wert</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feuchtigkeit</td>
<td>&lt; 0,1 %</td>
</tr>
<tr>
<td>Kornform</td>
<td>Rundkorn</td>
</tr>
<tr>
<td>Kornrohdichte</td>
<td>ca. 2,65 g/cm³</td>
</tr>
<tr>
<td>Schüttichte</td>
<td>ca. 1,4-1,5 g/ml</td>
</tr>
<tr>
<td>SiO₂ (MA.-%)</td>
<td>ca. 97,9</td>
</tr>
<tr>
<td>Fe₂O₃ (MA.-%)</td>
<td>ca. 0,02</td>
</tr>
<tr>
<td>Al₂O₃ (MA.-%)</td>
<td>ca. 0,47</td>
</tr>
<tr>
<td>TiO₂ (MA.-%)</td>
<td>ca. 0,03</td>
</tr>
</tbody>
</table>

**Kornverteilung**

<table>
<thead>
<tr>
<th>Siebdurchgang in Gew.%</th>
<th>0</th>
<th>0,1</th>
<th>0,2</th>
<th>0,3</th>
<th>0,4</th>
<th>0,5</th>
<th>0,8</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maschenweite in mm</td>
<td>0</td>
<td>0,1</td>
<td>0,2</td>
<td>0,3</td>
<td>0,4</td>
<td>0,5</td>
<td>0,8</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>
Thesis - Filling process of a river plough
Appendix L

Pump

Submersible electric pumps for foul waste water in AISI 304 stainless steel.

APPLICATIONS
- Moving foul waste liquids containing solid substances and/or suspended filamentary substances
- Emptying seepage water
- Moving foul waste waters (sanitary services)
- Emptying cesspools and draining into sewers

TECHNICAL DETAILS
- Equipped with 5 m of H07 RN-F power supply cable
  (on request: 10 m of H07 RN-F cable)
- Available with or without float

TECHNICAL DATA
- Maximum immersion: 10 m
- Maximum temperature of the liquid: 50°C
- Max. solids size for passage: 35 mm
- Self-ventilated 2 pole asynchronous motor
- Class of insulation F
- IPX6 Protection rating
- 230V ± 10%, 50Hz single phase voltage
- 400V ± 10%, 50Hz three phase voltage
- Permanent capacitor inserted and thermo-ampereometric protection with automatic rearm incorporated for the single phase motor
- Protection under user’s responsibility for the three phase version
- Discharge connection: G1½

MATERIALS
- Body, impeller, motor cover, seal housing disc and motor case in AISI 304
- Shaft in AISI 303
- Twin mechanical seal with oil chamber:
  - upper in Carbon/Ceramic/HBN (motor side)
  - lower in SiC/SiC/AlN (pump side)

SPECIAL VERSIONS
- MA version with float
- Version with 10 m of cable

For accessories and control panels see from page 56.
Appendix M

Lists of experiments with videos

M.1 basic experiments

In this section one will find all basic experiments with the name of the Excel file and the according video file. The basic plough with no spokes is used. Here, the water depth is always 20 cm except for the last two rows of experiments.

<table>
<thead>
<tr>
<th>Experiments dry</th>
<th>excell file</th>
<th>video file</th>
</tr>
</thead>
<tbody>
<tr>
<td>04_nowater_45</td>
<td>0.4-short-45-nowater</td>
<td></td>
</tr>
<tr>
<td>05_nowater_45</td>
<td>0.5-short-45-nowater</td>
<td></td>
</tr>
<tr>
<td>06_nowater_45</td>
<td>0.6-short-45-nowater</td>
<td></td>
</tr>
<tr>
<td>07_nowater_45</td>
<td>0.7-short-45-nowater</td>
<td></td>
</tr>
<tr>
<td>08_nowater_45</td>
<td>0.8-short-45-nowater</td>
<td></td>
</tr>
<tr>
<td>09_nowater_45</td>
<td>0.9-short-45-nowater</td>
<td></td>
</tr>
<tr>
<td>10_nowater_45</td>
<td>1.0-short-45-nowater</td>
<td></td>
</tr>
<tr>
<td>11_nowater_45</td>
<td>1.1-short-45-nowater</td>
<td></td>
</tr>
</tbody>
</table>

Experiments with water, no flow

<table>
<thead>
<tr>
<th>Experiments no flow (batch 2)</th>
<th>excell file</th>
<th>video file</th>
</tr>
</thead>
<tbody>
<tr>
<td>04_noflow_45</td>
<td>0.4-noflo-water</td>
<td></td>
</tr>
<tr>
<td>05_noflow_45</td>
<td>0.5-noflo-water</td>
<td></td>
</tr>
<tr>
<td>06_noflow_45</td>
<td>0.6-noflo-water</td>
<td></td>
</tr>
<tr>
<td>07_noflow_45</td>
<td>0.7-noflo-water-verkeerd (video failed)</td>
<td></td>
</tr>
<tr>
<td>08_noflow_45</td>
<td>0.8-noflo-water</td>
<td></td>
</tr>
<tr>
<td>09_noflow_45</td>
<td>0.9-noflo-water</td>
<td></td>
</tr>
<tr>
<td>10_noflow_45</td>
<td>1.0-noflo-water</td>
<td></td>
</tr>
<tr>
<td>11_noflow_45</td>
<td>1.1-noflo-water</td>
<td></td>
</tr>
<tr>
<td>12_noflow_45</td>
<td>1.2-noflo-water</td>
<td></td>
</tr>
<tr>
<td>13_noflow_45</td>
<td>1.3-noflo-water</td>
<td></td>
</tr>
<tr>
<td>15_noflow_45</td>
<td>1.5-noflo-water</td>
<td></td>
</tr>
<tr>
<td>18_noflow_45</td>
<td>1.8-noflo-water</td>
<td></td>
</tr>
<tr>
<td>20_noflow_45</td>
<td>2.0-noflo-water</td>
<td></td>
</tr>
</tbody>
</table>
Experiments with 20cm water, against current, 1 $\frac{cm}{s}$ current

<table>
<thead>
<tr>
<th>Experiments against flow 1 $\frac{cm}{s}$ current</th>
</tr>
</thead>
<tbody>
<tr>
<td>excell file</td>
</tr>
<tr>
<td>08_flow1cms_45</td>
</tr>
<tr>
<td>09_flow1cms_45</td>
</tr>
<tr>
<td>10_flow1cms_45</td>
</tr>
<tr>
<td>11_flow1cms_45</td>
</tr>
<tr>
<td>12_flow1cms_45</td>
</tr>
<tr>
<td>13_flow1cms_45</td>
</tr>
<tr>
<td>15_flow1cms_45</td>
</tr>
<tr>
<td>18_flow1cms_45</td>
</tr>
<tr>
<td>20_flow1cms_45</td>
</tr>
</tbody>
</table>

Experiments with 20cm water, against current, 2.5 $\frac{cm}{s}$ current (50%)

Table M.3: Experiments against flow 2.5 $\frac{cm}{s}$ current

<table>
<thead>
<tr>
<th>Experiments against flow 2.5 $\frac{cm}{s}$ current</th>
</tr>
</thead>
<tbody>
<tr>
<td>excell file</td>
</tr>
<tr>
<td>05_aflow50p_45</td>
</tr>
<tr>
<td>08_aflow50p_45</td>
</tr>
<tr>
<td>09_aflow50p_45</td>
</tr>
<tr>
<td>10_aflow50p_45</td>
</tr>
<tr>
<td>11_aflow50p_45</td>
</tr>
<tr>
<td>12_aflow50p_45</td>
</tr>
<tr>
<td>13_aflow50p_45</td>
</tr>
<tr>
<td>15_aflow50p_45</td>
</tr>
<tr>
<td>18_aflow50p_45</td>
</tr>
<tr>
<td>20_aflow50p_45</td>
</tr>
</tbody>
</table>

Experiments with 20cm water, against current, 5 $\frac{cm}{s}$ current (100%)

Table M.4: Experiments against current, 5 $\frac{cm}{s}$ current (100%)

<table>
<thead>
<tr>
<th>Experiments against current, 5 $\frac{cm}{s}$ current</th>
</tr>
</thead>
<tbody>
<tr>
<td>excell file</td>
</tr>
<tr>
<td>08_aflow100p_45</td>
</tr>
<tr>
<td>09_aflow100p_45</td>
</tr>
<tr>
<td>10_aflow100p_45</td>
</tr>
<tr>
<td>11_aflow100p_45</td>
</tr>
<tr>
<td>12_aflow100p_45</td>
</tr>
<tr>
<td>13_aflow100p_45</td>
</tr>
<tr>
<td>15_aflow100p_45</td>
</tr>
<tr>
<td>18_aflow100p_45</td>
</tr>
<tr>
<td>20_aflow100p_45</td>
</tr>
</tbody>
</table>

Experiments with flow, 5 $\frac{cm}{s}$ current (100%)

M.P.J. Wildenberg

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Table M.5: Experiments with current, $\frac{cm}{s}$ current (100%)

<table>
<thead>
<tr>
<th>Experiments with flow</th>
<th>excell file</th>
<th>video file</th>
</tr>
</thead>
<tbody>
<tr>
<td>05_flow100p_45</td>
<td>0.5-withflow-100%</td>
<td></td>
</tr>
<tr>
<td>08_flow100p_45</td>
<td>0.8-withflow-100%</td>
<td></td>
</tr>
<tr>
<td>09_flow100p_45</td>
<td>0.9-withflow-100%</td>
<td></td>
</tr>
<tr>
<td>10_flow100p_45</td>
<td>1.0-withflow-100%</td>
<td></td>
</tr>
<tr>
<td>11_flow100p_45</td>
<td>1.1-withflow-100%</td>
<td></td>
</tr>
<tr>
<td>12_flow100p_45</td>
<td>1.2-withflow-100%</td>
<td></td>
</tr>
<tr>
<td>13_flow100p_45</td>
<td>1.3-withflow-100%</td>
<td></td>
</tr>
<tr>
<td>15_flow100p_45</td>
<td>1.5-withflow-100%</td>
<td></td>
</tr>
<tr>
<td>18_flow100p_45</td>
<td>1.8-withflow-100%</td>
<td></td>
</tr>
<tr>
<td>20_flow100p_45</td>
<td>2.0-withflow-100%</td>
<td></td>
</tr>
</tbody>
</table>

Experiments with flow, $2.5 \frac{cm}{s}$ current (50%)

Table M.6: Experiments with current, $\frac{cm}{s}$ current (50%)

<table>
<thead>
<tr>
<th>Experiments with flow</th>
<th>excell file</th>
<th>video file</th>
</tr>
</thead>
<tbody>
<tr>
<td>05_flow50p_45</td>
<td>0.8-withflow-50%</td>
<td></td>
</tr>
<tr>
<td>08_flow50p_45</td>
<td>0.9-withflow-50%</td>
<td></td>
</tr>
<tr>
<td>09_flow50p_45</td>
<td>0.8-withflow-50%</td>
<td></td>
</tr>
<tr>
<td>10_flow50p_45</td>
<td>1.0-withflow-50%</td>
<td></td>
</tr>
<tr>
<td>11_flow50p_45</td>
<td>1.1-withflow-50%</td>
<td></td>
</tr>
<tr>
<td>12_flow50p_45</td>
<td>1.2-withflow-50%</td>
<td></td>
</tr>
<tr>
<td>13_flow50p_45</td>
<td>1.3-withflow-50%</td>
<td></td>
</tr>
<tr>
<td>15_flow50p_45</td>
<td>1.5-withflow-50%</td>
<td></td>
</tr>
<tr>
<td>18_flow50p_45</td>
<td>1.8-withflow-50%</td>
<td></td>
</tr>
<tr>
<td>20_flow50p_45</td>
<td>2.0-withflow-50%</td>
<td></td>
</tr>
</tbody>
</table>

Now the two rows of experiments where the water depth is lowered to 10 cm water.

Experiments with flow, 10 cm water depth, $\frac{cm}{s}$ current (100%)

Table M.7: Experiments with current, 10 cm water $\frac{cm}{s}$ current (100%)

<table>
<thead>
<tr>
<th>Experiments with flow, 10 cm depth</th>
<th>excell file</th>
<th>video file</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8-with-100%-10cm</td>
<td>0.8-withflow-100%-10cm</td>
<td></td>
</tr>
<tr>
<td>0.9-with-100%-10cm</td>
<td>0.9-withflow-100%-10cm</td>
<td></td>
</tr>
<tr>
<td>1.0-with-100%-10cm</td>
<td>1.0-withflow-100%-10cm</td>
<td></td>
</tr>
<tr>
<td>1.1-with-100%-10cm</td>
<td>1.1-withflow-100%-10cm</td>
<td></td>
</tr>
<tr>
<td>1.2-with-100%-10cm</td>
<td>1.2-withflow-100%-10cm</td>
<td></td>
</tr>
<tr>
<td>1.3-with-100%-10cm</td>
<td>1.3-withflow-100%-10cm</td>
<td></td>
</tr>
<tr>
<td>1.5-with-100%-10cm</td>
<td>1.5-withflow-100%-10cm</td>
<td></td>
</tr>
<tr>
<td>1.8-with-100%-10cm</td>
<td>1.8-withflow-100%-10cm</td>
<td></td>
</tr>
<tr>
<td>2.0-with-100%-10cm</td>
<td>2.0-withflow-100%-10cm</td>
<td></td>
</tr>
</tbody>
</table>

Experiments against flow, 10 cm water depth, $\frac{cm}{s}$ current (100%)
Table M.8: Experiments against current, 10 cm water depth 5 \( \frac{cm}{s} \) current (100%)

<table>
<thead>
<tr>
<th>Experiments against flow, 10 cm depth 5 ( \frac{cm}{s} ) current</th>
<th>video file</th>
</tr>
</thead>
<tbody>
<tr>
<td>excell file 0.8-with-100%-10cm-against</td>
<td>video failed</td>
</tr>
<tr>
<td>0.9-100%-10cm-against</td>
<td>video failed</td>
</tr>
<tr>
<td>1.0-100%-10cm-against</td>
<td>1.0-against-100%-10cm</td>
</tr>
<tr>
<td>1.1-100%-10cm-against</td>
<td>1.1-against-100%-10cm</td>
</tr>
<tr>
<td>1.2-100%-10cm-against</td>
<td>1.2-against-100%-10cm</td>
</tr>
<tr>
<td>1.3-100%-10cm-against</td>
<td>1.3-against-100%-10cm</td>
</tr>
<tr>
<td>1.5-100%-10cm-against</td>
<td>1.5-against-100%-10cm</td>
</tr>
<tr>
<td>1.8-100%-10cm-against</td>
<td>1.8-against-100%-10cm</td>
</tr>
<tr>
<td>2.0-100%-10cm-against</td>
<td>2.0-against-100%-10cm</td>
</tr>
</tbody>
</table>

These are all basic experiments, from here the main experiments start

**M.2 main experiments**

From here the basic plough is adjusted. It is fitted with spokes. Plough is called adjusted plough. Water depth is 10 cm. The water current is 5 \( \frac{cm}{s} \) unless it is stated otherwise. Here, also photo’s have been taken from the spillage at the end of the plough track. First all the against current experiments are given.

Experiments against flow, 10 cm water depth, 5 \( \frac{cm}{s} \) current (100%), High back plough

Table M.9: Experiments against current, 10 cm water depth 5 \( \frac{cm}{s} \) current (100%). High back plough

<table>
<thead>
<tr>
<th>Experiments against flow, 10 cm depth 5 ( \frac{cm}{s} ) current</th>
<th>video file</th>
</tr>
</thead>
<tbody>
<tr>
<td>excell file 0.8-againstflow-100%-10cm-high back</td>
<td>0.8-againstflow-100%-10cm-high back</td>
</tr>
<tr>
<td>0.9-againstflow-100%-10cm-high back</td>
<td>0.9-againstflow-100%-10cm-high back</td>
</tr>
<tr>
<td>1.0-againstflow-100%-10cm-high back</td>
<td>1.0-againstflow-100%-10cm-high back</td>
</tr>
<tr>
<td>1.1-againstflow-100%-10cm-high back</td>
<td>1.1-againstflow-100%-10cm-high back</td>
</tr>
<tr>
<td>1.2-againstflow-100%-10cm-high back</td>
<td>1.2-againstflow-100%-10cm-high back</td>
</tr>
<tr>
<td>1.3-againstflow-100%-10cm-high back</td>
<td>1.3-againstflow-100%-10cm-high back</td>
</tr>
<tr>
<td>1.5-againstflow-100%-10cm-high back</td>
<td>1.5-againstflow-100%-10cm-high back</td>
</tr>
<tr>
<td>1.8-againstflow-100%-10cm-high back</td>
<td>1.8-againstflow-100%-10cm-high back</td>
</tr>
<tr>
<td>2.0-againstflow-100%-10cm-high back</td>
<td>2.0-againstflow-100%-10cm-high back</td>
</tr>
</tbody>
</table>

Experiments against flow, 10 cm water depth, 5 \( \frac{cm}{s} \) current (100%), High back plough, 8 mm cutting depth.
Table M.10: Experiments against current, 10 cm water 5 cm/s current (100%). High back plough, 8 mm cutting depth

<table>
<thead>
<tr>
<th>Experiments against flow, 10 cm depth 5 cm/s current, 8mm cutting depth</th>
<th>excell file</th>
<th>video file</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8-againstflow-100%-10cm-high back-8mmcuttingdepth</td>
<td>0.8-againstflow-100%-10cm-high back-8mmdeep</td>
<td></td>
</tr>
<tr>
<td>0.9-againstflow-100%-10cm-high back</td>
<td>0.9-againstflow-100%-10cm-high back-8mmdeep</td>
<td></td>
</tr>
<tr>
<td>1.0-againstflow-100%-10cm-high back-8mmcuttingdepth</td>
<td>1.0-againstflow-100%-10cm-high back-8mmdeep</td>
<td></td>
</tr>
<tr>
<td>1.1-againstflow-100%-10cm-high back-8mmcuttingdepth</td>
<td>1.1-againstflow-100%-10cm-high back-8mmdeep</td>
<td></td>
</tr>
<tr>
<td>1.2-againstflow-100%-10cm-high back-8mmcuttingdepth</td>
<td>1.2-againstflow-100%-10cm-high back-8mmdeep</td>
<td></td>
</tr>
<tr>
<td>1.3-againstflow-100%-10cm-high back-8mmcuttingdepth</td>
<td>1.3-againstflow-100%-10cm-high back-8mmdeep</td>
<td></td>
</tr>
<tr>
<td>1.5-againstflow-100%-10cm-high back-8mmcuttingdepth</td>
<td>1.5-againstflow-100%-10cm-high back-8mmdeep</td>
<td></td>
</tr>
<tr>
<td>1.8-againstflow-100%-10cm-high back-8mmcuttingdepth</td>
<td>1.8-againstflow-100%-10cm-high back-8mmdeep</td>
<td></td>
</tr>
<tr>
<td>2.0-againstflow-100%-10cm-high back-8mmcuttingdepth</td>
<td>2.0-againstflow-100%-10cm-high back-8mmdeep</td>
<td></td>
</tr>
</tbody>
</table>

Experiments against flow, 10 cm water depth, 9 cm/s current (200%), High back plough.

Table M.11: Experiments against current, 10 cm water 9 cm/s current (200%). High back plough

<table>
<thead>
<tr>
<th>Experiments against flow, 10 cm depth 9 cm/s current</th>
<th>excell file</th>
<th>video file</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8-200%-10cm-against-adaptedplough</td>
<td>0.8-200%-10cm-against-adaptedplough</td>
<td></td>
</tr>
<tr>
<td>0.9-200%-10cm-against-adaptedplough</td>
<td>0.9-200%-10cm-against-adaptedplough</td>
<td></td>
</tr>
<tr>
<td>1.0-200%-10cm-against-adaptedplough</td>
<td>1.0-200%-10cm-against-adaptedplough</td>
<td></td>
</tr>
<tr>
<td>1.1-200%-10cm-against-adaptedplough</td>
<td>1.1-200%-10cm-against-adaptedplough</td>
<td></td>
</tr>
<tr>
<td>1.2-200%-10cm-against-adaptedplough</td>
<td>1.2-200%-10cm-against-adaptedplough</td>
<td></td>
</tr>
<tr>
<td>1.3-200%-10cm-against-adaptedplough</td>
<td>1.3-200%-10cm-against-adaptedplough</td>
<td></td>
</tr>
<tr>
<td>1.5-200%-10cm-against-adaptedplough</td>
<td>1.5-200%-10cm-against-adaptedplough</td>
<td></td>
</tr>
<tr>
<td>1.8-200%-10cm-against-adaptedplough</td>
<td>1.8-200%-10cm-against-adaptedplough</td>
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</tr>
<tr>
<td>2.0-200%-10cm-against-adaptedplough</td>
<td>2.0-200%-10cm-against-adaptedplough</td>
<td></td>
</tr>
</tbody>
</table>

Experiments against flow, 10 cm water depth, 9 cm/s current (100%), High back plough, front flaps/side flaps installed

Table M.12: Experiments against current, 10 cm water 9 cm/s current (100%). High back plough, front flaps

<table>
<thead>
<tr>
<th>Experiments against flow, 10 cm depth 5 cm/s current, front flaps, high back</th>
<th>excell file</th>
<th>video file</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8-100%-10cm-against-adapted-frontflaps</td>
<td>0.8-100%-10cm-against-adapted-frontflaps</td>
<td></td>
</tr>
<tr>
<td>0.9-100%-10cm-against-adapted-frontflaps</td>
<td>0.9-100%-10cm-against-adapted-frontflaps</td>
<td></td>
</tr>
<tr>
<td>1.0-100%-10cm-against-adapted-frontflaps</td>
<td>1.0-100%-10cm-against-adapted-frontflaps</td>
<td></td>
</tr>
<tr>
<td>1.1-100%-10cm-against-adapted-frontflaps</td>
<td>1.1-100%-10cm-against-adapted-frontflaps</td>
<td></td>
</tr>
<tr>
<td>1.2-100%-10cm-against-adapted-frontflaps</td>
<td>1.2-100%-10cm-against-adapted-frontflaps</td>
<td></td>
</tr>
<tr>
<td>1.3-100%-10cm-against-adapted-frontflaps</td>
<td>1.3-100%-10cm-against-adapted-frontflaps</td>
<td></td>
</tr>
<tr>
<td>1.5-100%-10cm-against-adapted-frontflaps</td>
<td>1.5-100%-10cm-against-adapted-frontflaps</td>
<td></td>
</tr>
<tr>
<td>1.8-100%-10cm-against-adapted-frontflaps</td>
<td>1.8-100%-10cm-against-adapted-frontflaps</td>
<td></td>
</tr>
<tr>
<td>2.0-100%-10cm-against-adapted-frontflaps</td>
<td>2.0-100%-10cm-against-adapted-frontflaps</td>
<td></td>
</tr>
</tbody>
</table>

Experiments against flow, 10 cm water depth, 5 cm/s current (100%), High back plough, 30 degree angle cutting blade (6 mm cutting depth)
Thesis - Filling process of a river plough

Table M.13: Experiments against current, 10 cm water 5 \( \text{cm/s} \) current (100%). High back plough, 30\textdegree\ cutting blade

<table>
<thead>
<tr>
<th>Experiments against flow, 10 cm depth 5 ( \text{cm/s} ) current, 30 degree cutting blade, high back</th>
<th>M.P.J. Wildenberg 171</th>
</tr>
</thead>
<tbody>
<tr>
<td>excell file</td>
<td>video file</td>
</tr>
<tr>
<td>0.8-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}30</td>
<td>0.8-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}30</td>
</tr>
<tr>
<td>0.9-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}30</td>
<td>0.9-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}30</td>
</tr>
<tr>
<td>1.0-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}30</td>
<td>1.0-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}30</td>
</tr>
<tr>
<td>1.1-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}30</td>
<td>1.1-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}30</td>
</tr>
<tr>
<td>1.2-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}30</td>
<td>1.2-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}30</td>
</tr>
<tr>
<td>1.3-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}30</td>
<td>1.3-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}30</td>
</tr>
<tr>
<td>1.5-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}30</td>
<td>1.5-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}30</td>
</tr>
<tr>
<td>1.8-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}30</td>
<td>1.8-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}30</td>
</tr>
<tr>
<td>2.0-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}30</td>
<td>2.0-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}30</td>
</tr>
</tbody>
</table>

Experiments against flow, 10 cm water depth, 5 \( \text{cm/s} \) current (100%), High back plough, front flaps with a partly filled plough

Table M.14: Experiments against current, 10 cm water 5 \( \text{cm/s} \) current (100%). High back plough, front flaps, filled

<table>
<thead>
<tr>
<th>Experiments against flow, 10 cm depth 5 ( \text{cm/s} ) current, filled, front flaps, high back</th>
<th>M.P.J. Wildenberg 171</th>
</tr>
</thead>
<tbody>
<tr>
<td>excell file</td>
<td>video file</td>
</tr>
<tr>
<td>0.8-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}filled</td>
<td>0.8-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}filled</td>
</tr>
<tr>
<td>0.9-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}filled</td>
<td>0.9-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}filled</td>
</tr>
<tr>
<td>1.0-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}filled</td>
<td>1.0-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}filled</td>
</tr>
<tr>
<td>1.1-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}filled</td>
<td>1.1-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}filled</td>
</tr>
<tr>
<td>1.2-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}filled</td>
<td>1.2-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}filled</td>
</tr>
<tr>
<td>1.3-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}filled</td>
<td>1.3-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}filled</td>
</tr>
<tr>
<td>1.5-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}filled</td>
<td>1.5-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}filled</td>
</tr>
<tr>
<td>1.8-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}filled</td>
<td>1.8-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}filled</td>
</tr>
<tr>
<td>2.0-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}filled</td>
<td>2.0-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}filled</td>
</tr>
</tbody>
</table>

Experiments against flow, 10 cm water depth, 5 \( \text{cm/s} \) current (100%), High back plough, front flaps with a partly filled plough

Table M.15: Experiments against current, 10 cm water 5 \( \text{cm/s} \) current (100%). High back plough, front flaps, filled

<table>
<thead>
<tr>
<th>Experiments against flow, 10 cm depth 5 ( \text{cm/s} ) current, filled, front flaps, high back</th>
<th>M.P.J. Wildenberg 171</th>
</tr>
</thead>
<tbody>
<tr>
<td>excell file</td>
<td>video file</td>
</tr>
<tr>
<td>0.8-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}filled</td>
<td>0.8-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}filled</td>
</tr>
<tr>
<td>0.9-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}filled</td>
<td>0.9-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}filled</td>
</tr>
<tr>
<td>1.0-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}filled</td>
<td>1.0-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}filled</td>
</tr>
<tr>
<td>1.1-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}filled</td>
<td>1.1-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}filled</td>
</tr>
<tr>
<td>1.2-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}filled</td>
<td>1.2-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}filled</td>
</tr>
<tr>
<td>1.3-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}filled</td>
<td>1.3-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}filled</td>
</tr>
<tr>
<td>1.5-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}filled</td>
<td>1.5-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}filled</td>
</tr>
<tr>
<td>1.8-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}filled</td>
<td>1.8-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}filled</td>
</tr>
<tr>
<td>2.0-100%\text{-}10\text{cm}-against-adapted-frontflaps\text{-}filled</td>
<td>2.0-100%\text{-}10\text{cm}-against-adapted-highack-frontflaps\text{-}filled</td>
</tr>
</tbody>
</table>

Now the experiments in the with current situation:
Experiments with flow, 10 cm water depth, 5 \( \text{cm/s} \) current (100%), High back plough
Table M.16: Experiments with current, 10 cm water depth, 5 m/s current (100%). High back plough

<table>
<thead>
<tr>
<th>Excel file</th>
<th>Video file</th>
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</thead>
<tbody>
<tr>
<td>0.8-withflow-100%-10cm-high back</td>
<td>0.8-withflow-100%-10cm-high back</td>
</tr>
<tr>
<td>0.9-withflow-100%-10cm-high back</td>
<td>0.9-withflow-100%-10cm-high back</td>
</tr>
<tr>
<td>1.0-withflow-100%-10cm-high back</td>
<td>1.0-withflow-100%-10cm-high back</td>
</tr>
<tr>
<td>1.1-withflow-100%-10cm-high back</td>
<td>1.1-withflow-100%-10cm-high back</td>
</tr>
<tr>
<td>1.2-withflow-100%-10cm-high back</td>
<td>1.2-withflow-100%-10cm-high back</td>
</tr>
<tr>
<td>1.3-withflow-100%-10cm-high back</td>
<td>1.3-withflow-100%-10cm-high back</td>
</tr>
<tr>
<td>1.5-withflow-100%-10cm-high back</td>
<td>1.5-withflow-100%-10cm-high back</td>
</tr>
<tr>
<td>1.8-withflow-100%-10cm-high back</td>
<td>1.8-withflow-100%-10cm-high back</td>
</tr>
<tr>
<td>2.0-withflow-100%-10cm-high back</td>
<td>2.0-withflow-100%-10cm-high back</td>
</tr>
</tbody>
</table>

Experiments with flow, 10 cm water depth, 5 m/s current (100%), High back plough, 8 mm cutting depth.

Table M.17: Experiments with current, 10 cm water depth, 5 m/s current (100%). High back plough, 8 mm cutting depth

<table>
<thead>
<tr>
<th>Excel file</th>
<th>Video file</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8-withflow-100%-10cm-high back-8mmcuttingdepth</td>
<td>0.8-withflow-100%-10cm-high back-8mmcuttingdepth</td>
</tr>
<tr>
<td>0.9-withflow-100%-10cm-high back-8mmcuttingdepth</td>
<td>0.9-withflow-100%-10cm-high back-8mmcuttingdepth</td>
</tr>
<tr>
<td>1.0-withflow-100%-10cm-high back-8mmcuttingdepth</td>
<td>1.0-withflow-100%-10cm-high back-8mmcuttingdepth</td>
</tr>
<tr>
<td>1.1-withflow-100%-10cm-high back-8mmcuttingdepth</td>
<td>1.1-withflow-100%-10cm-high back-8mmcuttingdepth</td>
</tr>
<tr>
<td>1.2-withflow-100%-10cm-high back-8mmcuttingdepth</td>
<td>1.2-withflow-100%-10cm-high back-8mmcuttingdepth</td>
</tr>
<tr>
<td>1.3-withflow-100%-10cm-high back-8mmcuttingdepth</td>
<td>1.3-withflow-100%-10cm-high back-8mmcuttingdepth</td>
</tr>
<tr>
<td>1.5-withflow-100%-10cm-high back-8mmcuttingdepth</td>
<td>1.5-withflow-100%-10cm-high back-8mmcuttingdepth</td>
</tr>
<tr>
<td>1.8-withflow-100%-10cm-high back-8mmcuttingdepth</td>
<td>1.8-withflow-100%-10cm-high back-8mmcuttingdepth</td>
</tr>
<tr>
<td>2.0-withflow-100%-10cm-high back-8mmcuttingdepth</td>
<td>2.0-withflow-100%-10cm-high back-8mmcuttingdepth</td>
</tr>
</tbody>
</table>

Experiments with flow, 10 cm water depth, 200% current (200%), High back plough.

Table M.18: Experiments with current, 10 cm water depth, 200% current (200%). High back plough

<table>
<thead>
<tr>
<th>Excel file</th>
<th>Video file</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8-200%-10cm-with-adaptedplough</td>
<td>0.8-200%-10cm-with-adaptedplough</td>
</tr>
<tr>
<td>0.9-200%-10cm-with-adaptedplough</td>
<td>0.9-200%-10cm-with-adaptedplough</td>
</tr>
<tr>
<td>1.0-200%-10cm-with-adaptedplough</td>
<td>1.0-200%-10cm-with-adaptedplough</td>
</tr>
<tr>
<td>1.1-200%-10cm-with-adaptedplough</td>
<td>1.1-200%-10cm-with-adaptedplough</td>
</tr>
<tr>
<td>1.2-200%-10cm-with-adaptedplough</td>
<td>1.2-200%-10cm-with-adaptedplough</td>
</tr>
<tr>
<td>1.3-200%-10cm-with-adaptedplough</td>
<td>1.3-200%-10cm-with-adaptedplough</td>
</tr>
<tr>
<td>1.5-200%-10cm-with-adaptedplough</td>
<td>1.5-200%-10cm-with-adaptedplough</td>
</tr>
<tr>
<td>1.8-200%-10cm-with-adaptedplough</td>
<td>1.8-200%-10cm-with-adaptedplough</td>
</tr>
<tr>
<td>2.0-200%-10cm-with-adaptedplough</td>
<td>2.0-200%-10cm-with-adaptedplough</td>
</tr>
</tbody>
</table>

Experiments with flow, 10 cm water depth, 9 m/s current (100%), High back plough, front flaps/side flaps installed.
Table M.19: Experiments with current, 10 cm water depth, 9 cm current (100%). High back plough, front flaps

<table>
<thead>
<tr>
<th>Experiments with flow, 10 cm depth 5 cm/s current, front flaps, high back</th>
<th>excell file</th>
<th>video file</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8-100%-10cm-with-adapted-frontflaps</td>
<td>0.8-100%-10cm-with-adapted-frontflaps</td>
<td></td>
</tr>
<tr>
<td>0.9-100%-10cm-with-adapted-frontflaps</td>
<td>0.9-100%-10cm-with-adapted-frontflaps</td>
<td></td>
</tr>
<tr>
<td>1.0-100%-10cm-with-adapted-frontflaps</td>
<td>1.0-100%-10cm-with-adapted-frontflaps</td>
<td></td>
</tr>
<tr>
<td>1.1-100%-10cm-with-adapted-frontflaps</td>
<td>1.1-100%-10cm-with-adapted-frontflaps</td>
<td></td>
</tr>
<tr>
<td>1.2-100%-10cm-with-adapted-frontflaps</td>
<td>1.2-100%-10cm-with-adapted-frontflaps</td>
<td></td>
</tr>
<tr>
<td>1.3-100%-10cm-with-adapted-frontflaps</td>
<td>1.3-100%-10cm-with-adapted-frontflaps</td>
<td></td>
</tr>
<tr>
<td>1.5-100%-10cm-with-adapted-frontflaps</td>
<td>1.5-100%-10cm-with-adapted-frontflaps</td>
<td></td>
</tr>
<tr>
<td>1.8-100%-10cm-against-adapted-frontflaps</td>
<td>1.8-100%-10cm-with-adapted-frontflaps</td>
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</tr>
<tr>
<td>2.0-100%-10cm-with-adapted-frontflaps</td>
<td>2.0-100%-10cm-with-adapted-frontflaps</td>
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</tr>
</tbody>
</table>

Experiments with flow, 10 cm water depth, 5 cm/s current (100%), High back plough, 30 degree angle cutting blade (6 mm cutting depth)

Table M.20: Experiments with current, 10 cm water depth, 5 cm/s current (100%). High back plough, 30 degree cutting blade

<table>
<thead>
<tr>
<th>Experiments with flow, 10 cm depth 5 cm/s current, 30 degree cutting blade, high back</th>
<th>excell file</th>
<th>video file</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8-100%-10cm-with-adapted-frontflaps-filled</td>
<td>0.8-100%-10cm-with-adapted-highack-frontflaps-filled</td>
<td></td>
</tr>
<tr>
<td>0.9-100%-10cm-with-adapted-frontflaps-filled</td>
<td>0.9-100%-10cm-with-adapted-highack-frontflaps-filled</td>
<td></td>
</tr>
<tr>
<td>1.0-100%-10cm-with-adapted-frontflaps-filled</td>
<td>1.0-100%-10cm-with-adapted-highack-frontflaps-filled</td>
<td></td>
</tr>
<tr>
<td>1.1-100%-10cm-with-adapted-frontflaps-filled</td>
<td>1.1-100%-10cm-with-adapted-highack-frontflaps-filled</td>
<td></td>
</tr>
<tr>
<td>1.2-100%-10cm-with-adapted-frontflaps-filled</td>
<td>1.2-100%-10cm-with-adapted-highack-frontflaps-filled</td>
<td></td>
</tr>
<tr>
<td>1.3-100%-10cm-with-adapted-frontflaps-filled</td>
<td>1.3-100%-10cm-with-adapted-highack-frontflaps-filled</td>
<td></td>
</tr>
<tr>
<td>1.5-100%-10cm-with-adapted-frontflaps-filled</td>
<td>1.5-100%-10cm-with-adapted-highack-frontflaps-filled</td>
<td></td>
</tr>
<tr>
<td>1.8-100%-10cm-with-adapted-frontflaps-filled</td>
<td>1.8-100%-10cm-with-adapted-highack-frontflaps-filled</td>
<td></td>
</tr>
<tr>
<td>2.0-100%-10cm-with-adapted-frontflaps-filled</td>
<td>2.0-100%-10cm-with-adapted-highack-frontflaps-filled</td>
<td></td>
</tr>
</tbody>
</table>

Experiments with flow, 10 cm water depth, 5 cm/s current (100%), High back plough, front flaps with a partly filled plough

Table M.21: Experiments with current, 10 cm water depth, 5 cm/s current (100%). High back plough, front flaps, filled

<table>
<thead>
<tr>
<th>Experiments with flow, 10 cm depth 5 cm/s current, filled, front flaps, high back</th>
<th>excell file</th>
<th>video file</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8-100%-10cm-with-adapted-frontflaps-filled</td>
<td>0.8-100%-10cm-with-adapted-highack-frontflaps-filled</td>
<td></td>
</tr>
<tr>
<td>0.9-100%-10cm-with-adapted-frontflaps-filled</td>
<td>0.9-100%-10cm-with-adapted-highack-frontflaps-filled</td>
<td></td>
</tr>
<tr>
<td>1.0-100%-10cm-with-adapted-frontflaps-filled</td>
<td>1.0-100%-10cm-with-adapted-highack-frontflaps-filled</td>
<td></td>
</tr>
<tr>
<td>1.1-100%-10cm-with-adapted-frontflaps-filled</td>
<td>1.1-100%-10cm-with-adapted-highack-frontflaps-filled</td>
<td></td>
</tr>
<tr>
<td>1.2-100%-10cm-with-adapted-frontflaps-filled</td>
<td>1.2-100%-10cm-with-adapted-highack-frontflaps-filled</td>
<td></td>
</tr>
<tr>
<td>1.3-100%-10cm-with-adapted-frontflaps-filled</td>
<td>1.3-100%-10cm-with-adapted-highack-frontflaps-filled</td>
<td></td>
</tr>
<tr>
<td>1.5-100%-10cm-with-adapted-frontflaps-filled</td>
<td>1.5-100%-10cm-with-adapted-highack-frontflaps-filled</td>
<td></td>
</tr>
<tr>
<td>1.8-100%-10cm-with-adapted-frontflaps-filled</td>
<td>1.8-100%-10cm-with-adapted-highack-frontflaps-filled</td>
<td></td>
</tr>
<tr>
<td>2.0-100%-10cm-with-adapted-frontflaps-filled</td>
<td>2.0-100%-10cm-with-adapted-highack-frontflaps-filled</td>
<td></td>
</tr>
</tbody>
</table>

Experiments with flow, 10 cm water depth, 5 cm/s current (100%), High back plough, front flaps with a partly filled plough
Table M.22: Experiments with current, 10 cm water $\frac{cm}{s}$ current (100%). High back plough, frontflaps, filled

<table>
<thead>
<tr>
<th>excell file</th>
<th>video file</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8-100%-10cm-with-adapted-frontflaps-filled</td>
<td>0.8-100%-10cm-with-adapted-highack-frontflaps-filled</td>
</tr>
<tr>
<td>0.9-100%-10cm-with-adapted-frontflaps-filled</td>
<td>0.9-100%-10cm-against-adapted-highack-frontflaps-filled</td>
</tr>
<tr>
<td>1.0-100%-10cm-with-adapted-frontflaps-filled</td>
<td>1.0-100%-10cm-with-adapted-highack-frontflaps-filled</td>
</tr>
<tr>
<td>1.1-100%-10cm-with-adapted-frontflaps-filled</td>
<td>1.1-100%-10cm-with-adapted-highack-frontflaps-filled</td>
</tr>
<tr>
<td>1.2-100%-10cm-with-adapted-frontflaps-filled</td>
<td>1.2-100%-10cm-with-adapted-highack-frontflaps-filled</td>
</tr>
<tr>
<td>1.3-100%-10cm-with-adapted-frontflaps-filled</td>
<td>1.3-100%-10cm-with-adapted-highack-frontflaps-filled</td>
</tr>
<tr>
<td>1.5-100%-10cm-with-adapted-frontflaps-filled</td>
<td>1.5-100%-10cm-with-adapted-highack-frontflaps-filled</td>
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<td>1.8-100%-10cm-with-adapted-frontflaps-filled</td>
<td>1.8-100%-10cm-with-adapted-highack-frontflaps-filled</td>
</tr>
<tr>
<td>2.0-100%-10cm-with-adapted-frontflaps-filled</td>
<td>2.0-100%-10cm-with-adapted-highack-frontflaps-filled</td>
</tr>
</tbody>
</table>

Also, a no flow row of experiments has been done:

Experiments no flow, 10 cm water depth, $\frac{cm}{s}$ current (100%), High back plough, frontflaps

Table M.23: Experiments no current, 10 cm water. High back plough, frontflaps

<table>
<thead>
<tr>
<th>excell file</th>
<th>video file</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8-noflow-10cm-frontflaps</td>
<td>0.8-noflow-10cm-highack-frontflaps</td>
</tr>
<tr>
<td>0.9-noflow-10cm-frontflaps</td>
<td>0.9-noflow-10cm-highack-frontflaps</td>
</tr>
<tr>
<td>1.0-noflow-10cm-frontflaps</td>
<td>1.0-noflow-10cm-highack-frontflaps</td>
</tr>
<tr>
<td>1.1-noflow-10cm-frontflaps</td>
<td>1.1-noflow-10cm-highack-frontflaps</td>
</tr>
<tr>
<td>1.2-noflow-10cm-frontflaps</td>
<td>1.2-noflow-10cm-highack-frontflaps</td>
</tr>
<tr>
<td>1.3-noflow-10cm-frontflaps</td>
<td>1.3-noflow-10cm-highack-frontflaps</td>
</tr>
<tr>
<td>1.5-noflow-10cm-frontflaps</td>
<td>1.5-noflow-10cm-highack-frontflaps</td>
</tr>
<tr>
<td>1.8-noflow-10cm-frontflaps</td>
<td>1.8-noflow-10cm-highack-frontflaps</td>
</tr>
<tr>
<td>2.0-noflow-10cm-frontflaps</td>
<td>2.0-noflow-10cm-highack-frontflaps</td>
</tr>
</tbody>
</table>

Experiments with flow, 10 cm water depth, $\frac{cm}{s}$ current (100%), High back plough, frontflaps, topflaps

Table M.24: Experiments no current, 10 cm water. High back plough, frontflaps, topflaps

<table>
<thead>
<tr>
<th>excell file</th>
<th>video file</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8-noflow-10cm-frontflaps-topflaps</td>
<td>0.8-noflow-10cm-highack-frontflaps-topflaps</td>
</tr>
<tr>
<td>0.9-noflow-10cm-frontflaps-topflaps</td>
<td>0.9-noflow-10cm-highack-frontflaps-topflaps</td>
</tr>
<tr>
<td>1.0-noflow-10cm-frontflaps-topflaps</td>
<td>1.0-noflow-10cm-highack-frontflaps-topflaps</td>
</tr>
<tr>
<td>1.1-noflow-10cm-frontflaps-topflaps</td>
<td>1.1-noflow-10cm-highack-frontflaps-topflaps</td>
</tr>
<tr>
<td>1.2-noflow-10cm-frontflaps-topflaps</td>
<td>1.2-noflow-10cm-highack-frontflaps-topflaps</td>
</tr>
<tr>
<td>1.3-noflow-10cm-frontflaps-topflaps</td>
<td>1.3-noflow-10cm-highack-frontflaps-topflaps</td>
</tr>
<tr>
<td>1.5-noflow-10cm-frontflaps-topflaps</td>
<td>1.5-noflow-10cm-highack-frontflaps-topflaps</td>
</tr>
<tr>
<td>1.8-noflow-10cm-frontflaps-topflaps</td>
<td>1.8-noflow-10cm-highack-frontflaps-topflaps</td>
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<tr>
<td>2.0-noflow-10cm-frontflaps-topflaps</td>
<td>2.0-noflow-10cm-highack-frontflaps-topflaps</td>
</tr>
</tbody>
</table>

M.3 Stability experiments

In the stability experiments, the force measurement was of lesser importance so not all tests have excel files.
Some video footage is taken:

- a small test with dunes in the sand bed:
  0.8-noflo-dunetest

- a small test with dunes in the sand bed using the top flaps:
  0.8-noflow-dunetest-topflaps

Using only the backwire and a flat sandbed:

- 0.8-noflow-topflaps-backwire

The topview video: topview-0.8-noflow-backwire-topflaps

A view from above, two vertical front wires and a back wire:

- topview-0.8-noflow-vertical front wires-backwire-topflaps

Flat sand bed with a wire in the middle of the plough:

- topview-0.8-noflow-backwire-middle frontwire-topflaps

An instable plough with topflaps:

- topview-instable-0.8-noflow-vertical front wires-backwire-topflaps-2

Instable plough from above to compare the topflaps:

- topview-instable-0.8-noflow-vertical front wires-backwire

A plough with no vertical suspension starting unstable:

- topview-instable-1.0-noflow-no vertical wires

An instable plough with topflaps in order to stabilise:

- topview-instable-1.0-noflow-backwire-middle frontwire-topflaps

A plough with a side ski installed:

- topview-instable-1.0-noflow-backwire-middle frontwire-topflaps-sideflap