Could the capability of the current trenching equipment be improved with the use of different jet nozzle setups?

HZ university of applied science
Bachelor of engineering

Report

Creating new Horizons

Improving trenching equipment by using alternative jet nozzles configurations

By

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ABSTRACT

The increasing demand on renewable energy in the past decade resulted in the development of more windmill parks in the north-sea. The north-sea is an ideal sea for the development of offshore structures such as windmill parks due to its morphological benefits of being a shallow sea with soft soils consist of sand and clay. The generated energy from the windmills is collected in the transformer. The collected energy is being transferred from the transformer to the mainland through export cables. The cables that transfer the energy towards land are buried to protect them from other activities in the sea such as commercial fishing. The process of burring the cables in the seabed is called trenching. The trenching equipment use pressured water jets to create trenches for export cables that connect offshore windmill parks with the mainland. Boskalis B.V. is an international service provider in the field of dredging, maritime infrastructure and related services such as subsea, heavy transport, hoisting and installation. Their current trenching equipment is developed for soils consisting mainly out of fine-grained sand. However, the soils of the north-sea also contain sections of clay. This means that the equipment must go multiple times of the same area to get the required depth. This takes up valuable time.

The goal of this research was to improve the current trenching equipment by using alternative jet nozzle configurations. This research has been divided in a theoretical and practical part. In the theoretical part a literature study is performed to gain more knowledge about the jet nozzles and the effects of jet trenching on cohesive soils such as clay and loam. The practical part of this research has been conducted in the hydro-lab located at Boskalis in Papendrecht. These tests are conducted on clay samples where numerus tests have been done to see the effects of the different jet nozzle configurations. During the testing phase, the focus was on three variables that changed. Throughout the testing three different nozzle sizes has been used to see their effectiveness on the clay. Also, the distance between the nozzle and the plough was also changing variable. In this way we could see what happened if the water jet sprays inside, on the edge or outside the area of influence created by the plough. Finally, the pressure of the water jet varies. That way the water jet would always cut through the entire block of clay to get rid of the excess water more effectively.

Research shows that different nozzle setups can make a difference in the trench making capability. The 5mm nozzle shows to have a bigger impact on the trenching process. When checking the distance between the nozzle and plough, the smallest distance appears to have the largest effect on the force reduction. Because this nozzle is inside the area of influence, it actively removes the clay being pushed forward by the plough. The middle distance appears to have mixed results and more tests needs to be done. However, the results show that the active nozzle is on the edge of the area of influence. The plastic zone in front of the plough cannot properly develop making more resistance in the clay pushing forward.

In order to have a better conformation on how to improve the trenching capabilities in cohesive soils, the recommendation is that more test must be conducted. to have more reliable results and a more accurate conclusion. At the end possible alternatives for future researches within the field of water jetting in cohesive soils are included

PREFACE

To complete the bachelor's degree program in Civil Engineering at The HZ university of Applied sciences, I have been working on the thesis that lies ahead of you. For this thesis I researched if different jet nozzles setups could improve the trench making capacities which as burying the electric cables in the seabed, so they are protected. This research was carried on behalf of Royal Boskalis Westerminster N.V located in Papendrecht. With the results I hope to give the client and other professionals more information about the trench forming capabilities using different jet setups and distances. I would like to thank everyone who helped me while writing my thesis. I have worked with great pleasure on this thesis and learned a lot about research during my internship at the research and development division cable and flexibles department of Boskalis. I would therefore like to thank all employees for the fun and instructive internship period, especially my supervisor Lennart van Baalen and teacher counselors Marco Gatto and Piet Dekker. I want to thank you very much for the great guidance and tips when writing my thesis!

I wish you much pleasure in reading my thesis.

Mark Roos

Vlissingen, January 2020

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1

INTRODUCTION

1.1 Background

In 2015, a total 194 states and the European union signed the Paris Agreement. The Paris Agreement central aim is to strengthen the global response to the threat of climate change by keeping the global temperature rise below 2 degrees this century (Unfccc, 2016). With the Paris Agreement, every participating state has their own goals to achieve before 2030. For example, the Netherlands for example has agreed they want a reduction of 49% in greenhouse gas emissions by 2030, compared to the levels in 1990 and a 95% reduction by 2050 (Government of the Netherlands, 2019). In order to achieve these goals a transition to more sustainable energy sources is required, some examples are:

- Solar power
- Tidal power
- Wave energy
- Wind energy
- Hydro electric energy

Currently Europe is producing the equivalent amount of renewable energy of 22 coal plants in gigawatts. However with current estimations this will increase up towards the equivalent of 170 coal plants by 2040. (Boskalis, 2019) With the transition to more renewable energy sources, new technology is being develop on a daily base. In the last decade, wind energy is one of the most upcoming source of renewable energy (our world in data, 2018).

Wind energy can be produced on land and in the sea. The most development of offshore wind energy is in the North Sea due to its morphology. As a shallow sea with soft soil makes the North Sea an ideal to place windmill parks. The cables transferring the energy towards land are buried to protect them from other activities in the sea, such as commercial fishing. The soils in the North Sea is a mixture of sandy and cohesive particles. Water jets are used to create the trenches where the cables are positioned in. due to the characteristics of the cohesive soils, these jets can't reach the required depth as easy as in sandy soils which take up valuable time.

Jets use pressured water to loosen or remove soils. This process is highly effective for non-cohesive soils like sand. However, in clay these jets are less effective because clay is a cohesive soil and will therefore not be loosened. Instead small holes are created during the jetting process. Boskalis applies this technique on drag heads of their trailing suction hopper dredgers (TSHD) and on jetting swords of their trenching-machines. The jetting sword is connected to the back of the trenching machines and holds all the jets nozzles that create the trench

A jetting sword of a trenching machine is used to make a trench to bury a cable. These cables are mainly used to connect windmill parks and offshore platforms to the shore for electricity. In areas with significant morphodynamical activity (such as migrating sand waves), larger burial depths are often required. Since geo-technical and geophysical conditions of the seabed differ per region and are more uncertain in deeper ground layers, conventional jetting and ploughing with a depth up to 2 -3 meters do not comply anymore with the current standards (Barthhollanddrain, 2018).

One of these machines that uses a jetting sword is the “BBS-II” (Burial sledge system II). The BBS-II is a sledge that gets pulled behind an anchor barge and buries the cable in a trench with a jetting sword (figure 1.1). This system works very well in sandy soils, but when there is clay in its path the jetting sword that is mounted on the BBS-II can’t trench through this clay. This part must be skipped and must be done by another machine. A possible solution for this problem may possibly be the use of rotating jets inside the jetting sword. The trenchformer is another tool from Boskalis that uses the jetting sword. The trenchformer is a remotely operated vehicle (ROV) that can be operated from a central control room (figure 1.2). One of the differences between the trenchformer and the BSS-II is that the trenchformer can move on its own and can be operated on the beach and through the surf zone. The Trenchformer also can bury the cable after it has been laid on the seabed by a ship (post-trenching). Another big difference between the trenchformer and the BSS-II is the direction the jets are facing. At the BSS-II the jets are facing horizontally where the jets of the trenchformer are facing in a vertical direction (figure 1.3) (Groen, 2013).

Figure 1.1: BSS II (VBMS, 2017)

Figure 1.2: The trenchformer (VBMS, 2017)

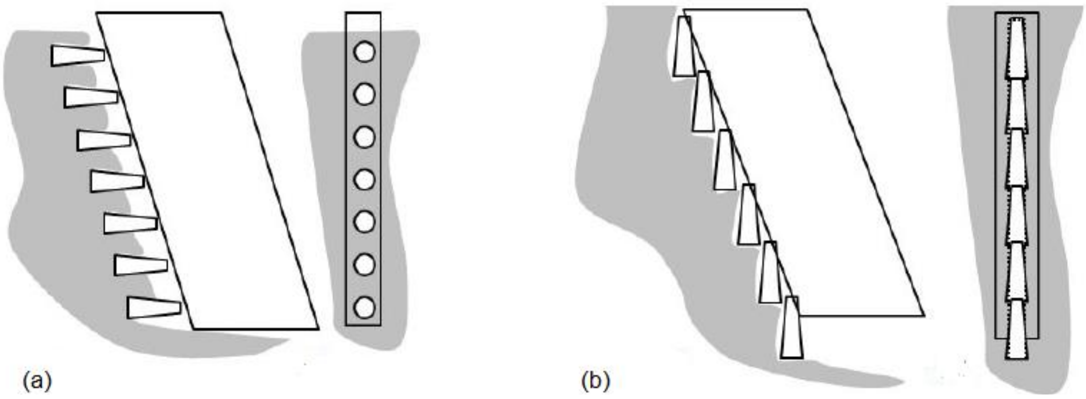


Figure 1.3: (a) Jet orientation on the BSS-II (b) jet orientation on a trenchformer (Groen, 2013)

1.2 Problem definition

The current trenching equipment of Boskalis is designed to effectively trench through sandy soils, but when the machines reach a section with clay soil the machines are not able to reach the required depth. In most scenarios the trenching tool must go over the same trajectory multiple times to reach the required depth. The main objective of this research is to obtain more knowledge about the increased jet trenching capacity of rotational jetting in stiff clay compared to the conventional non-rotational jetting. For this research a main question and sub questions are formulated.

1.2.1 Research question

The research question is as follows: "*Could the capability of the current trenching equipment be improved with the use of different jet nozzle setups?"* In order to answer this research question, the following questions will be answered by means of literature and practical research:

- What knowledge is currently known and what is missing in the field of trenching?
- What different type of jet nozzles are currently used during jet trench cutting?
- What is the difference between rotational and conventional nozzles?
- How can the different nozzle setups be simulated in the experimental setup?
- Can the trench making capability be improved with different nozzle setups?

1.3 Knowledge before the assignment

At the start of this research there already was a lot of knowledge available the trenching about trenching in stiff clay within Boskalis. researches where conducted on the ploughing forces in clay (Gurp, 2014) and in sand (Beindorff, 2011) also, knowledge of conventional jets in stiff clay (Nobel, 2013) and (Kemperman 2017) was known. Knowledge was also gathered about the effects of rotational jetting in stiff clay (Groen, 2016).

During these researches Boskalis gained more knowledge and insight on improvement of their equipment or working processes. The following information is already acquired for Boskalis.

- Ploughing forces in sand and clay.
- Jetting forces in sand and clay.
- Development of cable burial tools.
- Improvement on ploughing sword.
- Improvement of jetting sword.
- The differences between different trenching tools and when to apply them in the field.

Knowledge that is missing for this research:

- Force reduction on a jetting sword with different jet nozzle setups.
- The reduction factor (N_c) on stiff clay when using different jet nozzle setups.

The missing information will be acquired during this research with the help of literature reviews and practical tests in the hydro lab of Boskalis.

1.4 Scope of the research

This research contains a theoretical part and a practical part. The practical part will be conducted in the hydro lab, located in the main office of Boskalis in Papendrecht. The aim of the practical experiments is to confirm the theory found in this research. The three main components of the experiment that will be checked are:

- The distance between the plough and jet nozzle: this will check if the area of influence in front of the plough does affect the forces acting on the plough.
- The size of the nozzle: with the use of different nozzle sizes a check will be done to see if this effect the forces on the nozzle.
- The water pressure: with the current test setup the power of the nozzles can be changed. The aim for the experiment is to cut through the entire block of clay placed in the test setup.

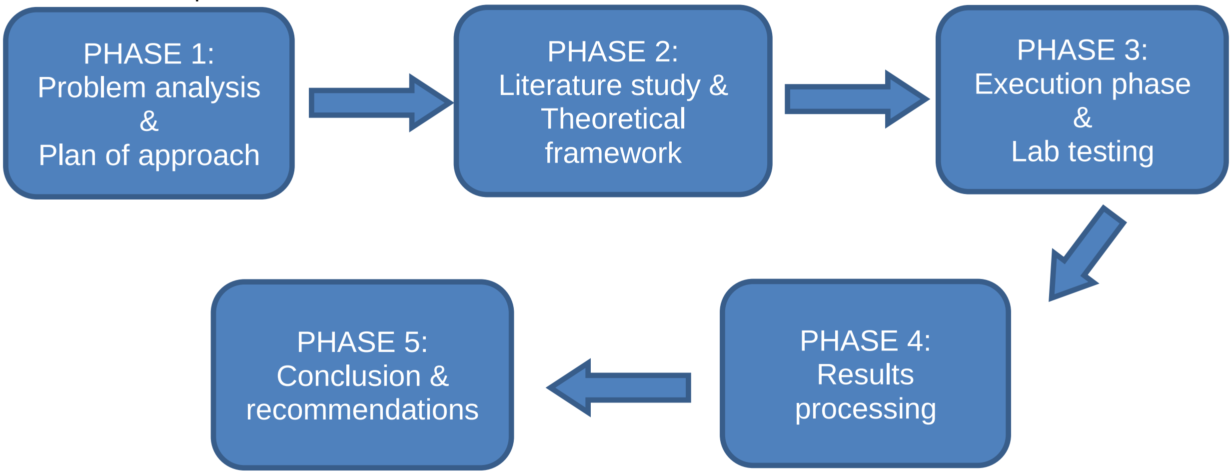
The test results will be compared against each other and will have to show which distance and nozzle size is most beneficial for the bearing capacity factor. The lower the bearing capacity factor becomes, the less force the plough needs to go through the clay.

1.5 Structure of thesis report

The graduation research consists 5 phases:

1. The first phase is a problem analysis that will be performed to determine the problem of involving the jetting through stiff clay, in this phase the research question will be determined.
2. During the second phase a literature study is performed to gain more knowledge about the jet nozzles and the effects of jet trenching on stiff clay. A test program is also being set up.
3. The third phase will be executed in the hydro-lab of Boskalis, where the clay samples will be tested according to the test program.
4. In the fourth phase all the test results will be processed and assessed.
5. With the completion of the practical tests the fifth phase will start. This phase will be about making the conclusions based on the findings of this research.

Table 1.2: Graduation phases.



2

2. THEORETICAL FRAMEWORK

2.1 Introduction

In this chapter the following is described: What are cohesive soils and what are the properties of these soils? In section 2.2 the properties and behavior of clays are described and explained. In section 2.3 the jetting process of conventional nozzles are described. In section 2.4 you can find the theory and explanation of how rotational jetting is applied. In section 2.5 a comparison is made between conventional and rotational jetting

2.2 Clays

Soils can be divided by their grain size (table 2.1). As noticeable in this table, clay consists of relatively fine-grained particles.

Table 2.1 Grain size (Soils, 2019).

Soil type	Min	Max
Coarse sand	0.5 mm	1.0 mm
Medium sand	0.25 mm	0.5 mm
Fine sand	0.10 mm	0.25 mm
Silt	0.002 mm	0.050 mm
Clay		0.002 mm

The soil consists of small solid particles. At the seabed the pores in between the particles are fully saturated with water. The solid will behave as a cohesive soil due to the presence of the clay particles. The main characteristics of cohesive soils are:

- *Very low water permeability:*
- *Plasticity:*
- *Swell properties*
- *Very small particles (clay)*

2.2.1 Clay particles

Clay particles are relatively small (<2 µm) and are created by chemical weathering. Chemical weathering is caused by rainwater reacting with the mineral grains in rock to form new minerals (Society, 2019). Clay often forms colloidal suspensions when immersed in water, but the clay particles flocculate (clump) and settle quickly in water. Non-cohesive soils mainly consist of non-clay particles, like sand. The water permeability of these soils is relatively high, resulting in a drained behavior which results in mud for example (Nobel, 2013). An overview of the unit weight values for various types of soils are given in Table 2.2.

Table 2.2 Bulk density and unit weight of soils (Gurp, 2014).

Soil type	*Bulk density [kg/m³]*	*Unit weight [kN/m3]*
Sand and gravel	1.600 - 2.200	16 – 22
Silt	1.600 – 2.000	16 – 20
Soft clay	1.700 – 2.000	17 – 20
Stiff clay	1.900 – 2.300	19 – 23
Peat	1.000 – 1.400	10 - 14
Weak rock	1.800 – 2.100	18 – 21
Hard rock	1.900 – 2.200	19 - 22

2.2.2 Shear strength

Shear strength is the strength of a material or component against the type of yield or structural failure where the material or component fails in shear. The shear strength is the load an object can hold in a parallel direction to the face of the material (Gurp, 2014).

$$\tau = c' + \sigma'_{\perp} * \tan\varphi$$

τ	Shear strength	[kPa]
c'	Cohesion	[-]
σ'	Effective compressive normal stress	[N/m^2]
φ	Internal friction angle	[°]

To mimic real trenching conditions during this research the clay will be considered in an undrained shear strength. The loading time during the experiment is only one minute and this is short compared to the drainage time so all access water pressure will not dissipate. Therefore, the effective strength remains the same so the clay can be considered in the undrained form. In this research the shear strength of clay will be mentioned as S_{uv}.

2.2.3 Soil consistency

Soil consistency is the strength in which soil materials are held together or the resistance of soils to deformation and rupture. The soil consistency can be measured for wet, moist and dry soil samples. Wet soil types are generally expressed in the stickiness and plasticity of the soil. Soil consistency can be estimated in the field with simple tests or can be measured more accurately by tests in the laboratory (Food and agriculture organization, 2019). The field test for stickiness can be done by squeezing a small amount of clay in your hand or between your fingers. If slowly open your hand you can rate the shear strength of the clay according to table 2.3.

Table 2.3: Field test consistency guide (Food and agriculture organization, 2019).

Cohesive soils 'consistency'		
Very soft	<20 kN/m^2	Exudes between fingers when squeezed in the hand
Soft	20 kN/m^2 to 40 kN/m^2	Can be molded by light finger pressure
Firm	40 kN/m^2 to 75 kN/m^2	Cannot be molded by the fingers, but rolled in the hand to 3mm thick threads without breaking or crumbling
Stiff	75 kN/m^2 to 150 kN/m^2	Crumbles and breaks when rolled to 3mm threads but still sufficiently moist to be molded to a lump again
Very stiff	>150 kN/m^2	Has dried out and is mostly light colored. It can no longer be molded but crumbles under pressure. It can be indented by the thumbnail
Hard	>300 kN/m^2	

2.3 Jetting process

Jet nozzles are used in dredging and trenching operations. The performance of the trenching tools is based on the performance of these jet nozzles. The pressure at the nozzle determents the time it takes for the seabed to be fluidized and the trenching speed. These two factors determents the production speed of the trenching tools (Kemperman, 2017).
In sandy soils the shear force exerted by a jet removes an individual grain from the seabed. To remove a sand grain the void space behind the grain must be filled with water, see figure 2.1 (a). The flow velocity and the permeability of the soil are the determining factors for the velocity of this erosion. The lower the water permeability, the slower the erosion process. (Nobel, 2013). This process is called liquification, which is a phenomenon in which the strength and stiffness of a soil is reduced. Liquefication occurs in fully saturated soils where the water exerts a pressure on the soil particles that influences how tightly the particles themselves are pressed together (Washington, 2019). Clay is loosened by the pressure exerted of the jet. Due to the cohesive properties of the soils, individual grains will not be lifted from the soil, but rather small slices of clay will be exerted. See Figure 2.1 (b).

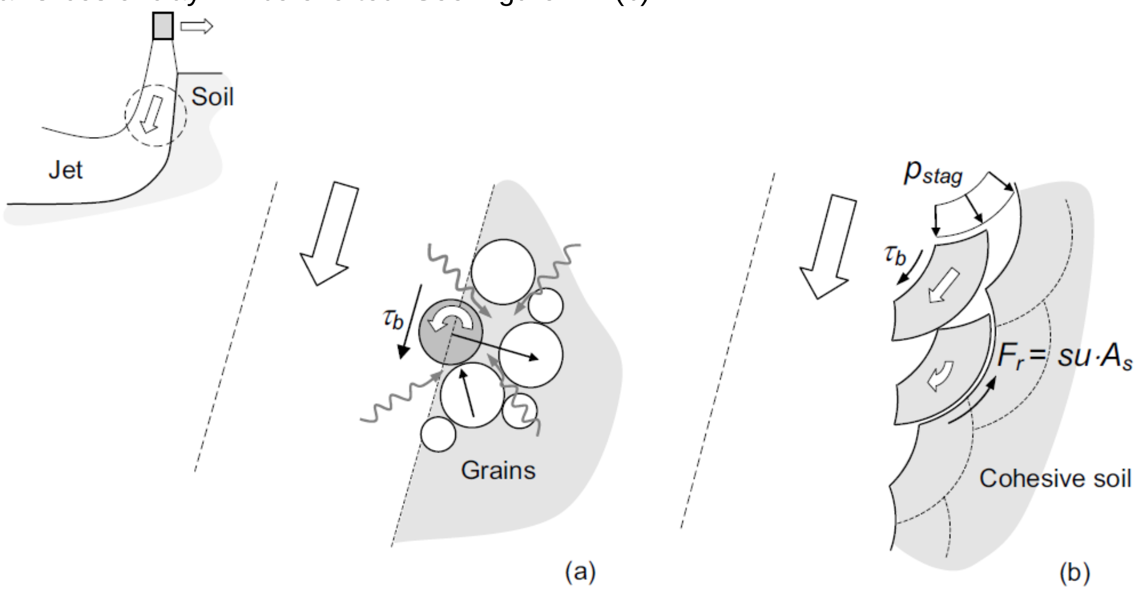


Figure 2.1: The failure process of soils during the jetting process (Nobel, 2013).

This results in narrow vertical jet cavities. This in turn results in a jet cavity soil structure of straight small vertical nerves which is called the non-deflection zone. Only at the bottom of the cavity the jet will deflect backwards. Opposite to the traverse direction of the nozzle this is called the deflection zone. In figure 2.2 you see a typical cavity made by a vertical jet in non-cohesive soils (Groen, 2013).

Figure 2.2: typical cavity made by a vertical jet in cohesive soils

The jet cavity of the penetrating jets is deep and rectangular, with a constant cavity with of approx. 1 to 1.4 times the jet diameter at the soil surface ($W_{C=}$ 1 ~ 1.4 D_{jet}). Jetting in cohesive soils like clay with standard traversing jets requires lots of energy. The cavity depth (penetration depth) decrease a little with increasing traversing velocity. Because the relation between cavity width and traversing velocity is independent from each other, the highest production can be realized when the highest traversing velocity is applied. The highest traversing velocity of the nozzle is not always possible. Therefore, the fully potential of the jet cannot be applied: in other words, the jet can process more clay then the tool is offering. To increase the offering of more clay, rotational jetting can be applied. By increasing the cavity width, more clay can be offered without increasing the jetting power (Groen, 2013).

2.4 Rotational Jetting

Rotational jetting is currently used in high pressured washing operations, so the concept of rotational jetting is not new. However, literature and calculation models about how to apply for rotating nozzle for different used are still missing. Pressure washers are using rotating nozzles mainly because of the increasing affected area provided by these nozzles. Figure 2.3 shows the differences between the different nozzles.
The rotating nozzle is one of the most useful nozzles because it combines the force of the 0-degree nozzle and the spray area of a 25-degree nozzle and adds in a pulsing action by rotating the water jet at 1800-3000 rpm (Pressurewashr, 2019). The rotating action is caused by a straight pressured jet that is forced on a moving little ball. This ball makes the pressured jet spin around.

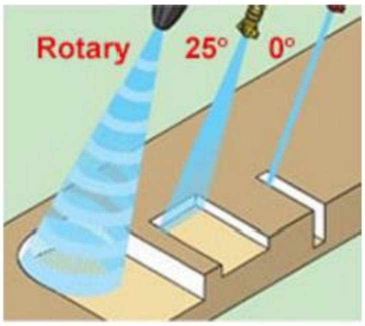


Figure 2.3: Differences between different nozzle types (Pressurewashr, 2019).

For this research this concept will not be used because the clay can clough up the nozzle. Instead to simulate the effects of a rotating jet different nozzle sizes will be used to simulate the increasing area of a rotating nozzle. During the test a nozzle of 5,10 and 14 will be used to simulate the larger area of influence created by a rotating nozzle.

2.5 Nozzle comparison

The main difference between conventional jetting and rotational jetting is the affected area. With conventional jetting the cavity depth (penetration depth) is deeper than the depth of rotational jetting. But with rotational jetting, the width of the cavity is larger. In figure 2.4 you can see the difference between the two nozzles.

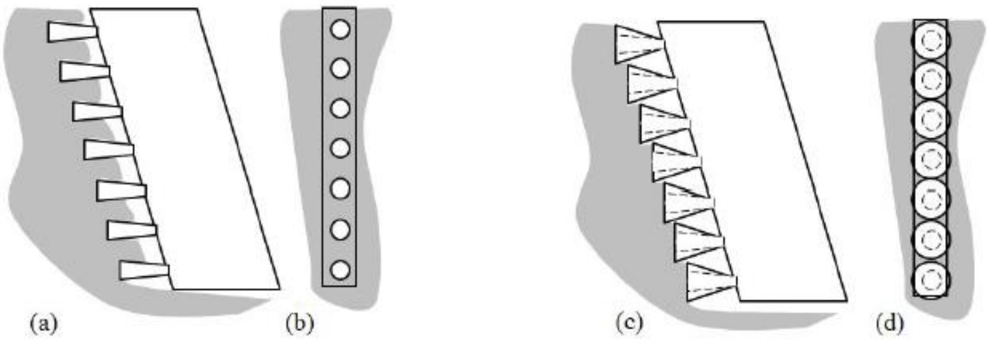


Figure 2.4: a) Side view of conventional jetting, b) frontal view of conventional jetting, c) Side view of rotational jetting, d) front view of rotational jetting (Groen, 2013).

Due to the larger cavity width of rotational jetting, more clay will be removed by the jetting process, which results in less forces that act on the jetting sword.

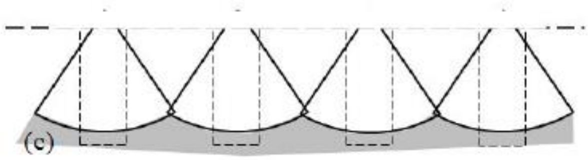


Figure 2.5: The difference between rotational and conventional jetting (Nobel, 2013).

Every soil has a maximum angle of repose which is the steepest angle of a granular material relative to the horizontal plane in which a material can be piled without slumping or the surface material sliding. The internal angle between the surface of the pile and the horizontal surface (typically the surface which the material is piled on) is known as the angle of repose and is related to the density, surface area, liquid content, shapes of the particles, and the frictional coefficient of the material. For a cohesive soil this is approx. 15° (Structx, 2019). With a larger cavity depth, the area influenced by the angle of repose will be wider.

3

METHODOLOGY

3.1 Introduction

Due to limitations such as height and width of the tank some changes had to be made in order to conduct a test that could give enough data. The exact amount of force acting on the plough in this model is the minimum expected force acting on the plough., using calculation due to a limited amount of information know of this topic. Therefore, the Meyerhof/Terzaghi theory about shallow strip foundations is used to calculate the minimum expected force on the plough, this theory will be discussed in the section 3.2. In section 3.3 the pressure of the jet nozzles necessary to go through the clay is explained and why there are some effects that occur in field cannot be recreated in the practical test setup.

3.2 Meyerhof method

The Meyerhof method (1951) is adopted based on the Terzaghi method (1943), which is about the ultimate bearing capacity of an infinite foundation strip in cohesive soils

$$Q_{ult} = C * N_c + Y * D$$

The N_C coefficient is depending on the shape of the plastic zone which is, are according to this theory, given by the shapes shown in figure 3.1

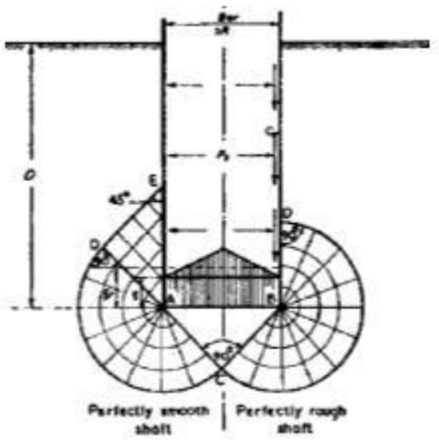


Figure 3.1: Plastic zone in a deep foundation (Gurp, 2014).

According to the theory from Gurp 2014, the Terzaghi theory can be used to predict the cutting force during ploughing. The strip used for the ultimate bearing capacity can be rotated to a vertical position to present the frontal area of the plough (Gurp, 2014).

In the calculation of the ultimate bearing capacity, there is no parameter for the moving speed of the plough, this is due to the foundation is not designed to move. Therefor the ultimate bearing capacity calculation is the minimum to be expected cutting force during ploughing.

In the ultimate bearing capacity calculation for foundations the soil is being pushed sideward, where with the ploughing model of this research the soil will is pushed upwards due to the clay takes the path of the least resistance. This requires less force and cannot be accounted for in the ultimate bearing capacity calculation.

Based on the research conducted by Gurp 2014, the influence area of the clay caused by the plough would be between 0,7 > 2 * width plough. Which can mean that the area of influence is approximately between 28mm and 80mm in front of the plough, where the cohesive soil still will be influenced by the plough (Gurp, 2014).

The clay holder has a maximum width of 150mm, the dimensions of the plough are based on this dimension. With the above-mentioned information, the area of influence to the side is approx. 1 * width plough. In addition, a clearance of 15mm had to be added on both sides of the plough to have no influence from the steel wall of the clay holder. Therefor the maximum plough width was determined at 40mm.

To make sure that the plough would hold all the forces an additional diagonal beam of 45° has been welded to the back of the plough. This way the forces can directed away from the front of the plough. Appendix E shows the design of the plough.

3.3 Required pressure

The experimental setup is a scaled version of a jetting sword where the 3 meter long jetting swords of the trenchformer and BSS-III have 23 nozzles with a distance of 295mm between each other (VBMS, 2017). With the experimental setup the effects of a single nozzle will be tested. Therefor some adjustments had to be made that are different. Due to the height of the setup the full range of a jetting nozzles cannot be tested, this includes the narrow shaft and the deflection zone. In Figure 3.2 a cross-section is show of a cavity created by a nozzle and the locations of the narrow shaft and the deflection zone. In the experimental setup only, the narrow shaft will be tested, this is done due to the size of the setup and safety reasons of the deflected water.

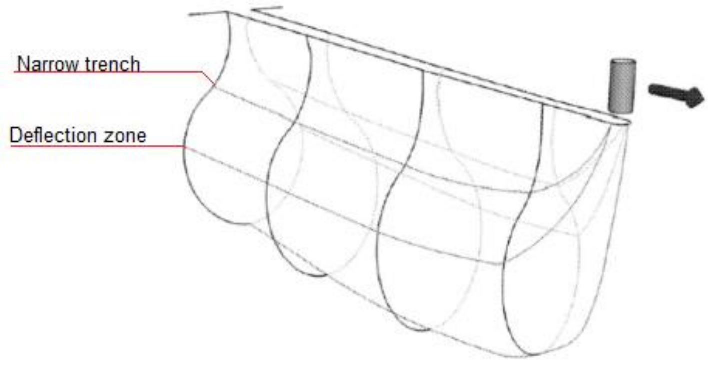


Figure 3.2: Cross-section of the cavity created by a nozzle in non-cohesive soils (Nobel, 2013).

In order to get the required nozzle pressure to go through the clay blocks, the following formula was used (Kemperman, 2017).

$$P_{Nozzle} = \frac{Z_c * S_{uv} * (\frac{V_{trench}}{V_{ref}})^{0.2}}{0.2 * D_{nozzle}}$$

Z_c	Cavity depth	[m]
P_{nozzle}	Pressure at nozzle	[bar]
S_{uv}	Undrained shear strength	[kPa]
D_{nozzle}	Diameter nozzle	[m]
μ_{nozzle}	Coefficient friction	[-]

The minimum required cavity depth during the experiment is 110mm. To make sure that the jet nozzle will cut through the entire block of clay, an additional 10mm is used during the calculation, making the required cavity depth during this experiment 120mm.

In addition to the nozzle pressure, additional pressure loss caused by the hose must be considered. All the necessary calculations for the pomp and nozzle pressure can be found in Appendix A.

4

EXPERIMENTAL SETUP

4.1 Description test

4.1.1 Introduction

For my research, tests will be performed at the hydro-lab of Boskalis with a jet in the clay. With these tests I will be testing if the implementation of Rotating jets instead of fixed jets could increase the trenching capabilities for the equipment of Boskalis. To simulate the actual situation in the field, the tests will be scaled accordingly. Different nozzle will be used. This nozzle will have a wider base and will penetrate the clay less like the commonly fixed jets. The results should confirm or deny the expectations that the rotating jets could improve the jetting capacity in stiff clay. With the results it is possible to develop new jetting sword.

4.1.2 Risk during practical stages of the research

During the practical stage of this research, there are several risks that can obstruct the progress of the research. It is good to know which risks could obstruct this research. In that way there is a mitigating measure available. Below are three risks described that could influence this research.

- *Complication of the calculations*
  During my research I will constantly ask for feedback with the professionals and experts within Boskalis and Hogeschool Zeeland about my progress and how the calculations are going. To make sure that all the calculations are going according to plan, online computer models are made to check them.
- *Delivery problems with the practical setup*
  The chances are that there will be struggles with carrying out the lab tests, to minimize this risk equipment is ordered in an early stage so that it will arrive on time.
- *Insufficient amount of tests results*
  Due to the amount of option that can be tested within the scope of this research, only a limited number of tests will be conducted.

4.2 Main goal of the test

The main goal of this test is to see whether different jet setups will improve the trenching capabilities in cohesive soils. The test will be executed to find out how the forces are acting on the jetting sword with different nozzle sizes and distances in front of the plough.

The research in this thesis is limited to a fully saturated homogeneous cohesive soil exposed to a moving submerged vertical jet. The range of the jet parameters is listed in table 4.1:

Table 4.1: Range of jet parameters.

Maximum jet pressure (P_J)	32	bar
Jet flowrate (Q_{jet})	5.09	m^3/hr.
Nozzle diameter (D_n)	5/10/14	mm
Angle of jet sword towards the clay (β)	90	°
Stand of distance (SoD)	10	Mm
Undrained shear strength clay (S_u)	45	kPa

4.3 Tests

Due to the limited amount of time available and the complexity of the test setup, only a limited amount of test could be performed. These tests can be performed with a large variety of parameters. Such as different nozzles sizes, trenching speed, types of clay and Jet pressure. In total sixteen tests will be executed during the practical phase of this research. In table 4.2 an overview of the tests is given. The goal behind these tests is to find out if the forces on the plough could be limited by using different nozzle diameters and distances between the nozzle and the plough. Within the hydro-lab there will be a large variety of tools to support the test. All tests will be executed under water (fresh water). To perform the tests a high-pressured water pump is rented at Rental pump, a specification sheet about the pump can be found in Appendix B.

Table 4.2: Scope experimental setup.

Test	*Jet*	*Pressure [bar]*	*Nozzle [mm]*	*Distance [mm]*	*Test objective*
1	-	-	-	-	0-test for boundary conditions
2a	Yes	21	5	45	Check forces on plough inside effective area
2b	Yes	21	5	75	Check forces on plough inside effective area
2c	Yes	21	5	75	Verify results from test 2b
2d	Yes	21	5	105	Check forces on plough outside effective area
3a	Yes	11	10	45	Check forces on plough inside effective area
3b	Yes	11	10	75	Check forces on plough inside effective area
3c	Yes	11	10	75	Verify results from test 3b
3d	Yes	11	10	105	Check forces on plough outside effective area
4a	Yes	8	14	45	Check forces on plough inside effective area
4b	Yes	8	14	75	Check forces on plough inside effective area
4c	Yes	8	14	75	Verify results from test 4c
4d	Yes	8	14	105	Check forces on plough outside effective area
5	No	-	45	-	Simulate the effects of a rotating nozzle
6	No	-	45	-	Simulate the effects of a rotating nozzle

4.4 Test setup

For my test I will be using an already existing setup. In figure 4.1 a visual of the test setup is shown. On top is a rail where over a cart is guided. The plough and jets are attached to the cart, which will be pulled through a clay sample. In this test setup the horizontal and vertical forces on the plough will be measured, see figure 4.2 for the placement of the sensors on the jetting sword.

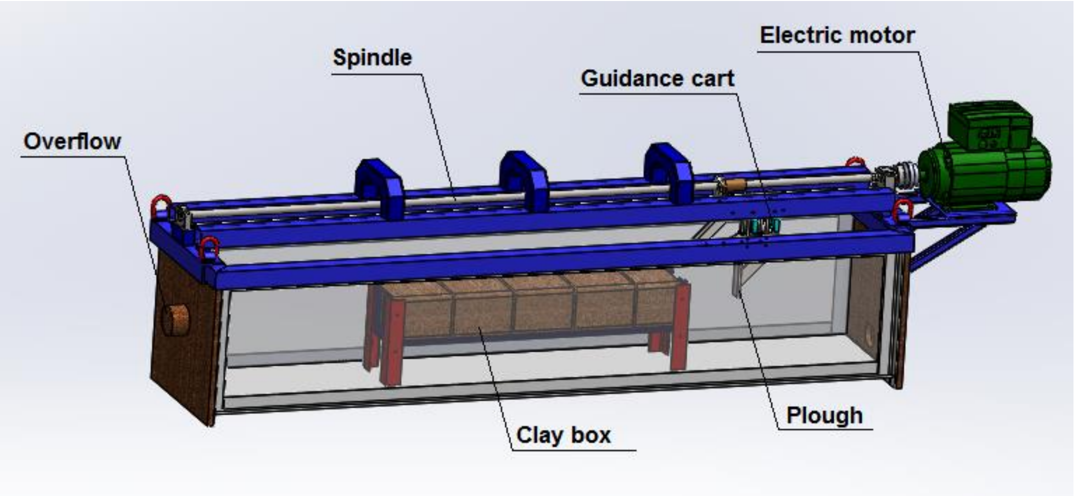


Figure 4.1: Test setup

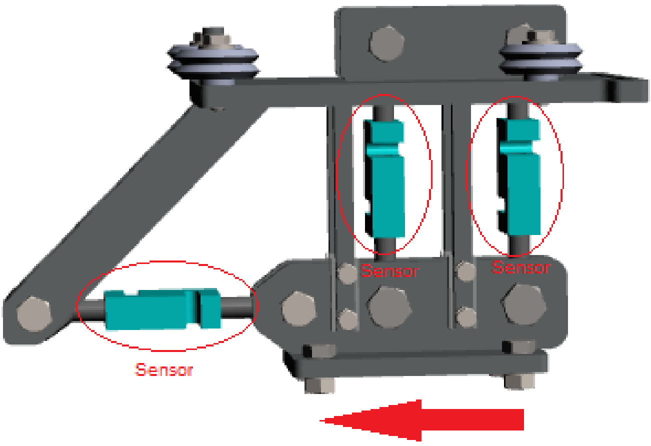


Figure 4.2: Plough guide cart including sensors

In figure 4.3 the final design of the plough is shown. The dimensions of the jetting sword will be 145*40*10mm. The length is based on the ploughing depth of 60mm + the length that the plough will hang above the clay. The width of the plough is based on the maximal available width of the test setup without being influenced by the side panels. To determent this width a rule of thumb was used of 15mm clear of the sides + three times the width of the plough.

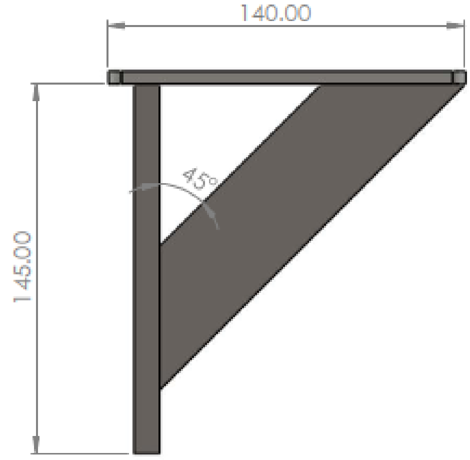


Figure 4.3: Left sideview of the plough

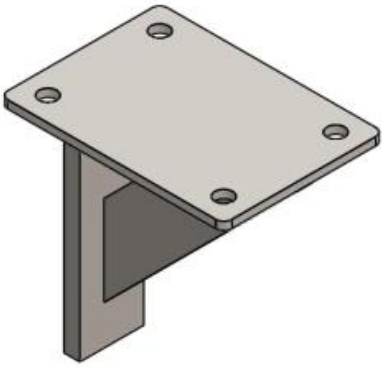


Figure 4.4: Isometric view of the plough

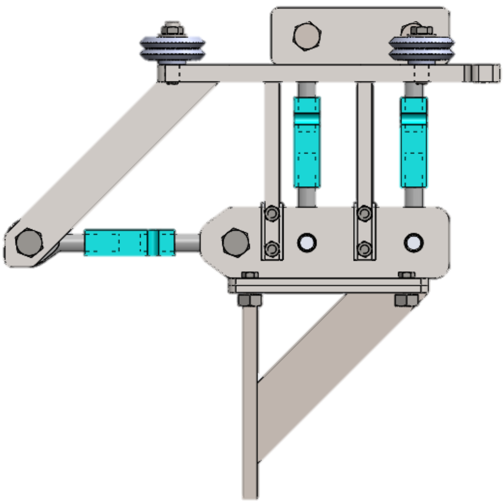


Figure 4.5: Overall view plough including plough holder.

4.5 Description of the tests

4.5.1 Test 1

Test one will be the test to set the boundary conditions for the practical research. The first test will be without a jet attached to the plough to see what the forces are that are acting on the plough when going through the clay.

- Plough depth: 65mm
- Plough width: 40mm
- Ploughing speed: 66 m/h

4.5.2 Test 2: 5mm nozzle

The first three tests that will be conducted are with the 5mm nozzle. This is the smallest nozzle that will be applied during these tests. All three tests have a different distance between the nozzle and plough. In test 2a the distance between nozzle and plough will be 45mm, this will be increased in test 2b to 75mm. Test 2c will be a repeat of test 2b to check if the results from both tests are comparable and no mistakes are made. The final test with the 5mm nozzle will be conducted with 105mm between plough and nozzle. The 90mm distance will be outside of the effective range of the plough.

- Plough depth: 65mm
- Plough width: 40mm
- Ploughing speed: 66 m/h

4.5.3 Test 3: 10mm nozzle

Test 3 is comparable to test 2. The difference between test 2 and 3 will be the nozzle. The nozzle diameter in these tests will be 10mm. With the increased nozzle diameter, the main objective of these test is to see with which factor the forces on the plough will increase or decrease, and if this could be of any benefit for Boskalis. The test with 60mm between the plough and nozzle will be done twice to compare whether any mistakes are made.

- Plough depth: 65mm
- Plough width: 40mm
- Ploughing speed: 66 m/h

4.5.4 Test 4: 14mm nozzle

Test 4 is like test 2 and 3 but with a bigger nozzle. During these tests a nozzle of 14mm diameter will be used.

- Plough depth: 65mm
- Plough width: 40mm
- Ploughing speed: 66 m/h

4.5.5 Test 5 & 6: Larger nozzle

In test 5 and 6 a rotating nozzle of 45mm will be simulated. Due to the capacity of the pump it is not possible to do a test with a 45mm rotating nozzle. To simulate the effects of the rotating nozzles, calculation have been made that show what the cavity depth and width is with the pressure of 11.3 bar. This cavity depth and width will be removed manually instead of by a jet so that the pressures action on the plough could be accurately measured.

- Plough depth: 65mm
- Plough width: 40mm
- Ploughing speed: 66 m/h

4.6 Clay sample

The block of clay is selected based on:
Undrained shear strength
Shear strength is the strength of a material or component against the type of yield or structural failure where the material or component fails in shear. The shear strength is the load an object can hold in a parallel direction to the face of the material (Gurp, 2014). The selected clay had an undrained shear strength in a range of 35 to 45 kPa.

Geometry of the block
The clay will be placed in a clay holder, due to the restricted dimensions of the holder the options were limited. The decision was between one large slap of clay that fills the holder completely or fill the holder with a couple smaller blocks. Due to the easier manageability, the smaller blocks of 16*15.5*20.5mm were selected.

Homogeneity
It is important that the characteristics of the clay are constant over the whole block. High deviation in undrained shear strength can influence the test results.

Consistency
is wanted for the accuracy of the tests furthermore, all clay blocks must be like have results that are comparable. The selected clay was acquired from Ginjaar clay factory. These bricks are made of river clay and have a high homogeneity throughout the entire clay block. The properties of the clay are tested in the Boskalis Dolman laboratory and are shown in table 4.3. Additional information of the clay sample can be found in Appendix D.

Table 4.3: Results of Dolman laboratory clay test

Test	Ginjaar Clay	Unit
Moister content	27,9	%
Dry matter content	78,2	%
Density (dry)	1537	Kg/m^3
Density (situ)	1969	Kg/m^3
Specific gravity	2601	Kg/m^3
Shear strength	45	kPa
Plastic limit	16	%
Liquid limit	45	%
Plasticity index	29	%
D50	9	μm

4.7 Shear strength

In order to determine the shear strength of the clay, two tests will be conducted before and after the test. First the hand vane in figure 4.6 is used to check the shear strength of the clay on the outside. The remolded shear strength is conducted straight after the shear strength, in the same hole created by the first shear strength. Secondly a field vane, as shown in figure

4.7, is used to measure the shear strength at 50mm inside the clay block. In total, six times a measurement is taken with the hand vane, and three times with the field vane. In the final report of each test, the averages of the shear and remolded strength tests from the hand vane and field vane are shown. Figure 4.8 shows an overview of the measurements taken before the test is conducted.

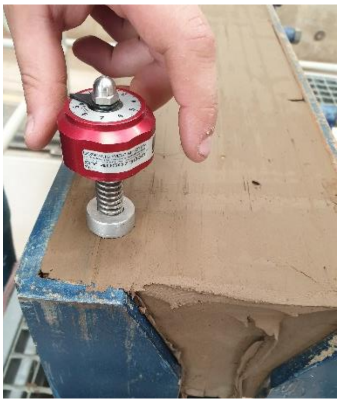


Figure 4.6: Hand vane

Figure 4.7: Field vane

Figure 4.8: Overview of the shear strength measurements

5

TEST RESULTS

5.1 Introduction

In this chapter the results from each nozzle type will be presented. The goal of the tests is to find out what the reduction factors are for ploughing when using different sizes of nozzles compared to using a plough only setup. Test 7,8 and 13 are conducted with the 5 mm nozzle. Test 9,10 and 14 are conducted with the 10 mm nozzle. Test 15 and 16 are tests conducted to have extra information which will be explained in section 5.2. The results of all the test can be found in Appendix E.

5.2 Final testing program

During the execution of the test some changes are made to the test program in order to get the necessary results. The main reason for changing the test program was the malfunctioning of the horizontal sensor after test 4. With the replacing of the broken sensor the tests that are conducted after test 4 had a different configuration then the test conducted before the malfunctioning before, therefore the tests conducted before test 4 are not reliable enough to be taken into the results during this research. An overview of the conducted tests can be found in table 5.1.

5.2.1 14 mm nozzle

Test 11 was the first test of the 14 mm nozzle. The test was conducted with 45 mm between nozzle and plough and a pressure of 17 bar. After the test, once the water was drained, it was clear that the 14 mm nozzle did not have the necessary pressure to go through the entire clay block. It only had a penetration depth of 53 mm. Therefore, the decision was made to cancel the 14mm nozzle tests and add two other test in the form of test 15 and 16.

5.2.2 Test 15

The first replacement test was test 15. This test was conducted with nozzles, only first half of the clay box was used for the 10 mm nozzle and the last part of the clay box was used for the 5 mm nozzle. The aim of this test was to see what the cavity width and depth of the 5 mm and 10 mm nozzle was.

5.2.3 Test 16

In replacement test 16, the cavity's width of the 5 mm and 10 mm nozzle was cut out of the clay before the test started. The test was conducted with only a plough attached to the cart.

The aim of this test was to see what the reduction force was when there was no active nozzle in front, that would jet away the clay inside the area of influence during a test.

Table 5.1: Overview of the conducted experimental tests

Test No.	***Jet***	***Pressure [bar]***	***Nozzle diameter [mm]***	***Distance of nozzle [mm]***	***Objective***	***Valid***
1	No	-	-	-	Determine boundary conditions	
2	Yes	32	5	45	Check forces& deformation inside influence area	
3	Yes	32	5	45	Check forces & deformation inside influence area	
4	Yes	32	5	75	Check forces & deformation on the edge of influence area	
5	Yes	32	5	75	Check reliability of broken sensor	
6	No	-	-	-	Determine boundary new conditions	
7	Yes	32	5	75	Force comparison with test 4	
8	Yes	32	5	105	Check forces & deformation outside of the influence area	
9	Yes	20	10	45	Check forces& deformation inside influence area	
10	Yes	20	10	105	Check forces& deformation outside of the influence are	
11	Yes	17	14	45	Check forces& deformation inside influence area	
12	Yes	20	10	75	Check forces & deformation on the edge of influence area	
13	Yes	32	5	45	Results comparison with test 3, with new boundary conditions set up	
14	Yes	32	10	75	Results comparison with test 12	
15	Yes	32/20	5/10	-	Visual see what the cavity width & depth is with only a active nozzle.	
16	No	-	-	-	Measuring ploughing forces without nozzle attached but with nozzle cavity cut out	

5.3 Test accuracy

During testing, one test was done twice, because the result was high compared to the results from another nozzle. So to check if this result was correct, test 12 was repeated and named test 14. The average horizontal force measured in test 12 was 295,9 Newton, when the same test was repeated in test 14 the average horizontal force was 245,6 Newton, making it a difference of 50 Newton in total.

Because the difference between test 12 and 14 is 50 newtons, there could be a possibility that all the tests have the same deviation. With the 50 newton deviation either added or subtracted from the average measured horizontal force it is not possible to conclude which size nozzle would bring the best results without doing more test.

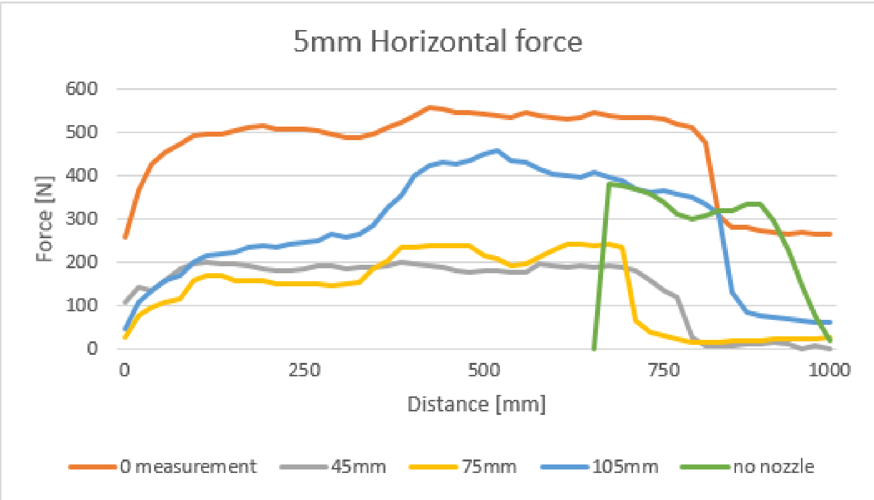
This could have been prevented if the decision was made to have less variants and do all the test multiple times.

5.4 Horizontal forces acting on the plough

Table 5.2 shows the horizontal measured forces that were acting on the plough during the tests conducted with the 5mm nozzle. Table 5.3 shows the horizontal forces measured with the 10mm nozzle. Pictures and results of the individual test can be found in Appendix E. All forces in the graphs are from the data directly from the tests. The shear strength of the clay blocks used during testing ranged between 40 and 50 kPa. The graph shows that there is a visible reduction in the horizontal forces between jetting without plough (0 measurement) and Pre trench ploughing with the use of a nozzle in front of the plough. There is also a significant difference between pre trenched without a nozzle (no nozzle) and pre trenching with an active jet nozzle in front of it.

Notes on Table 5.2:
During the tests the plough was stopped at approx. 800mm. This was to visually see what the behavior of the clay is in front of the plough, within the area of influence. The no nozzle test (green line), as described in paragraph 5.2.3 was half conducted with a 10mm nozzle and half with a 5mm nozzle. The second half of the test was the 5mm. In the 105mm test the jet nozzle was turned off at approx. 400mm. This was to see how the horizontal force would behave after the jet nozzle was turned off. The forces in table 5.2 are not scaled.

Table 5.2: Overview of the horizontal forces of the 5mm nozzle



Notes on Table 5.3:
During the test at approx. 750mm all tests were stopped to see what the behavior of the clay is in front of the plough. The no nozzle test (green line), as described in paragraph 5.2.3 was half conducted with a 10mm nozzle and half with a 5mm nozzle. The first half of the test was the 10mm nozzle.

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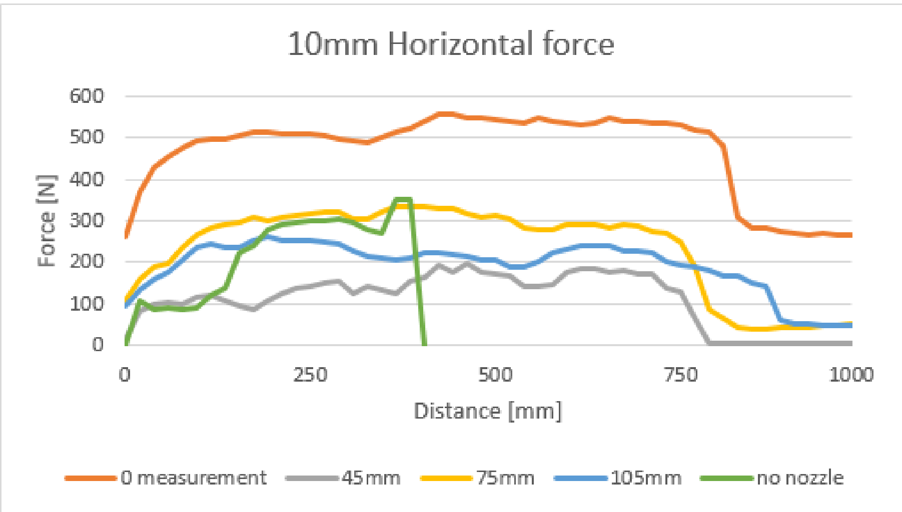
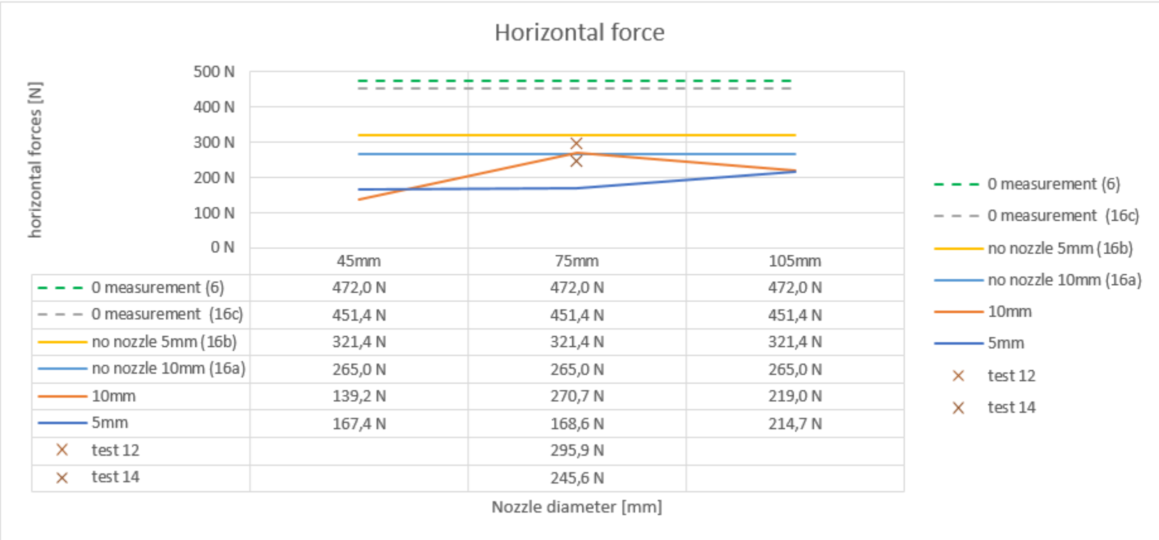
Table 5.3: Overview of the horizontal forces of the 10mm nozzle



5.5 Reduction percentage by jetting

In Table 5.4 all the forces are scaled to 45 kPa so that any differences in the shear strength of the clay blocks is eliminated. The double tests as described in paragraph 5.3 are indicated with crosses in the table.

Table 5.4: Summary of the horizontal forces



	45mm	75mm	105mm
0 measurement (6)	472,0 N	472,0 N	472,0 N
0 measurement (16c)	451,4 N	451,4 N	451,4 N
no nozzle 5mm (16b)	321,4 N	321,4 N	321,4 N
no nozzle 10mm (16a)	265,0 N	265,0 N	265,0 N
10mm	139,2 N	270,7 N	219,0 N
5mm	167,4 N	168,6 N	214,7 N
test 12		295,9 N	
test 14		245,6 N	

As mentioned in paragraph 5.3, due to a difference of 50 N in two similar test all the test results are close to each other, which makes it not possible to say which nozzle has a better reduction. In Table 5.5 a reduction range is given, which indicated the possible horizontal reduction the test could give. All results are based on the average measured horizontal force plus and minus 50 Newton.

Table 5.5: Reduction range of nozzles

Test number	***Nozzle diameter***	***Nozzle – plough distance [mm]***	***Average measured horizontal force [N]***	***Reduction range [%]***
Average 0 measurement	-	-	461.7	-
13	5	45	167.4	52.9 - 74.6
7	5	75	168.6	52.6 - 74.3
8	5	105	214.7	42.7 - 64.3
16 (B)	-	-	321.4	19.6 - 41.2
9	10	45	139.2	59.0 – 80.7
12	10	75	295.9	25.1 – 46.7
14	10	75	245.6	36.0 – 57.6
10	10	105	219.0	41.7 – 63.4
16 (A)	-	-	265.0	31.8 – 53.4

5.6 Bearing capacity factor

Traditionally, bearing capacity factors are used to correlate the soil strength values to the resulting ultimate bearing capacity (as for instance is done with the Brinch-Hansen shallow foundation method). In this method bearing capacity factors are used to correlate the effect of:

- Cohesion
- Internal friction angle
- Overburden pressure

However, when looking at the set-up one can ascertain certain similarities between the ploughing with its accompanying slip-surfaces and the failure mode of a shallow foundation. It is therefore an idea to create an own "bearing capacity factor". By doing this and correlating the soils strength properties to its ploughing resistance one could possibly extrapolate these results to out-door, real life projects and use this in an advantageous manner.

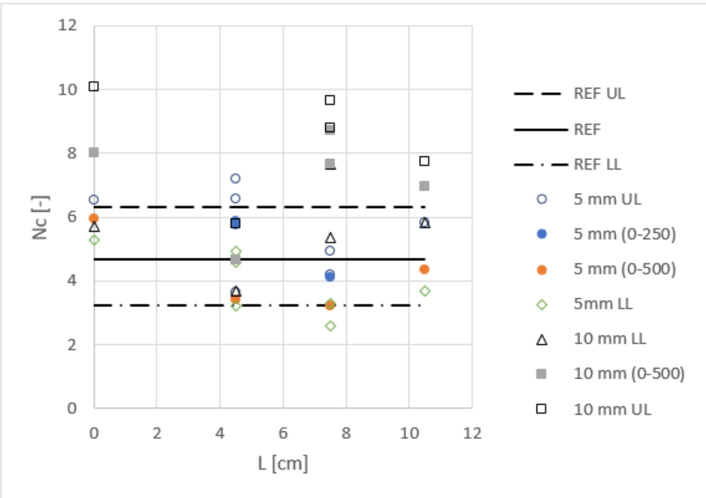
To calculate the horizontal forces on the plough the following equation used by Gurp (2014) can be used (Gurp, 2014).

$$F_{Horizontal} = N_c * (A_{plough} - A_{jet}) * S_{uv}$$

$F_{horizontal}$	Horizontal force measured in test	[N]
N_c	Dimensionless coefficient for cohesion	[-]
A_{plough}	Area of the plough	[m^2]
A_{jet}	Area created by jet nozzle	[m^2]
S_{uv}	Undrained shear strength	[Pa]

In Table 5.6 the N_c coefficient of the tests is determined with the use of EQ-4.

Table 5.6: N_c Factor reductions.



In Table 5.6 the upper limit (UL), Lower limit (LL) and average of each test is given, these indicate the lowest and highest measured value during the tests. The solid line shows the N_c value from the boundary condition test. The required N_c for the boundary condition test is 4.7 and can be used as a base reference towards the other tests. A lower N_c Value means a decreased in resistance on the plough and is beneficial for the trenching process.

Comparing the results from the 5mm and 10mm nozzle with the boundary condition test, a decrease is visible with the 5mm nozzle and an increase is visible in the 10mm nozzle. This means the 5mm nozzle does have a positive effect on the trenching process, but with a decrease to only 3.5 the 5mm nozzle still falls within the lower limit of the reference tests.

Therefor can be said that the 5mm nozzle does have a positive effect on the trenching process but more tests need to be conducted to have a more reliable N_c value.

6
DISCUSSION

6.1 Introduction

Chapter six will be a reflection on the experimental setup. In this chapter there will be a reflection on what the causes of the inaccuracy's are and on how this can be prevented in future experiments. An improved testing scope and description will be proposed in section 6.3 that would represent the testing purposes better.

6.2 Test inaccuracy's

In this section the causes of the test inaccuracies are explained, and an indication will have been given to how this could have been prevented.

6.2.1 Clay box dimensions

As explained in section3.3, the test setup is a scaled version of the jetting sword and only the effects of a single nozzle were tested. For the test, the jet nozzle had to jet through the entire block of clay. To get rid of the excess water created by the jetting nozzles, some precautionary actions were taken. These actions were the removing of a part of the steel so more water could flow away and the placing of a wooden frame so that more water could flow away. Figure shows 6.1 the difference between the clay holding boxes with and without the precautionary actions.

Figure 6.1: precautionary actions for water pressure

The expectation is that not enough water could flow away when the test was being performed and that the water got deflected upwards creating a larger cavity. A similar example of this is given in figure 6.2. This could have been prevented by having additional places where water could leave the clay box.

Due to the deflection of the water a reverse tapered cavity is created. A reverse taper is a cavity where the jet stream removes more material at the bottom of the cut than at the top. The natural shape of an waterjet stream is conical, and as the stream travels farther from the nozzle, the shape will become more spread (Metalformingmagazine, 2018). In figure 6.3 a reverse taper cavity is shown.

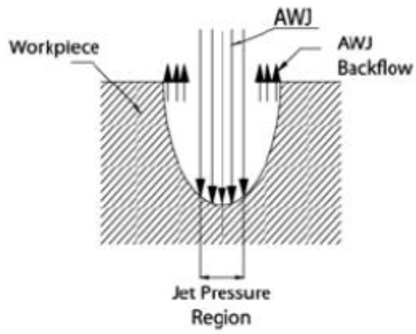


Figure 6.2: Cavity of water deflection

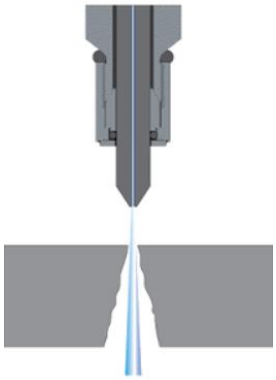


Figure 6.3: Reverse taper cavity

There are many strategies to control taper. One of these strategies is to increase/decrease the speed of the plough. Also, the standoff distance (the distance between the end of the cutting nozzle and the material) can be decreased to have less effect from the taper.

6.2.2 Cavity width

Test 15 was the test where no plough and only an active nozzle is attached. The goal of this test was to see what the cavity width of a 5mm and 10mm nozzles was. In figure 6.4 the results of the test are shown.

Figure 6.4: Results of test 15

If test 15 was conducted at the beginning, the decision could have been made to change the nozzles. The results of the test were that the 5mm nozzle had a cavity width of 22mm and the 10mm had a cavity width of 29mm. If this test was done at the beginning the decision could have been made to change one nozzle to 3mm and see if the difference between both nozzles was bigger. In this way, the results would be more spread, and a more defined conclusion could have been given.

6.2.3 Test accuracy.

To improve the accuracy of the test results, more tests must be conducted. At least all tests must be repeated twice or more so that a more accurate average test result can be found.
The scope of the experiments should have been changed to two nozzles and three distances. This way all the test could have been done twice. Another reason for having less valid tests is the malfunctioning of the horizontal sensor in test 4. If this did not happen five other tests could have been conducted. This would have made it possible to do every test twice.

6.3 Improved testing scope

Reflecting on the test that where conducted during the practical phase of this research, a new test scope was made that would have fit better with the goals set for this research. In table 6.1 the new test proposal is presented and a description on the decisions that are made for this new proposal are explained in this chapter.

- The first test that should be conducted is the test with only nozzles. In this test the difference between both cavity widths should be checked. If the cavity widths are too close to each other go for one or two different nozzle's and conduct an extra test and see if the range between both nozzles is larger. The larger the range, the better it is for the test because when comparing the results there is a bigger difference between the outcome of the test results and a better conclusion can be made. A minimum of three times this test should be conducted to have a good indication of the cavity width.
- After the first tests a minimum of two tests should be conducted with only a plough attached to the cart. In this test the boundary conditions will be determined, this will be the maximum force that will be put on the plough because there will be no clay removed by an active jet. When the results of both the boundary condition tests are not similar, a third test should be conducted to see if this one is comparable.
- Once the diameters of the nozzles are determined and the boundary condition of the tests are verified, all the tests with the nozzle and plough can be conducted. Every nozzle distance should be conducted at least three times to have a more trustworthy result. If any strange results come out of the tests, no further test should be conducted until it is clear what caused these strange results.
- Once all the test with nozzle and plough are conducted, a final test should be done, where manually the cavity width should be removed and only a plough should be used during this experiment. The main objective of this test is to see what the force reduction is when the area of the nozzle has been removed, but no active nozzle is used during the test, to remove the clay building up in the area of influence.

Table 6.1: New proposal of the tests

Test no.	Jet	Nozzle	Pressure	Distance	Objective
1	Yes	5/10	32/20	-	Check the cavity width and determined if the difference between the cavity widths are good large enough
2	Yes	5/10	32/20	-	Check the cavity width and determined if the difference between the cavity widths are good large enough
3	Yes	5/10	32/20	-	Check the cavity width and determined if the difference between the cavity widths are good large enough
4	No	-	-	-	Set boundary conditions of the test
5	No	-	-	-	Set boundary conditions of the test
6	Yes	5	32	45	Three tests to see what the force reduction is when the nozzle is active in the area of influence of the plough
7	Yes	5	32	45	
8	Yes	5	32	45	
9	Yes	5	32	75	Three tests to see what the forces are when the nozzle is active on the edge of the area of influence form the plough
10	Yes	5	32	75	
11	Yes	5	32	75	
12	Yes	5	32	105	Three tests to see what the force reduction is when the nozzle is active outside of the area of influence from the plough
13	Yes	5	32	105	
14	Yes	5	32	105	
15	Yes	10	20	45	Test 13 to 15 is conducted with the large nozzle and small distance. The comparison is made with test 4 to 6 and the boundary conditions
16	Yes	10	20	45	
17	Yes	10	20	45	
18	Yes	10	20	75	Three tests to see what the forces are when the nozzle is active on the edge of the area of influence form the plough
19	Yes	10	20	75	
20	Yes	10	20	75	
21	Yes	10	20	105	Three tests to see what the force reduction is when the nozzle is active outside of the area of influence from the plough
22	Yes	10	20	105	
23	Yes	10	20	105	
24	No	5/10	-	-	One test is conducted that shows the forces on the plough with the cavity widths cut out but not with an active nozzle that breaks the clay inside the area of influence.
25	-	-	-	-	Room for extra experiments in case off test failure

7
CONCLUSION

7.1 Introduction

In chapter seven the conclusions of the research are presented. First all the sub questions will be answered. Then the main question will be answered and finally a general conclusion of the research and the results will be presented.

7.2 Sub-Question one

Sub-question one was: *"What knowledge is currently known and what is missing in the field of trenching?"*
The following information is already acquired for Boskalis.

- Ploughing forces in sand and clay.
- Jetting forces in sand and clay.
- Development of cable burial tools.
- Improvement on ploughing sword.
- Improvement of jetting sword.
- The differences between different trenching tools and when to apply them in the field.

Knowledge that is missing for this research:

- Force reduction on a jetting sword with different jet nozzle setups.
- The effects on the Bearing capacity factor (N_c) of stiff clay when using different jet nozzle setups.

7.3 Sub-Question two

What different type of jet nozzles are currently used during jet trench cutting?

The current trenching equipment of Boskalis is equipped with straight conventional nozzles. Currently researches are being conducted by the R&D department of Boskalis to see what the impact off rotational jetting is on the trenching process of the current equipment, that is being used by the offshore division and also on the possible implementation on the drag heads of the dredging fleet. Additional research is being conducted to investigate how to install rotational jets on these assets.

7.4 Sub-Question Three

What is the difference between rotational and conventional nozzles?

With conventional jet nozzles you get a single water jet that creates a small and deep cavity. Which results in a larger area that will be influenced by the angle of repose, that can be move into the created cavity by the nozzle.

A rotational jet combines the force of a conventional straight jet and the spray area of a 25-degree nozzle. This results in a larger effective area but a shallower cavity. With a larger effective area more clay is being removed which results in less clay in between the individual nozzles this results in less forces acting on the jetting sword.

7.5 Sub-Question Four

How can the different nozzle setups be simulated in the experimental setup?

In order to simulate different nozzle setups, the following components where made in order to have to possibility to change the setup in different configurations.

- A jet attachment was made where different nozzles can be screwed on.
- The jet nozzle holder was made in order to change the nozzle – plough distance to 45/75 and 105mm distance.

The different nozzle sizes are used to simulate the larger effected area's that a rotating nozzle simulates.

Because the test setup is a scaled version of the equipment of Boskalis, the plough had a maximum width. This width is dependent of the width of the clay box where the clay was placed in. The ploughs maximum width was determined by having it not bigger than 1/3 of the total width of the clay box and with an additional safety of 15mm on either side, so that the area of influence created by the plough is not affected by the sides of the clay box.

7.6 Sub-Question five

Can the trench making capability be improved with different nozzle setup?

Different nozzle setups can make a difference in the trench making capability. As mentioned in chapter 5 the 5mm nozzle shows to have a bigger impact on the trenching process. But because the tests fall into the upper and lower limit of the boundary condition tests, more tests should be conducted to have a larger scope and a more reliable result.

When checking the distance between the nozzle and plough, the smallest distance appears to have the largest effect on the force reduction. Because this nozzle is inside the area of influence, it actively removes the clay being pushed forward by the plough. The middle distance appears to have mixed results and more tests needs to be done. However, the results show that the active nozzle is on the edge of the area of influence. The plastic zone in front of the plough cannot properly develop making more resistance in the clay pushing forward.

8

RECOMMANDATION

8.1 Introduction

The results of this research are not decisive, therefor more research is recommended. Throughout the duration of the research, more questions which can be used for future research are listed in the recommendations in section 8.3

8.2 Operational manual

In order to prevent the mistakes which were made during the practical phase of this research, an operational manual has been created to help future researchers in installing the trenching box the right way. In this manual the installation and operation of the trenching box is explained. The manual also shows an overview of the risks of the tests, where to find the correct equipment, the steps to follow and useful tips in order to operate the trenching box. The operational manual can be found in Appendix F and files used during the practical phase of this research can be acquired at the R&D cables & flexibles department of Boskalis.

8.3 Continuation of the research

Based on the results of this study more research is recommended. In this paragraph a separation is made between recommendations of the current research and recommendations for future researches.

8.3.1 Improvements on the current research

- Continuation of the current experiments

By performing more tests, a more decisive conclusion can be made on the current topic. Therefor it is recommended to perform more tests on this topic, with the current nozzles and other nozzles. A larger test scope can be made to have a better understanding of the effects of different nozzles.

- Enlarge the results of the nozzles

To have more conclusive results it is recommended to add more nozzles into the research. Not only the 5mm and 10mm nozzle should be tested, but more nozzle sizes should be tested to see what the effect of these nozzles is on the clay.

8.3.2 Future research topics

- Conduct tests in undrained clay

Clays in the seabed are in an undrained state and during this research all tests were conducted in clays of a drained state. In order to have a better understanding of the behavior of jetting nozzles in undrained clay, a follow up research should be conducted to see the difference in behavior between drained and undrained clays.

- Vertical forces

The results of the vertical forces from the test shows that the larger the area the jet removes, the larger the vertical forces become. an additional research is necessary to understand what the reasons are behind this phenomenon.

- Water lubrication of the plough

In the field a jet nozzle will not go through the entire clay layer in one time. The excess water that comes from the jet then functions as lubrication of for the plough. A research should be conducted to see what the effects are when a jet nozzle does not go through the entire clay layer and acts as lubrication for the plough.

- Nozzle effects on the area of influence

Research should be conducted to see what the nozzle effects are on the area of influence. does the location of the nozzle in front of the plough matter? And what happens to the area of influence when you put a nozzle on the boundary of this area? These are some questions that came up during this research and more research should be conducted in this field.

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