Rotational jetting in clay

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ROTATIONAL JETTING IN CLAY

by

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An electronic version of this thesis is available at http://repository.tudelft.nl/.
This study is conducted at Royal Boskalis Westminster N.V. in Papendrecht. Royal Boskalis Westminster N.V. is one of the leading companies operating in the dredging, maritime infrastructure and maritime services sectors. This report is written in order to graduate for the MSc degree in Offshore and Dredging Engineering at the Delft University of Technology.

I am very grateful to Boskalis for giving me the opportunity to graduate at their Research and Development department. I would like to thank the R & D department for offering me such an interesting graduation subject. I enjoyed the combination of developing a model and conducting experimental research. I especially would like to thank Arno Nobel, as my daily supervisor at Boskalis. I couldn't have asked for a better personal mentor than Arno. His enthusiasm and knowledge about this subject were really motivating and contributed to the fulfillment of this project. Furthermore thanks to Mark Biesheuvel for sharing his thoughts and almost famous “what if-question” during my experiments, to Ike van Giffen and Sjoerd van Bracht for sharing some knowledge about visualization functions in Matlab, to Axel Smit for giving me a helping hand when I needed one when I was working on the first test setup, to Cees van Rhee and Arno Talmon for their insight and advice during the graduation process, to Wim-Paul Breugem for willing to take place in the examination committee as external member. I also would like to thanks my fellow graduate students at the R & D department for the really nice working atmosphere at the office.

I am very grateful to my family who give me all the support and faith I needed during my entire educational career. Finally, I have to thank my dear girlfriend Anne for her support and understanding throughout my entire studies, especially the last year when I was talking about clay far too much.

Ezra Groen
Delft
In dredging activities submerged jets are widely used for different purposes. Two main applications are considered in this study: 1) a jetting sword on a cable trencher and 2) jets located on a draghead. Both jetting systems are especially designed for jetting sands and achieving large excavation productions in sandy soils. However when cohesive soils have to be jetted, the production decreases drastically. In sandy soils the jet creates wide cavities, while the cavity width produced by a jet in cohesive soils like clay is very narrow. Different researchers found that the cavity depth decreases only a little by an increasing traversing velocity of the nozzle and the cavity width to remain more or less constant, i.e. the jet can process more clay than generally is supplied. This results in the fact that the highest production will be achieved at the highest traversing velocities. However, the traversing velocity of the nozzle is limited by the tool (trencher/draghead). With the use of a rotating jet, more soil is supplied to the jet. The affected area is increased and the combined traversing velocity (normal traversing part + rotating velocity part) is increased as well.

In this research the possible increase in excavation production of clay of a rotating jet compared to a conventional non-rotating jet for two purposes is studied; a rotating jet on a trenching machine and a rotating jet on a draghead.

This research exists out of two models and two experimental test setups. Both models consist of two modules; a calculation module and a visualization module. The calculation module predicts the excavation production as a function of: 1) Jet pressure, 2) Undrained shear strength, 3) Traversing velocity, 4) Rotational velocity, 5) Nozzle angle, 6) Nozzle diameter. The model is based on the entrainment of water at the back-side of the jet and soil at the front-side of the jet. The more entrainment of soil, the greater the increase in jet mixture density and the higher the decrease in stagnation pressure, resulting in a smaller penetration depth.

The visualization module shows the cavity shape based on the cavity parameters modeled in the calculation module. The jet is modeled as a cone based on the geometry calculated in the calculated module. The jet will travel along a trajectory depending on traversing velocity and rotational velocity. The trajectory were the jet has been present, is removed and visualized as excavated volume.

Two experimental test setups are developed in order to validate the models. The main parameters varied were the traversing velocity, nozzle angle (45°/60°), rotational velocity and jet pressure. For the trenching setup the increase in excavation production found, lies in a range between 6 and 7 for a traversing velocity of 15 - 215 m/h. For the draghead setup the traversing velocity was varied between 35 and 1800 m/h. The increase in excavation production can be up to a factor 4.

The calculation module for the trenching application is able to produce a good estimation of the excavation production for the 45° nozzle. The calculation module overestimates the excavation production of the 60° nozzle compared to the experimental results. For the draghead application the developed model is able to give results close to the corresponding experimental results for traversing velocities lower than 1000 m/h. For larger traversing velocities the model underestimates the excavation production compared to the experimental results. The results of the experiments including the developed models can be used as a base for the design of rotating jets on a jetting sword or draghead.
## NOMENCLATURE

**Roman letters**

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<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<td>$A_c$</td>
<td>Cross-sectional cavity area</td>
<td>$m^2$</td>
</tr>
<tr>
<td>$A_n$</td>
<td>Cross-sectional nozzle flow area</td>
<td>$m^2$</td>
</tr>
<tr>
<td>$a_{1,2}$</td>
<td>Auxiliary variable</td>
<td>–</td>
</tr>
<tr>
<td>$b_{1,2}$</td>
<td>Auxiliary variable</td>
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<tr>
<td>$c'$</td>
<td>Cohesion</td>
<td>Pa</td>
</tr>
<tr>
<td>$c_f$</td>
<td>Friction coefficient</td>
<td>–</td>
</tr>
<tr>
<td>$D$</td>
<td>Diameter</td>
<td>m</td>
</tr>
<tr>
<td>$D_n$</td>
<td>Nozzle diameter</td>
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</tr>
<tr>
<td>$dQ$</td>
<td>Entrainment</td>
<td>$m^3/s$</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravitational constant</td>
<td>$m/s^2$</td>
</tr>
<tr>
<td>$h_c$</td>
<td>Height of soil layer</td>
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<tr>
<td>$I$</td>
<td>Momentum flux</td>
<td>N</td>
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<tr>
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<tr>
<td>$M_{ex}$</td>
<td>Excavation production rate</td>
<td>$m^3/s$</td>
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</tr>
<tr>
<td>$n$</td>
<td>Number of nozzle outlet's on nozzle head</td>
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<tr>
<td>$n$</td>
<td>Porosity</td>
<td>–</td>
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<td>$N_{bc}$</td>
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<td>$P_h$</td>
<td>Hydraulic power</td>
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<td>$p_{jet}$</td>
<td>Jet pressure at nozzle exit</td>
<td>Pa</td>
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<tr>
<td>$PI$</td>
<td>Plasticity index</td>
<td>–</td>
</tr>
<tr>
<td>$Q$</td>
<td>Jet flow rate</td>
<td>$m^3/s$</td>
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Specific discharge $m/s$
Radial distance to center-line of the jet $m$
Degree of saturation $–$
Distance from the central point of the nozzle $m$
Jet distance, measured along the center-line of the jet $m$
Stand Off Distance $m$
Undrained shear strength $Pa$
Time to failure $s$
Axial jet velocity at center-line $m/s$
Uniform jet velocity $m/s$
Initial jet velocity at nozzle exit $m/s$
Jet velocity at $(s,r)$ $m/s$
Volume $m^3$
Velocity $m/s$
Combined traversing velocity of jet $m/s$
Volume of pores $m^3$
Total volume $m^3$
Volume of water $m^3$
Weight $kg$
Water content $–$
Liquid limit $–$
Mass of particle $kg$
Plastic limit $–$
Mass of water $kg$
Cavity width $m$
Thickness of soil layer $m$
Jet cavity depth $m$
**Greek letters**

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<td>( \alpha_n )</td>
<td>Nozzle angle</td>
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</tr>
<tr>
<td>( \alpha_{mom} )</td>
<td>Entrainment coefficient</td>
<td>–</td>
</tr>
<tr>
<td>( \dot{\epsilon} )</td>
<td>Strain rate</td>
<td>1/s</td>
</tr>
<tr>
<td>( \epsilon )</td>
<td>Strain rate</td>
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<td>( \gamma )</td>
<td>Volumetric weight</td>
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<tr>
<td>( \mu_n )</td>
<td>Nozzle discharge coefficient</td>
<td>–</td>
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<td>( \omega_{cyc} )</td>
<td>Revolutions of jet axis</td>
<td>rev/s</td>
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<td>( \phi )</td>
<td>Internal friction angle</td>
<td>°</td>
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<tr>
<td>( \rho_m )</td>
<td>Mixture density of the jet</td>
<td>kg/m³</td>
</tr>
<tr>
<td>( \rho_p )</td>
<td>Density of particle</td>
<td>kg/m³</td>
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<td>( \rho_w )</td>
<td>Density of water</td>
<td>kg/m³</td>
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<tr>
<td>( \sigma )</td>
<td>Total stress applied normal to the shear plane</td>
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<td>( \sigma' )</td>
<td>Effective stress</td>
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<tr>
<td>( \sigma_d )</td>
<td>Cavitation index for cone development</td>
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<tr>
<td>( \tau )</td>
<td>Shear strength</td>
<td>Pa</td>
</tr>
<tr>
<td>( \rho_{pore} )</td>
<td>Pore water pressure</td>
<td>Pa</td>
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**Subscripts**

0  At nozzle exit, or initially
a  Ambient
bl Boundary layer
c  cavity
cav Cavitation
dr Flow development region
drag Draghead setup
f  Fictitious
h  Horizontal
j  Jet
k  Slice number
m  Mixture
ref Reference
s  Soil
ss Soil surface
ss Soil surface
t  Traversing
tan Tangential
trench Trenching setup
v  Vertical
w  Water
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INTRODUCTION

1.1. BACKGROUND

In dredging activities soil is often excavated with the use of jets. They are mainly designed for jetting sands, because a single jet can produce a wide cavity in sand, resulting in a large production. Large productions are possible because in sand the erosion capacity of the shear stresses exerted by the jet are high resulting in wide cavities. In clay however, the jetted cavities are very narrow resulting in a low excavation production. Two dredging applications where jets are often used are on a jetting sword of a trenching-machine and on a draghead.

A jetting sword is often used to make a trench to bury a cable. A cable like an export cable that connects a wind-farm to shore has to be buried to protect the cable against currents, anchors and fishing nets. An example of a trenching machine is a machine named “BSS-II” (Burial Sledge System II) from VBMS (Volker Boskalis Marine Solutions). The BSS-II is used to make a trench to bury a cable. A jetting sword on a trencher jets a trench and immediately buries the cable (see figure 1.1a). For sandy soils this procedure works very well, however when on the route some parts of clay are present a problem encounters. A jetting sword as mounted on the BSS-II isn’t able to jet through clay. The parts consisting clay have to be skipped and trenched later with another machine. Off-course this is very costly and could possibly be saved with the use of rotating jets.

Another trenching machine with a jetting sword is the Trenchformer also owned by VBMS. The nozzle’s of this jetting swords are orientated vertically while traversing horizontally instead of horizontal jets as mounted on the BSS-II (see figure 1.1a). Other differences of the Trenchformer compared to the BSS-II are the ability to move by its own without the need of a pulling cable and the ability to trench after a cable is laid (post-trench) (see figure 1.2).

A Trailing Suction Hopper Dredger (TSHD) is mainly used for the reclamation of land or excavation of soil. For example, the excavation of soil can be required for deepening a canal or harbor. Another excavation application were TSHD’s are used, is the flattening of the seabed in need of the installation of sub-sea structures like manifolds, pipes and foundations for windmills or excavating a pre-trench for burying pipelines. Hopper dredgers are also widely used for the reclamation of land. Soil is excavated at a borrowing zone and trans-
ported to the reclamation zone where it is discharged with the use of floating pipelines, discharge valves in the hopper or discharge nozzle at the bow-side of the ship ("rainbowed"). A TSHD uses one or two dragheads to excavate soil from the seabed. The dragheads are mounted to a drag-arm (suction tube) that is mounted to the ship (see figure 1.3). Multiple jets are placed at the front-side of the draghead (see figure 1.4). The vertically orientated jets loosens the soil after which it can easily be sucked up by the draghead. In sand the jets are able to obtain a large excavation production. In cohesive soils like clay however, the jets don't achieve a large production. In these soils consisting mainly out of clay, the soil is removed by the cutting teeth at the backside of the draghead (see figure 1.5), resulting in high cutting forces. Large cutting forces are especially a problem when dredging at larger water depth's. At larger depth the drag-arm will be orientated more vertically and the moment equilibrium about the drag-tube becomes problematic, i.e. the draghead isn't able to produce enough horizontal pulling forces to overcome the required cutting forces. When the excavation production of jetting clay can be increased with the use of rotating jets, the cutting forces could possibly be significantly reduced.

A jet exerts different forces on the soil. The two main forces are a shear force parallel to the flow direction (shear stress) and a normal force (stagnation pressure) in the main direction of the jet flow (see figure 1.6). In sand the shear stresses exerted by the jet are mainly responsible for the characteristic large cavity width, i.e. the shear forces "pull" grains out of the cavity wall (see figure 1.7).
Clay is mainly loosened by the stagnation (normal) pressures exerted by the jet, i.e. the jet “pushes” the soil away (see figure 1.6). The stagnation pressure has to exceed the bearing stagnation pressure of the clay. The stagnation pressure of the jet decreases with distance to the nozzle exit. At a certain distance from the nozzle the jet stops penetrating the soil because the stagnation pressure equals the bearing capacity of the soil. The erosion capacity of the shear stresses exerted by the jet is negligible. This results in very narrow jet cavities; the cavities are only hardly wider than the jet diameter at the soil bed (see figure 1.8).
The specific energy of jetting a cohesive soil like clay with standard traversing jets is very high, i.e. the required power to jet a certain amount of clay is very large.

The influence of the traversing velocity of the nozzle on the decrease in stagnation pressure with distance to the nozzle exit is limited. This means that the jet cavity depth (penetration depth) only decreases a little with increasing traversing velocity. Because the cavity width is more or less independent of the traversing velocity, the highest productions are realized at the highest traversing velocities.

It is not always possible to increase the traversing velocity of the nozzle in order to use the full potential of the jet. In other words; the jet is able to “process” more clay than the tool is able to offer due to the limited traversing velocity of the tool. In these cases, the use of rotational jetting can be considered. With the use of rotating jets the effective cavity diameter can probably be increased, without increasing the jetting power, i.e. the specific energy can be lowered.

A schematic overview of how the jet cavity can be increased with the use of a rotating jets is shown in figure 1.9 for a jet sword and in figure 1.10 for draghead purposes.

Currently, rotating jets are mainly used for high pressure cleaning operations. Therefore the concept of rotating jets isn’t new. However, little literature and calculation models are available. The concept of rotational jets are widely used in pressure washers. Pressure washers make use of rotational jets because of the increase
1.1. BACKGROUND

Figure 1.9: (a) Jet cavities of jet sword, (b) Frontal view of jet cavities, (c) Jet cavities of jet sword utilized with rotating jets, (d) Frontal view of jet cavities rotating jets

Figure 1.10: (a) Jet cavities realized by a draghead (frontal view), (b) Jet (longitudinal section), (c) Jet cavities realized by draghead utilized with rotating jets.

affected area compared to a straight non-rotating jet. The increase in affected area can clearly be seen in figure 1.11.

Figure 1.11: Increase in affected area pressure washer

The working principle of a pressure washer is based on a high pressure straight jet that is forced in a direction by a constantly moving little ball causing the jet to make a rotary movement at a rotational velocity of about 3000 rpm. For this study this concept can't be used, because the rotational velocity cannot be monitored and adjusted.
1.2. **Problem Definition**

The main objective of this study is to obtain more knowledge about the possible increase in excavation production of rotational jetting in clay compared to a conventional non-rotating jet. For this research a main research question and sub questions are formulated.

**Main Research Question**

How much increase in excavation production can be achieved with rotational jetting in clay with respect to conventional jetting in case of:

- A horizontal jet, moving in horizontal direction (trenching machine)
- A vertical jet, moving in horizontal direction (draghead)

**Sub Questions**

- What is the optimal ratio between the traversing velocity \( v_t \) and the rotational velocity of the nozzle at a certain stagnation ratio (jet pressure \( p_{jet} \)/undrained shear strength of the clay \( p_{jet}/s_u \)) for both cases?
- What is the optimal distance between the nozzles (center to center) in both cases?
- What is the jetting pattern by different ratios of \( v_t/\omega_{cyc} \)?

1.3. **Scope and Outline of this Thesis**

A model is developed in order to predict the excavation production of a single moving rotating jet, based on the following input parameters:

- Jet pressure \( p_j \)
- Undrained shear strength \( s_u \)
- Traversing velocity \( v_t \)
- Rotational velocity \( \omega_{cyc} \)
- Nozzle angle \( \alpha_n \)
- Nozzle diameter \( D_n \)

The model consists of a calculation module and a visualization module. A visualization module is developed to visualize the 3D-impact of a traversing rotating jet.

Tests are conducted with two experimental test setups; a setup for the trenching application and a setup for the draghead application.

1.3.1. **Scope**

In this thesis two applications of a rotating jet are studied. The range of the jet parameters are close to each other and listed in table 1.1.

\(^1\)At small stand off distances of the nozzle the stagnation pressure of the jet is approximately equal to the jet pressure.
### Table 1.1: Scope of rotating jet parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Trenching application</th>
<th>Draghead application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traverse velocity $v_t$</td>
<td>0.004 - 0.070 m/s</td>
<td>0.01 - 1.80 m/s</td>
</tr>
<tr>
<td>Jet pressure $p_j$</td>
<td>$6.4 \cdot 10^2$ - $8.8 \cdot 10^2$ kPa</td>
<td>$8.8 \cdot 10^2$ kPa</td>
</tr>
<tr>
<td>Nozzle diameter $D_n$</td>
<td>5 mm</td>
<td>5 mm</td>
</tr>
<tr>
<td>Undrained shear strength $s_u$</td>
<td>34 - 40 kPa</td>
<td>34 - 90 kPa</td>
</tr>
<tr>
<td>Stand Of Distance $SOD$</td>
<td>-</td>
<td>5 - 10 mm</td>
</tr>
<tr>
<td>Rotational velocity $\omega_{yc}$</td>
<td>200 - 600 rpm</td>
<td>200 - 600 rpm</td>
</tr>
<tr>
<td>Nozzle angle $\alpha_n$</td>
<td>45 / 60 deg</td>
<td>45 / 60 deg</td>
</tr>
</tbody>
</table>

### 1.3.2. Outline

Not many studies are published about jetting in clay. In chapter 2 literature found about cohesive soils and jetting is reviewed.

In chapter 3 the calculation module of the model is explained. The model is mainly based on entrainment of soil and water, which is the main cause of the decrease of stagnation pressure with distance. Also the visualization module is described in this chapter.

Two experimental test setups are developed. In chapter 4 the setups and the experimental study are described.

In chapter 5 information is given about the execution of the experiments.

Chapter 6 describes the collected results from the experiments and the model. In this chapter the predicted values from the model are also compared to the experimental values.

The conclusions of this study are drawn in chapter 7. The answers to the research question are given as well.

Finally recommendations are presented in chapter 8. These recommendations concern suggested research topics and improvements of the present model.
2.1. INTRODUCTION

In dredging activities different soils have to be excavated. These different soils could be separated in non-cohesive soils and cohesive soils. Clay's are an example of cohesive soils. A cohesive soil tends to have fine grains and a high water content. Examples of non-cohesive soils are sands and gravels. They have relatively large or irregular grains. The grains of a non-cohesive soil won't have the tendency to bond to other grains, where grains of a cohesive soil like to stick to each other. A non-cohesive soil will not have the ability to retain its shape unless confined or affected by external forces, where a cohesive soil tends to retain its shape. The failure mechanisms during excavation with jets are different for these different types of soils. In section 2.2.2 the literature found about the stress-strain dependency of clay's is reviewed. The failure mechanisms of clay's during jetting will be described in section 2.3. In section 2.3.1 the failure mechanism of traverse jetting is reviewed. Lastly, in section 2.4 the effect of the rotational movement of the jet is explained.

2.2. CLAY

2.2.1. CLAY CHARACTERISTICS

Soils are characterized into different types. They are often divided by their grain size (see table 2.1). It can be seen that clay's mostly consist of particles with a very small grain size.

Table 2.1: Grain sizes (NEN)(Verruijt, 2001)

<table>
<thead>
<tr>
<th>Soil type</th>
<th>min.</th>
<th>max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>clay</td>
<td>0.002 mm</td>
<td>0.002 mm</td>
</tr>
<tr>
<td>silt</td>
<td>0.063 mm</td>
<td>0.063 mm</td>
</tr>
<tr>
<td>sand</td>
<td>2 mm</td>
<td>2 mm</td>
</tr>
<tr>
<td>gravel</td>
<td>63 mm</td>
<td>63 mm</td>
</tr>
</tbody>
</table>

A soil substance consists of a mixture of solid particles, water and air. The pores of a soil contain water and air. The degree of saturation $S$ describes the ratio of the volume of water and the total volume of the pore
space. In this study only fully saturated soils \((S = 1)\) will be considered.

\[
S = \frac{V_w}{V_p}
\]  

(2.1)

where:

- \(S\): degree of saturation
- \(V_w\): volume of water \(\text{m}^3\)
- \(V_p\): volume of pores \(\text{m}^3\)

The porosity \(n\) is defined as the ratio of the volume of the pore space and the total volume of the soil.

\[
n = \frac{V_p}{V_t}
\]  

(2.2)

where:

- \(n\): porosity
- \(V_t\): total volume \(\text{m}^3\)

The volumetric weight \(\gamma\) of a soil can now be calculated using:

\[
\gamma = \frac{W}{V} = S \rho_w g + (1 - n) \rho_p g
\]  

(2.3)

where:

- \(W\): weight of soil \(\text{kg}\)
- \(V\): volume of soil \(\text{m}^3\)
- \(\rho_w\): density of water \(\text{kg/m}^3\)
- \(\rho_p\): density of particle \(\text{kg/m}^3\)
- \(g\): gravitational constant \(\text{m/s}^2\)

The air content can often be neglected for mass related calculations because of the large difference in density. The water content however is an important parameter in clay's. The water content \(w\) is the ratio of the mass of the water and solids:

\[
w = \frac{W_w}{W_p} = \frac{S n \rho_w}{1 - n \rho_p}
\]  

(2.4)

where:

- \(W_w\): mass of water \(\text{kg}\)
- \(W_p\): mass of particles \(\text{kg}\)

The mechanical behavior of the different types of soils are rather different. Clay is for example much less permeable than sand, furthermore clay is often softer than sand. Sand and gravel have a larger permeability because of the relatively large grain sizes. Large grain sizes result in large pores and a high permeability. A large difference between sand and clay is the property of clay to retain its shape without being confined or affected by external forces. The deformations of clay are time dependent. When a clay soil is loaded it will continuously deform (creep) while a sandy soil will deform immediately to its final deformation if the loading will be remain constant. A cohesive soil is usually a mixture of clay, silt and sand. The clay particles are responsible for the cohesive behavior of the soil. In this study only cohesive soils will be considered.
2.2. Clay

Characteristics

The main characteristics of cohesive soils are:

- very low water permeability
- high skeleton compressibility
- plasticity

Low water permeability

Flow through a soil structure is possible because of the pores in the soil. Larger pores and grains will increase the permeability of a soil. The grain sizes of clay’s are very small and therefore the pores are very small also. A small porosity leads to a low water permeability. The flow of a fluid through a porous medium has been formulated by Darcy’s law as:

\[ q = -k \frac{dh}{ds} \]  

(2.5)

where:

- \( q \) specific discharge \( \text{m/s} \)
- \( k \) hydraulic conductivity \( \text{m/s} \)
- \( \frac{dh}{ds} \) gradient

The hydraulic conductivity \( k \) shows the ease with which a fluid can move through the pores. Sand has a hydraulic conductivity \( k \) in the range of \( 10^{-6} \) to \( 10^{-3} \) \( \text{m/s} \), where clay has a value of \( k \) in the order of \( 10^{-9} \) \( \text{m/s} \) or lower. The permeability of a soil is approximately proportional to the square of the grain size of the soil. The grain size of clay’s is about 100 – 1000 times smaller than the grain size of sands.

Undrained failure conditions

Because of the rapid rate of loading caused by a jet, the failure conditions can be assumed to be undrained. This undrained behavior will occur when there is no consolidation of soil, because there is no time for outflow of water. This will occur with high loading rates and small permeability. In this study the process of jetting in clay is investigated, therefore the response of the soil is assumed to be undrained.

High skeleton compressibility

The skeleton compressibility of clay is usually higher than the compressibility of a granular-skeleton. In a clay-skeleton the relative particle movement is less constrained than in a granular-skeleton (Winterwerp and van Kesteren, 2004).

Plasticity

In cohesive soils like clay, the consistency is important. The resistance of a soil to mechanical stresses at various water contents is called soil consistency. The consistency depends mainly on the water content (see equation 2.4). When the water content is small, the soil can be very stiff. This state is called the solid state. When the water content is high, the soil is plastic. The soil can also be liquid, this can be possible at very high water contents. The transition between the liquid state and the plastic state is denoted as the liquid limit \( w_L \) and the transition from the plastic state to the solid state is denoted as \( w_p \). When the water content is increased just above the plastic limit the cohesion of the soil will be destroyed and the soil will be liquidized. The plasticity index \( PI \) describes the range of the plastic state:

\[ PI = w_L - w_p \]  

(2.6)
where:

\( PI \)  
plasticity index

\( w_L \)  
liquid limit

\( w_P \)  
plastic limit

### 2.2.2. Strength and Stresses

The drained shear strength \( \tau \) of a soil is often given by:

\[
\tau = c' + \sigma' \cdot \tan \phi
\]  
(2.7)

Where \( \sigma' \) is:

\[
\sigma' = \sigma - p_{pore}
\]  
(2.8)

where:

\( \tau \)  
shear strength  
Pa

\( c' \)  
cohesion  
Pa

\( \phi \)  
internal friction angle  
°

\( \sigma' \)  
effective stress  
Pa

\( \sigma \)  
pore water pressure  
Pa

\( p_{pore} \)  
total stress applied normal to the shear plane  
Pa

In undrained situations like jetting clay, it is useful to consider the total stresses to be able to predict the behavior of the clay. In figure 2.1b the total stresses of a consolidated undrained test are shown.

![Mohr circles for undrained tests](image1)

![Mohr circles for total stresses](image2)

**Figure 2.1: Mohr circles**

All critical stress circles will be of the same magnitude as the total stresses. From equation 2.7 it follows that when the results are interpreted in terms of total stresses only, the friction angle \( \phi \) is about zero. An undrained analysis is an analysis in which the friction of the material and the pore pressures are neglected. The undrained shear strength \( su \) is noted as half the maximum shear stresses, expressed in total stresses:

\[
su = \frac{1}{2}(\sigma_1 - \sigma_3)
\]  
(2.9)
2.2.3. STRESS STRAIN BEHAVIOUR

Different researchers found that in cohesive soils the undrained peak shear strength depends on the strain-rate. However most researches studied this process for low strain rates as for construction of buildings for example. During jetting the soil fails in a fraction of a second and will experience a large strain rate. Little is known about the stresses during these large strain rates. The higher the strain-rate the higher the viscous resistance of the soil. The increase in viscous resistance increases the undrained shear strength. This can be described by:

\[
\frac{s_u}{s_{u,ref}} = 1 + n_{sr} \log \left( \frac{\dot{\epsilon}}{\dot{\epsilon}_{ref}} \right)
\]  

(2.10)

where:

- \(s_u\) undrained shear strength, Pa
- \(s_{u,ref}\) reference undrained shear strength, Pa
- \(n_{sr}\) empirical constant
- \(\dot{\epsilon}\) strain rate, 1/s
- \(\dot{\epsilon}_{ref}\) reference strain rate, 1/s

Dayal and Allen and Winterwerp and van Kesteren (2004) found that the empirical constant \(n_{sr}\) depends on the undrained shear strength. The higher the undrained shear strength the lower the strain rate dependency.

Soga et al. (1996) obtained another formula for the strain-rate dependency of the undrained shear strength:

\[
\frac{s_u}{s_{u,ref}} = \left( \frac{\dot{\epsilon}}{\dot{\epsilon}_{ref}} \right)^{m_{sr}}
\]  

(2.11)

where \(m_{sr}\) is the rate parameter with a value between 0.0018 and 0.087.

From figure 2.2a three values for \(m_{sr}\) can be obtained. These values lies varied from 0.020 to 0.051 (see table 2.2. The found values for \(m_{sr}\) lies in the range Soga et al. (1996) found.

Table 2.2: Obtained experimental values for the rate parameter (Duncan and Wright, 2005)

<table>
<thead>
<tr>
<th>Time to failure (t_f)</th>
<th>Strain rate (\dot{\epsilon} / \dot{\epsilon}_{ref})</th>
<th>(s_u / s_{u,ref})</th>
<th>(m_{sr})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point 1 5 sec</td>
<td>100% 5 sec</td>
<td>1.45</td>
<td>0.033</td>
</tr>
<tr>
<td>Point 2 5 min = 300 sec</td>
<td>100% 300 sec</td>
<td>1.15</td>
<td>0.020</td>
</tr>
<tr>
<td>Point 4 2 weeks = 1.21 (\cdot) 10^6 sec</td>
<td>100% 1.21 (\cdot) 10^6 sec</td>
<td>0.94</td>
<td>0.051</td>
</tr>
<tr>
<td>Reference point</td>
<td>1% 60 sec</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In figures 2.2 and 2.3 it can be seen that the undrained shear strength during high strain rate can be up to 2 times the reference undrained shear strength.
2. LITERATURE REVIEW

(a) Effect of time to failure on undrained strength of San Francisco Bay mud (Duncan and Wright, 2005)

(b) Schematic illustration of strain rate effect for normally consolidated clays (Ladd and DeGroot, 2005)

Figure 2.2: Strain rate dependency of undrained shear strength

Figure 2.3: Strain rate dependency of the undrained shear strength (Nobel, 2013)
2.3. Jetting

Excavation with the use of jets is a hydraulic process. The jet flow penetrates the soil and brings the soil in suspension whereupon it can be transported to a suction pipe of a trailer suction hopper dredger for example. A moving jet can cause different soil failure mechanisms. In a sand bed the failure mechanism during jetting is based on the shear stresses exerted by the jet. When a grain is being removed the created void space behind this grain must be filled up with water. The permeability of the soil and the flow velocity of the jet are the two most important parameters of the velocity of this erosion process. This erosion process is a drained process (Rhee, 2010). In clay however the soil failure mechanism mainly depend on the stagnation pressures exerted by the jet. The mass flow of the moving vertical jet creates a normalized load of the jet (stagnation pressure). The soil will fail when the jet load is higher than the soil resistance. The shear surfaces, caused by this load, are mainly formed by the stagnation jet pressure (Nobel, 2013). The erosion capacity of the shear stresses exerted by the jet are negligible.

2.3.1. Stationary Jetting in Clay

The stagnation jet pressure is an important parameter in the excavation process of a moving vertical jet in cohesive soils like clay’s. Stagnation pressures are formed when a jet stream impacts on a perpendicular soil surface, because the jet stream is forced to stop and partially reflected a stagnation pressure is built up at the point of impact (see figure 2.4).

![Initial jet impact behavior](image)

Due to the entrainment of ambient fluid and soil in the jet, the stagnation pressure of the jet decreases with distance to the nozzle exit (jet distance). At small Stand Off Distances (SOD’s) of the nozzle the stagnation pressure of the jet is roughly equal to the jet pressure ($p_{stag} \approx p_{jet}$). When the jet distance increases, the jet flow velocity and thus stagnation pressure decreases. Experiments of Machin and Allan result in a model where the axial jet velocity $u$ at a distance of $x$ from the nozzle exit can be determined by (Machin and Allan, 2011):

$$\frac{u}{u_0} = \begin{cases} \frac{6.0D_n}{s} & : s > 6D_n \\ 1 & : s \leq 6D_n \end{cases} \quad (2.12)$$

where:
The pressure acting on the soil during jetting can be determined using the assumptions that there is no viscosity loss (Kondo et al., 1974). The stagnation pressure for a submerged free jet in water can be described by:

\[ p_{stag} = 0.5 \rho_w \cdot u^2 \]  \hspace{1cm} (2.13)

where:

- \( p_{stag} \) stagnation pressure \( \text{Pa} \)
- \( \rho_w \) density of water \( \text{kg/m}^3 \)

The initial flow velocity \( u_0 \) at the nozzle’s exit can be described by:

\[ u_0 = \sqrt{\frac{2p_{jet}}{\rho_w}} \]  \hspace{1cm} (2.14)

where:

- \( u_0 \) initial jet velocity at nozzle exit \( \text{Pa} \)
- \( p_{jet} \) initial jet pressure at nozzle exit \( \text{Pa} \)

At a certain jet distance the jet doesn’t penetrate the soil anymore, because the bearing capacity \( q = N_{bc}Su \) of the soil equals the stagnation pressure at that point. The minimum velocity to cause failure based on the Bearing Capacity Theory is:

\[ u_{min} = \sqrt{\frac{2N_{bc}Su}{\rho_w}} \]  \hspace{1cm} (2.15)

where:

- \( N_{bc} \) bearing capacity factor

Combining equations 2.12, 2.14 and 2.15 results in an equation for the value of the ultimate depth of the cavity using the threshold bearing pressure theory and substituting \( s = Z_c \) (Machin and Allan, 2011).

\[ Z_c = 6.0D_n \sqrt{\frac{p_{jet}}{N_{bc}Su}} \]  \hspace{1cm} (2.16)

where:

- \( Z_c \) jet cavity depth \( \text{m} \)
- \( D_n \) nozzle diameter

Ho (2005) derived a similar equation for the ultimate cavity depth \((Z_c)\):

\[ Z_c = 6.25D_n \sqrt{\frac{p_{jet}}{N_{bc}Su}} \]  \hspace{1cm} (2.17)
This is almost exactly equal to equation 2.16 except Ho (2005) used \(6.25D_n\) for the length of the potential core against \(6.0D_n\) Machin and Allan (2011) used. Equation 2.17 implies that the cutting depth (cavity depth) is not only a function of pressure and undrained shear strength but also of the diameter of the nozzle.

Experiment from Machin and Allan (2011) shows that during static nozzle tests the cavity develops in a very short time interval (estimated as a fraction of a second). Full cavity depth is reached in several seconds. (see figure 2.5)

![Figure 2.5: Observed cavity formation with static nozzle](Machin and Allan, 2011)

**FREE JET**

A moving vertical jet exerts a stagnation (normal) pressure \(p_{stag}\) on the soil. The soil will fail along shear surfaces that are created by the stagnation pressures when the stagnation pressure is larger than the soil resistance in the shear shear surfaces. The stagnation pressure is a function of the uniform jet velocity and decreases with distance from the nozzle exit:

\[
p_{stag} = 0.5\rho_m u_{u}^2
\]

where:

\[
\begin{align*}
p_{stag} & \quad \text{stagnation pressure} \\
\rho_m & \quad \text{mixture density of the jet} \\
u_{u} & \quad \text{uniform jet velocity}
\end{align*}
\]

Pa

kg/m³

m/s

The velocity development of turbulent jets is an important process. \(u_u\) is a theoretical value for the jet velocity while in reality a velocity profile is present. A jet stream exerted by a nozzle that is positioned a certain dis-
tance above a bed experiences two different velocity developments. At first the jet stream is fully surrounded by water between the nozzle outlet and the soil surface (free jet). After penetrating the soil, the jet is partly enclosed by water and partly by soil (confined jet). This will effect the velocity development. In a free jet a mixing layer is formed between the jet flow and ambient water as a result of the difference in velocity and water viscosity. In the mixing layer mass and momentum are being transferred. In this study $u_n$ is assumed to be the uniform jet velocity defined as:

$$u_n = \frac{I}{\rho_m Q} \tag{2.19}$$

where:

- $I$ momentum flux [N]
- $Q$ jet flow rate [m$^3$/s]
- $\rho_m$ mixture density [kg/m$^3$]

The potential core (see figure 2.6) is the region of unhindered velocity becomes smaller with distance, because of the development of the mixing layer. After the potential core has disappeared the flow is fully developed. In this region the velocity profile is Gaussian distributed and described by:

$$u_j(s, r) = \sqrt{\frac{k_1}{2}} u_0 \frac{D_n}{s} e^{-\frac{k_2}{r^2}} \tag{2.20}$$

where:

- $u_j(s, r)$ jet velocity at $(s,r)$ [m/s]
- $s$ jet distance, measured along the center-line of the jet [m]
- $r$ radial distance to center-line of the jet [m]
- $k_1$ empirical constant
- $k_2$ empirical constant

The fully developed flow starts when the velocity at the center-line equals the initial jet velocity: $u_j(s = s_{dr}, 0) = u_0$ The distance from the nozzle exit where the fully developed flow starts can now be calculated with:

$$s_{dr} = \frac{k_1}{2} \cdot D_n \approx 6.2 D_n \tag{2.21}$$

In equation 2.21 the region of fully developed flow starts slightly later than the model based on experiments of Machin and Allan (2011) (6.2 to 6.0 respectively). Fischer et al. (1979) found an average value of $77 \pm 2$ for $k_1$.

The flow of a turbulent jet is momentum driven. The momentum flux ($I$) on any cross section of the jet flow is conserved (Rajaratnam, 1976):

$$I(s) = \rho_w 2\pi \int_0^\infty u_j(s, r)^2 r \cdot dr = I_0 \tag{2.22}$$

$$I_0 = \rho_w Q_0 u_0 \tag{2.23}$$

$$Q_0 = \mu_n \frac{1}{4} \pi D_n^2 u_0 \tag{2.24}$$
where:

\[ I_0 \] momentum flux at nozzle exit \[ \text{N} \]
\[ Q_0 \] flow rate at nozzle exit \[ \text{m}^3/\text{s} \]
\[ \mu_n \] nozzle discharge coefficient \[-]\n
The nozzle discharge coefficient \( \mu_n \) is a measure of the amount of contraction that occurs when water flows out of an orifice (see figure 2.7). The discharge coefficient has a value between 0.6 and 1.0 depending on the nozzle inflow and geometry (White, 2009). For a bad geometry, the discharge coefficient has a value of 0.6 and for a perfect geometry the nozzle will have a discharge coefficient of 1.0. The nozzle discharge coefficient reduces the total cross-sectional flow area of the nozzle outlet resulting in a fictitious nozzle outlet area and diameter:

\[
A_{n,f} = \mu_n \cdot A_n
\] (2.25)

\[
D_{n,f} = \sqrt{\mu_n} \cdot D_n
\] (2.26)

Figure 2.7: Schematic example of contraction

The momentum flux can be obtained by substituting equation 2.20, 2.23 and 2.24 in equation 2.22 and integrating the result of this substitution.

\[
I(s) = \frac{\pi D_n^2 k_1 \rho w u_0^2 e^{-\frac{r^2}{r^2}}}{4 k_2} = \frac{\rho w \mu_n \pi D_n^2 u_0^2}{4} = I_0
\] (2.27)

For preservation of momentum it follows that \( k_1 = k_2 = 77 = k \) (Fischer et al., 1979)(Albertson et al., 1950) when assuming \( \mu_n = 1 \) and \( r = 0 \) (axial center-line).

\[
Q(s) = Q_0 \sqrt{\frac{k}{D_n}} \text{ for } s \geq s_{dr}
\] (2.28)

The entrainment per unit length can be found by differentiating equation 2.28:

\[
\frac{dQ}{ds} = Q_0 \sqrt{\frac{k}{D_n}} \text{ for } s \geq s_{dr}
\] (2.29)
Substituting equation 2.24 in 2.29 and assuming $\mu_n = 1$ results in:

$$\frac{dQ}{ds} = \alpha_{\text{mom}} \pi D_n u_0 \text{ for } s \geq s_{\text{dr}}$$

(2.30)

Where $\alpha_{\text{mom}}$ is the entrainment coefficient for a non-cavitating jet in the fully developed flow area:

$$\alpha_{\text{mom}} = \frac{1}{\sqrt{2k}}$$

(2.31)

For $s < s_{\text{dr}}$ the mixing layer of the flow isn’t fully developed. This region is called the flow development zone. The entrainment coefficient isn’t constant for this region and increases with distance from the nozzle exit. An entrainment coefficient for the flow development region of a non-cavitation jet is derived by Albertson et al. (1950) and can be described by:

$$\alpha_{\text{mom},dr} = \frac{1}{4} f_1 + \frac{1}{2} f_2 \frac{s}{D_n}$$

(2.32)

where:

$$f_1 = 2 \sqrt{\frac{\pi}{k}} - \sqrt{\frac{8}{k}} \approx 0.081$$

(2.33)

$$f_2 = \frac{6 - \sqrt{8\pi}}{k} \approx 0.013$$

(2.34)

### 2.3.2. Traversing Horizontally with a Vertical Orientated Jet

When a vertical jet is traversing horizontally the vertical jet flow is partly enclosed by soil. This will affect the development of the mixing layer. At the back side of the jet stream there is only entrainment of ambient water, while at the front side soil is entrained. The entrainment of soil per unit length depends mainly on the traverse velocity of the jet ($v_t$) and the jet cavity width ($W_c$). This will change the flow rate and the jet flow density. A no-slip condition always exists at an interface between a flowing fluid and a solid surface where the velocity is zero (Daily and Harleman, 1966). The velocity gradient and shear stress at any cross-section of the flow will have a maximum value at the solid boundary. Viscous shear forces dominate within a very thin layer parallel to the wall. The thickness of the boundary layer increases with distance from the nozzle exit. Outside this boundary layer the velocity gradient decreases very rapidly and viscous shear effects become small.

Nobel (2013) concluded that the development of the boundary layer in the jet can be compared to the development of the boundary layer in an uniform flow on a rough plate. It is assumed that the influences of the decelerating flow and the soil entrainment can be neglected. The bed shear stresses are given by:

$$\tau_b = c_f \frac{1}{2} \rho_m u_{bl,\text{max}}^2$$

(2.35)

where:

$c_f$ friction coefficient $-$

$u_{bl}$ jet velocity at the edge of the boundary layer $\text{m/s}$

In the laminar regime the friction coefficient is assumed to be constant and equal to the value at the beginning
of the turbulent zone. The turbulent friction coefficient is (Schlichting, 1979):

\[ c_f = (2.87 + 1.58 \log \frac{s_{bl}}{k_s})^{-2.5} \]

where:
- \( k_s \): equivalent roughness height, m
- \( s_{bl} \): Distance to the initiation of the boundary layer, m

In the present study the bed shear stresses are assumed to be very small and therefore are neglected.

The entrainment of water and soil for a horizontally moving vertical penetrating jet per unit length can be calculated using:

\[ \frac{dQ}{ds} = W_c v_t + \frac{1}{2} \pi W_c u_a x_{mom} \]

where:
- \( v_t \): traverse velocity, m/s
- \( W_c \): cavity width, m

The entrainment of soil depends mainly on the traverse velocity of the jet. The influence of the entrainment of soil on the development of the jet velocity is limited. For low jet traverse velocities \( (v_t < 0.1 \, \text{m/s}) \) the influence of the entrainment of soil on the jet velocity development can be neglected. For higher traverse velocities the entrainment of soil will increase the mixture density of the jet yielding a decrease in stagnation pressure of the jet. For traverse velocities larger than 0.1 m/s the entrainment of soil on the jet velocity cannot be neglected (Nobel, 2013).
2.3.3. Failure Modes

Nobel (2013) has studied the excavation process of a horizontally moving vertical jet in a cohesive soil. He distinguished four different types of failure modes based on the cavity dimensions and wall structure of the soil samples after conducting tests.

- **Penetrating jet**
  - $\frac{p_{\text{jet}}}{u_s} > 12$
  - narrow deep cavities
  - a soil wall structure with small straight nearly vertical nerves
  - completely dissolved excavated soil in the jet and ambient water

- **Deflecting jet**
  - $7.3 < \frac{p_{\text{jet}}}{u_s} < 12$
  - shallow cavities
  - a soil wall structure with nerves deflecting in opposite of the traverse direction
  - after tests only a few dislodged soil lumps can be found

- **Dispersing jet**
  - $5.4 < \frac{p_{\text{jet}}}{u_s} < 7.3$
  - wide shallow cavities
  - irregular soil structure
  - after tests dislodged soil lumps can be found

- **Hydro-fracturing**
  - $v_t < 0.15 \text{m/s}$
  - irregular cavity dimensions
  - soil fails along preferred weak surfaces
  - cavity dimensions can increase significantly compared to the penetrating and deflecting jet

Most of the test samples could be assigned to the failure mode of a penetrating jet with a characterized cavity width of 1 to 2 times the nozzle diameter. In this research the failure mode of a penetrating jet is considered. A schematic sketch of a penetrating jet can be seen in figure 2.9

The wall structure of a cavity is characterized by three zones:

- **Non-deflection zone**
  - This is the first affected layer by the jet. The wall structure of this cavity zone consists of small nearly vertically nerves. The height of the non-deflection zone depends mainly on the jet ratio $(p_{\text{jet}}/u_s)$ and for a small amount on the traverse velocity of the nozzle $(v_t)$.

- **Deflection zone**
  - In this zone the vertical nerves from the non-deflection zone starts to deflect backwards.

- **Transport zone**
2.3.4. Failure Mechanism

For failure of cohesive soil the jet load has to exceed the undrained shear strength in localized shear planes, because the soil fails along the shear planes.

There are different loading conditions exerted by the jet on the soil. These loading conditions are schematically viewed in figure 2.10

- figure 2.10(a): Normal pressure parallel to the jet flow, equal to the stagnation pressure
- figure 2.10(b): Normal pressure perpendicular to the main direction of the jet flow
- figure 2.10(c): Normal pressure perpendicular to the jet flow, as result of the deflection of the jet
- figure 2.10(d): Shear stresses exerted by the jet flow
- figure 2.10(e): Temporary normal pressure differences perpendicular to the jet flow, caused by turbulent pressure fluctuations

The shear stresses exerted by the jet flow are assumed to be negligible, because the shear stresses exerted by the jet flow (figure 2.10(d)) are an order magnitude lower than the normal pressures (figure 2.10(a,b,c)). The shear stresses caused by the temporary normal pressure differences are neglected as well.

An important parameter is the jet ratio \( p_{jet}/su \). Nobel (2013) found a linear dependency between the
normalized cavity depth \( (Z_c/D_n) \) and the jet ratio up to a jet ratio of 400 and in laboratory tests he found that the measured cavity widths were 1 to 1.5 times the nozzle diameter for jet ratio between 12 and 200. For higher jet ratios the traverse velocity will affect the cavity depth as well.

**CAVITY WIDTH AND DEPTH FOR LOW TRAVERSING VELOCITIES**

For low traverse velocities \( (v_t < 0.1\text{m/s}) \) an approximation of the upper limits from the cavity width and depth can be made. When small stand off distances are present the jet ratio \( (p_j/su) \) is about equal to the stagnation ratio \( (p_{stag,ss}/su) \) at the original soil surface. When the stagnation ratio is significantly larger than the required stagnation ratio for soil failure two assumption can be made; 1) the entire jet flow is able to penetrate the soil surface, 2) the cavity width is equal to the jet diameter of the jet at the original soil surface \( (W_j = D_{j,ss}) \).

\[
W_c = \sqrt{\frac{7}{k}} SOD + D_n, \text{ if } SOD < s_{dr}
\]

\[
W_c = \sqrt{\frac{8}{k}} SOD, \text{ if } SOD \geq s_{dr}
\]

The cavity width is mainly determined by the nozzle diameter. At small stand off distances the cavity width is close to the nozzle diameter.

Nobel (2013) derived a formula for the upper limit of the cavity depth for a penetrating jet:

\[
\frac{Z_c}{D_n} = a_1 \frac{p_j}{su} + b_1
\]  

(2.40)

Where for \( Z_c + SOD < s_{dr} \):

\[
a_1 = \sqrt{\frac{k}{2 N_{bc}(N_1 + 1)}}
\]

(2.41)

\[
b_1 = -\sqrt{\frac{k}{2}} (N_1 + 1)
\]

(2.42)

for \( Z_c + SOD \geq s_{dr} \):

\[
a_1 = \sqrt{\frac{k}{2 N_{bc}(2N_1 + 2)}}
\]

(2.43)

\[
b_1 = -\sqrt{\frac{k}{2}} N_1
\]

(2.44)

Where \( N_1 \) is defined as \( SOD/s_{dr} \). For \( SOD = D_n \) equation 2.40 becomes:

\[
\frac{Z_c}{D_n} = 0.65 \frac{p_j}{su} - 7.2, \text{ if } 15 < \frac{p_{jet}}{su} < 19
\]

(2.45)

\[
\frac{Z_c}{D_n} = 0.33 \frac{p_j}{su} - 1, \text{ if } \frac{p_{jet}}{su} \geq 19
\]

(2.46)
When the jet ratio $\frac{p_{\text{jet}}}{\mu}$ become smaller than 19, the jet must be considered as a deflecting jet instead of a penetrating jet.

This formula for the upper limit of the cavity depth is based on some assumptions:

- At the soil surface the cavity width is equal to the jet diameter
- In the fully developed flow region the entrainment coefficient is $\alpha_{\text{mom}} \approx 0.083$
- In the developing flow region the entrainment coefficient is half the entrainment coefficient of the entrainment coefficient in fully developed flow
- The influence of the traverse velocity as well as the shear stresses exerted by the jet aren’t taken into account.

**Cavity width and depth for larger traversing velocities**

For traverse velocities ($\nu > 0.1 \text{m/s}$) the cavity width and depth are influenced by the traverse velocity. Experiments from different researchers have shown that the cavity depth decreases when the traverse velocity increases (see figure 2.11, 2.12 and 2.13). This relationship is found to depend on the traversing velocity to a negative power ($Z_c \propto \nu^{-C}$). Machin and Allan (2011) however did not publish the actual test data so only a trend of the line can be noticed.

![Figure 2.11: Observed cavity formation with translating nozzle (Machin and Allan, 2011)](image1)

![Figure 2.12: Correlation between depth and translational velocity of the nozzle (Zhang et al., 2016)](image2)
Zhang et al. (2016) performed experiments with relatively low traversing velocities (0.07 - 0.28 m/s). The executed tests were conducted with low jet ratio ($3 \leq \frac{p_{jet}}{su} \leq 10$). Nobel (2013) considered the minimum required jet ratio of 12 for a penetrating jet. For the jet ratio’s Zhang et al. (2016) tested three different failure modes are present; a deflecting jet, a dispersing jet flow and the occurrence of hydro-fracturing. Because of the different failure modes these tests could not be compared to the executed tests of Nobel (2013).

The shapes of these graphs are very interesting. It can clearly be seen that the cavity depth isn’t linearly proportional to the traverse velocity. This means that excavation production rate should be higher with larger traverse velocities. The excavation production rate can be described by:

$$M_{ex} = W^2_c \cdot Z_c \cdot v_t$$

(2.47)

where:

$M_{ex}$: excavation production rate $m^3/s$

Unfortunately Machin and Allan (2011) and Zhang et al. (2016) didn’t came up with a model to predict the cavity depth as a function of the traversing velocity. Nobel (2013) developed a model to predict the cavity dimension as a function of the traversing velocity of the nozzle and the jet ratio. The model fits well with his test data (see figure 2.13). The 1D-approach model from Nobel (2013) is used as a starting point for the developed model for a rotating jet and will be described in chapter 3.

2.4. ROTATIONAL JETTING

Figures 2.11, 2.12 and 2.13 show that a production could be increased by increasing the traversing velocity of the nozzle. This should be possible because the figures suggest that the cavity depth only decreases a little with an increase in traversing velocity.

When the horizontally moving vertical positioned nozzle is tilted by an angle ($\alpha_n$) and rotates, the affected area increases and the traversing velocity of the jet stream increases as well. The traversing velocity of the jet is now a combination of the normal traversing velocity of the nozzle and the tangential velocity due to the angular velocity of the jet. More clay is offered to the jet by the additional rotations of the jet. Little is known about rotational jetting in clay for dredging applications. Ho (2005) studied the jet excavation in cohesive
soils for grouting applications. Jet grouting uses a horizontal rotating jet moving vertically. The rotary motion and the vertical retreat velocity are low. Jet grouting is a construction process which can be used to reinforce soils or reduce their permeability. Grouting is also used for underpinning of existing structures. The jet grouting process consists of soil excavation with the use of a high pressure rotational jet after which a cement mix is injected (see figure 2.14).

Ho (2005) conducted experiments during his study showing the effect of the rotational velocity on the penetration depth. At a higher rotational velocity, the time of interaction between the jet and the soil is limited and penetration of the jet is reduced as well. Ho (2005) found from experiments that the effect of number of revolutions is limited. In his research the nozzle didn’t traverse. His experiments showed that a maximum cutting distance is achieved after only one pass of the jet. These experiments were done with low rotational velocities (10 rpm) No obvious increase of the cutting distance was found with additional passes of the jet during tests with low rotational velocities. These low rotational velocities result in low combined traversing velocities.

Figure 2.14: Sequence of jet grout installation (Ho, 2005)

In the case of a horizontally moving rotating vertical jet. The jet stream will probably affect soil elements multiple times. This effect depends on the ratio between the vertical traversing velocity and the rotational velocity ($v_t/\omega_{yc}$).

When the nozzle is tilted with a certain angle and rotations are implemented, the affected area is increased. A schematic comparison between affected area’s can be seen in figure 2.15.

Figure 2.15: Schematic increase in affected area rotating jet, left (side view), right (frontal view)
Rotating jets are also widely used in cleaning operations of sewer systems (see figures 2.16 and 2.17). The rotary motion is often powered hydraulically. These kind of jets cannot be used for an experimental setup because little to none adjustments can be made to setup settings such as nozzle angle, flow rate, jet pressure and rotational velocities. Besides, it would be very hard to obtain accurate data for the required setup settings. However these kind of rotating jets show the possibility that the rotary motion can be flow driven. A flow driven rotation system is probably a major design requirement when a rotating jet would be designed for dredging purposes.

Figure 2.16: Rotating jets in sewage pressure washers (Park Mechanical)

Figure 2.17: Different rotating jets for sewage cleaning purposes (KOKS Group)
3.1. **INTRODUCTION**

A model is developed in order to predict the excavation production. This is done for two different setups; a rotating jet moving through the soil which can be used for trenching purposes and a rotating jet moving above the soil for dredging purposes using a draghead. Both models are built up from a calculation module and a visualization module to finally determine and visualize the excavation production.

3.2. **CALCULATION MODULES**

A model in Matlab is made to calculate the penetration depth out of parameters:

- Jet pressure $p_j$
- Undrained shear strength $s_u$
- Traversing velocity $v_t$
- Rotational velocity $\omega_{cyc}$
- Nozzle angle $\alpha_n$
- Nozzle diameter $D_n$

Both calculation modules are quite similar and are both based on the 1D approach from Nobel (2013). This model calculates the entrainment of water and soil at each thin slice $k$ for a vertical jet moving horizontally.

The 1D-approach is used because the mass balance of the jet can’t be solved analytically. The mass balance can be described by:

$$\rho_m \cdot Q_j = Q_0 \cdot \rho_w + \int_{0}^{z} \rho_s \cdot x_e \cdot v_j \, ds + \int_{0}^{z} \rho_w \cdot \alpha_{mom} \cdot u_u \cdot P_w \, ds$$  \hspace{1cm} (3.1)

where:
In the 1D-approach the jet is divided in slices with a thickness $ds$. For each slice a mass and momentum balance is solved numerically by discretizing the jet. This is done because the mass balance can’t be solved analytically. By solving the discretized mass and momentum balances an uniform jet velocity for a jet at each slice can be derived what will lead to a corresponding stagnation pressure at a point with distance $s$ from the nozzle outlet. A cohesive soil will fail along the shear surfaces created by the stagnation pressures exerted by the jet. Using Bernoulli’s principle the stagnation pressure can be calculated with:

$$p_{stag} = \frac{\rho_m \cdot u_u^2}{2}$$

where:

- $p_{stag}$: stagnation pressure [Pa]
- $\rho_m$: mixture density of the jet [kg/m$^3$]
- $u_u$: uniform jet velocity [m/s]

In the present study $u_u$ is assumed to be the uniform jet velocity defined as:

$$u_u = \frac{I}{\rho_m Q_j}$$

where:

- $I$: momentum flux [N]
- $Q_j$: jet flow rate [m$^3$/s]

A turbulent jet is momentum driven. The momentum flux ($I$) is conserved on any cross-section with distance $s$ of the jet flow $I(s) = I_0$ (Rajaratnam, 1976).

$$I(s) = I_0 = \rho_w \cdot Q_0 \cdot u_0$$

where:

- $I_0$: momentum flux at start [N]
- $\rho_w$: water density [kg/m$^3$]
- $Q_0$: jet flow rate at start [m$^3$/s]
- $u_0$: jet flow velocity at start [m/s]

The bed shear stresses result in a decay in momentum flux. In this study the decay in momentum flux is assumed to be negligible, because of the very limited influence on the decrease in uniform jet velocity.

The discretized mass balance for the jet can be described with:
\[ \rho_{m,k+1}Q_{j,k+1} = \rho_{m,k}Q_{j,k} + \rho_{w,k}dQ_{w,k} + \rho_{s,k}dQ_{s,k} \]  

(3.5)

where:

- \(dQ_w\) entrainment of water over the slice \(\text{m}^3/\text{s}\)
- \(dQ_s\) entrainment of soil over the slice \(\text{m}^3/\text{s}\)

The entrainment of ambient water can be calculated with:

\[ dQ_{w,k} = \alpha_{mom,k}u_{w,k}P_{w,k}\]  

(3.6)

where:

- \(ds\) thickness of slice \(\text{m}\)

The entrainment coefficient increases gradually with distance \(s\) to a constant value at the start of the region of fully developed flow (2.31).

The entrainment of soil in the mixing layer can be calculated by the width of the slice that is enclosed by soil times the traversing velocity of the jet:

\[ dQ_{s,k} = x_cv_j ds \]  

(3.7)

where:

- \(x_c\) thickness of soil layer that jet encounters \(\text{m}\)
- \(v_j\) combined traversing velocity of the jet \(\text{m/s}\)

The combined traversing velocity of the jet consists of two components. A tangential velocity component due to the revolutions and a velocity component due to the traversing nozzle. The width of the slice that is in contact with the soil depends on the ratio between traversing velocity of the nozzle and rotational velocity.

In sections 3.2.1 and 3.2.2 these parameters will be explained in more detail. Using equation 3.3 to 3.7 the stagnation pressure at a distance \(s\) from the nozzle can be calculated. The stagnation pressure is mainly responsible for the failure of the soil. The soils fails when the stagnation pressure exceeds the minimum value of the bearing capacity \((q = N_{bc} \cdot su)\). The penetration depth can finally be determined using this equation. When \(q = N_{bc} \cdot su\) the corresponding distance \(s\) and \(D_j\) are stored in the model.

**Cavitation** Entrainment of water and soil takes place in the mixing layer where mass and momentum is transferred. The mixing layer is created because of the velocity difference between the jet and the ambient water. The water that is entrained to the jet has to be replaced. Ambient water must flow towards the jet and causes a decrease in static pressure around it. The higher the jet pressure, the higher the entrainment of water and thus a larger pressure drop. Vapour is created inside the water when the static pressure is lower than the vapour pressure \((p_{va})\). This effect is called cavitation.

When cavitation occurs, a cone of bubbles is formed around the jet. The cone of bubbles affects the mixing layer and impedes the entrainment. Less entrainment takes place resulting in a slower increase in jet mixture density resulting in a slower decay in jet velocity. A higher jet velocity yields a higher stagnation pressure and
therefore the penetration depth will be larger than when no cavitation occurs. Another entrainment coefficient has to be used when cavitation occurs:

\[ \alpha_{mom,cav} = \frac{1}{\sqrt{2k_{cav}}} \]  

(3.8)

where:
- \( \alpha_{mom,cav} \) = entrainment coefficient
- \( k_{cav} \) = empirical constant for a developed cavitation cone

The empirical constant for a developed cavitation cone can be written as (Nobel and Talmon, 2012):

\[ k_{cav} = k_1 \sqrt{\sigma_d} \sqrt{\frac{p_j}{p_{a,0}}} \]  

(3.9)

where:
- \( \sigma_d \) = cavitation index for cone development
- \( p_{a,0} \) = initial ambient fluid pressure

### 3.2.1. TRENCHING

A trenching machine like the BSS-II has horizontally orientated stationary nozzles. The machine is towed by a tug. This means that the horizontal nozzles are moving horizontally (see figure 1.1b).

Because such an orientation is difficult for an experimental test setup the choice was made to tilt the whole orientation by 90 degrees. Instead of a horizontal jet moving horizontally through the soil, the test setup was designed in a vertical orientation (see figure 3.1), what means a vertical jet moving vertically through the soil. The model described in this section will be in the vertical orientation as well. The assumption is made that tilting the orientation won’t have an influence, because the relative orientation between jet and soil remains the same.

![Figure 3.1: Orientation of trenching experimental setup](image)

The amount of entrainment of soil depends on the vertical traversing velocity of the nozzle and the height \( (h_c) \) of the layer of soil what the nozzle encounters during rotations. The height of the layer depends on the ratio of vertical traversing velocity and rotational velocity, the nozzle angle and the number of nozzles (see figure 3.2). The height of this layer can be described by:
3.2. Calculation Modules

\[ h_c = \frac{v_{t,v} \sin \alpha_n}{n \cdot \omega_{cyc}} \]  

where:

- \( h_c \): height of soil layer that jet encounters \( \text{m} \)
- \( v_{t,v} \): vertical traversing velocity \( \text{m/s} \)
- \( \alpha_n \): angle of nozzle outlet in respect to the vertical axis \( \text{deg} \)
- \( n \): number of nozzle outlet’s on jet axis \( - \)
- \( \omega_{cyc} \): revolutions of jet axis per second \( \text{rev/s} \)

![Figure 3.2: Schematic view of cross-section of parameters used in equation 3.10](image-url)

The jet is divided in \( k \) slices with a thickness \( ds \). The distance \( s \) of the jet to the nozzle’s exit becomes \( s = k \cdot ds \). The entrainment coefficient \( a_{mom} \) gradually increases to a constant value at the start of the region of fully developed flow. The jet distance from the nozzle’s exit in the region of developing flow is described by:

\[ s_{dr} = \sqrt{\frac{k_1}{2} D_{nf}} \]  

where:

- \( s_{dr} \): jet distance of developing flow region \( \text{m} \)
- \( k_1 \): empirical constant \( - \)
- \( D_{nf} \): Fictitious nozzle diameter \( \text{m} \)

In the flow development region \(( s \leq s_{dr} )\) of a non-caviation jet the entrainment coefficient \( a_{mom} \) is given by:

\[ a_{mom} = 0.25 f_1 + 0.5 f_2 \frac{s}{D_{nf}} \]  

where:
When \( s > s_{dr} \) the flow is fully developed and the entrainment coefficient becomes equal to \( f_1 \) for a non-cavitation jet.

While executing tests, a cavitating jet was noted (see figure 3.3) and therefore the empirical coefficient of the cavitation entrainment coefficient (see equation 3.8) should be used for the entrainment equation of water. For the flow development region \( (s \leq s_{dr}) \) the entrainment coefficient for a cavitating jet is assumed to linearly increase from zero to the constant entrainment coefficient of a cavitating jet for fully developed flow. For both models a cavitating jet is considered using the following parameters:

Table 3.1: Assumed cavitation parameters (Nobel and Talmon, 2012)

<table>
<thead>
<tr>
<th></th>
<th>Trenching setup</th>
<th>Draghead setup</th>
<th>Draghead setup</th>
<th>Draghead setup</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( D_n = 5 )</td>
<td>( D_n = 5 )</td>
<td>( D_n = 7 )</td>
<td>mm</td>
</tr>
<tr>
<td>Water Depth ( WD )</td>
<td>0.30</td>
<td>0.2</td>
<td>0.2</td>
<td>m</td>
</tr>
<tr>
<td>Initial ambient fluid pressure ( p_{a,0} )</td>
<td>3.0</td>
<td>2.0</td>
<td>2.0</td>
<td>kPa</td>
</tr>
<tr>
<td>Cavitation index ( \sigma_d )</td>
<td>0.054</td>
<td>0.054</td>
<td>0.065</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 3.3: Images of cavitating jets in the draghead experimental test setup

\[
\alpha_{mom} = \begin{cases} 
\frac{S}{x_{dr}} \cdot \alpha_{mom,cav} & : s \leq s_{dr} \\
\alpha_{mom,cav} & : s > s_{dr}
\end{cases} \quad (3.13)
\]

Substituting equation 3.9 in equation 3.8 gives the used value for the entrainment coefficient for fully developed flow in the calculation module:

\[
\alpha_{mom,cav} = \sqrt{\frac{1}{2k}} \sqrt{\frac{p_{a,0}}{\sigma_d p_j}} \quad (3.14)
\]

For the

For every slice \( k \) the entrainment of water can be calculated using:
3.2. Calculation Modules

\[ dQ_{w,k} = \alpha_{mom, cav,k} u_{u,k} P_w d s \]  
\[ dQ_{s,k} = h c \cdot v_{trench,k} d s \]

where:
- \( dQ_{w,k} \): entrainment of water  \( \text{m}^3/\text{s} \)
- \( u_{u,k} \): uniform flow velocity  \( \text{m/s} \)
- \( P_w \): perimeter of jet surrounded by water  \( \text{m} \)
- \( dQ_{s,k} \): entrainment of soil  \( \text{m}^3/\text{s} \)
- \( v_{trench,k} \): combined tangential and traversing velocity  \( \text{m/s} \)

Besides entrainment of water there is also entrainment of soil. The influence of the rotational velocity and traversing velocity of the jet is included in this equation for the entrainment of soil:

The combined velocity \( v_{trench,k} \) depends on the rotational velocity and the vertical traversing velocity. Close to the nozzle's exit the combined velocity will be equal to the vertical traversing velocity, but when the jet distance increases the combined velocity will be closer to the tangential velocity due to the rotational velocity. The tangential velocity depends on the distance \( s \) from the nozzle exit, the nozzle angle \( \alpha_n \) and the rotational velocity \( \omega_{yc} \):

\[ v_{tan,k} = 2 \pi \cdot \omega_{yc} \cdot s_k \cdot \sin \alpha_n \]

The combined velocity can be calculated using:

\[ v_{trench,k} = \sqrt{v_{t,v}^2 + v_{tan,k}^2} \]

where:
- \( v_{t,v} \): tangential velocity due to the rotational velocity  \( \text{m/s} \)
- \( v_{tan,k} \): combined jet velocity  \( \text{m/s} \)

Variables \( v_{trench,k} \) and \( h_c \) (see equation 3.10) are responsible for the velocity dependency of the entrainment model.

Using equations 3.15 and 3.16 the volume flow can be calculated for the next slice \( k \) using:

\[ Q_{j,k+1} = Q_{j,k} + dQ_{w,k} + dQ_{s,k} \]

In order to calculate the uniform jet velocity (see 3.3) the mixture density has to be calculated first. This can be done by rewriting equation 3.5 to:

\[ \rho_{m,k+1} = \frac{\rho_{m,k} Q_{j,k} + \rho_{w,k} dQ_{w,k} + \rho_{s,k} dQ_{s,k}}{Q_{j,k+1}} \]

Now the uniform jet velocity is known the stagnation pressure at every slice can be calculated using 3.2. Finally the penetration depth \( Z_c \) can be determined using:
where:

\[
Z_c = s(p_{stag,k} = N_{bc} \cdot su)
\]  

(3.21)

**Bearing capacity factor**  The assumption is made that the bearing capacity factor varies linearly from 5.0 to 8.2 depending on the fraction of the diameter of the jet that is enclosed by soil. Nobel (2013) assumed a value of the bearing capacity factor \( N_{bc} \) at the cavity bottom limited up to 8.2 for a moving penetrating jet. For values of \( h_c \) smaller than the diameter of the jet \( D_j \) the jet is affecting a layer of soil more than one time. In other words; a part of the soil is already removed during a previous rotation. This results in a lower value of \( N_{bc} \). Theoretically the bearing capacity factor could have a minimum value of 2.

For this model a minimum bearing capacity of 5 is assumed when the jet passes the soil multiple times. When \( h_c \) is larger than \( D_j \) the jet only experiences fresh soil and the value of 8.2 for bearing capacity factor is used.

### 3.2.2. Draghead

The theory behind the calculation module for the draghead setup is almost identical to the theory behind the module for the trenching orientation. Instead of a vertical jet moving **vertically through** the soil, this setup consists of a vertical jet moving **horizontally above** the soil. The differences between these models are the combined jet velocity component \( v_{drag,k} \) and the introduction of a Stand Off Distance (SOD). In this section these variables are explained.

During one rotation the jet stream experiences many different combined jet velocities. In figure 3.5 different combined velocities during one rotating can be seen. Again the tangential velocity component increases linearly with distance \( s \) from the nozzle exit (see equation 3.17). These velocities are calculated at three different locations. One where the velocity of the horizontally moving nozzle is added with the tangential velocity \( v_{drag,k} = v_{tan,k} + v_{t,h} \). This point will have the highest combined velocity. The lowest velocities will occur half a revolution later at the point where the tangential velocity is subtracted from the horizontal traversing velocity \( v_{drag,k} = \sqrt{(v_{tan,k} - v_{t,h})^2} \). At this point the lowest velocities occur. In the middle between these maximum and minimum velocities the combined velocity can be described by:

![Figure 3.4: Orientation of draghead experimental setup](image1)

![Figure 3.5: Schematic top view of a rotating jet while traversing](image2)
\[ v_{\text{drag},k} = \sqrt{v_{\text{tan},k}^2 + v_{t,h}^2} \]  

(3.22)

where:

- \( v_{\text{drag},k} \) combined jet velocity for draghead setup (m/s)
- \( v_{\text{tan},k} \) tangential velocity (m/s)
- \( v_{t,h} \) horizontal traversing velocity (m/s)

An example of the difference in penetration depth for these three different combined jet velocities is shown in figure 3.6. It can be seen that the difference in penetration depth between these combined velocities increases with increasing horizontal traversing velocity.

For the visualization module a single equation for the combined velocity \( v_{\text{drag},k} \) had to be taken in order to model the jet dimensions. In order to simplify the problem, the choice was made to use equation 3.22 as the averaged equation for the combined jet velocity over the whole rotation. This results in a single jet geometry during a rotation that will be inserted in the visualization module. Unfortunately this will result in an increasing underestimation of the averaged combined velocity for horizontal velocities larger than 800 m/h.

![Figure 3.6: Example of modeled penetration depth for different \( v_{\text{drag},k} \)](image)

The amount of entrainment also depends on the thickness of the slice of soil the jet encounters every rotation. This thickness depends on the ratio between horizontal traversing velocity and the rotational velocity (see figure 3.7). In the draghead calculation module \( h_c \) in equation 3.16 is replaced by \( x_c \). The thickness of the layer \( x_c \) can be described by:

\[ x_c = \frac{v_{t,h} \cos \alpha_n}{n \cdot \omega_{cye}} \]  

(3.23)

where:

- \( x_c \) thickness of soil layer that jet encounters (m)

Substituting \( x_c \) for \( h_c \) in equation 3.16 leads to the equation of the entrainment of soil for the draghead setup:

\[ dQ_{s,k} = x_c \cdot v_{\text{drag},k} ds \]  

(3.24)
The distance between the nozzle exit and the soil surface is called the Stand Off Distance (SOD). Along this distance the jet is fully surrounded by water and will only entrain water.

### 3.3. Modeling Jetting Pattern

A visualization module is developed using the calculated values out of the calculation module. Furthermore this module is able to calculate the theoretical excavated volume of soil. For this module Matlab is used as well. In order to calculate the excavated volume the jet is modeled as a cone. The shape of the cone is modeled out of the calculated values of the calculation module. The cone moves in a 3-dimensional grid along a predefined path depending on the horizontal traversing velocity and rotational velocity. Every cell where the jet went through is saved as an excavated cell. At the end of a simulation the 3-dimensional grid consists of non-excavated and excavated cells. Using a "patch"-function this can be visualized to get a simulation of the process. The excavated volume can be calculated with the summation of all excavated cells multiplied with the volume of one cell. The excavation production can now easily be calculated. Modeling the jet as a cone is of course a simplification. In reality the jet will not make a cut as the cone would make. However, this simplification will give an estimation of the shape of the cavity that would be created and the jet trajectory is described well.

The visualization module is developed for both orientations. These models are again quite similar. The difference between them is the trajectory the jets are passing.

**Modeling jet shape** For both modules the shape of the jet is modeled as a cone. In the calculation module the penetration depth is calculated. From the nozzle exit to the final penetration depth the jet diameter increases gradually. The jet diameter at distance $s$ from the nozzle outlet can be calculated using:

$$D_{j,k} = \sqrt{\frac{4Q_{j,k}}{\pi u_{i,k}}}$$  \hspace{1cm} (3.25)

Using the calculated penetration depth and jet diameter a 3-dimensional grid can be generated which models the jet (cone). A simplification is made that implies that the jet diameter linearly increases from $D_{nf}$ to the jet diameter at full penetration $D_{j,k}$. The jet is modeled as many consecutive spheres linearly increasing in
radius. The center-line of the consecutive spheres describes the orientation and penetration depth of the jet at a certain moment.

At every time step the jet is modeled at a new location depending on the corresponding rotational velocity and either vertical or horizontal traversing velocity.

Finally using a patch-function in combination with the "isosurface" function in Matlab every time step can be visualized and saved in a movie.

### 3.3.1. Trenching Visualization

For the trenching orientation a cross section is made in the model to be able to see the process at the inside of the clay block. Because the cross-section is made in the middle, the excavation production can still easily be determined by multiplying the excavated volume by 2.

In the visualization two nozzle outlets on one jet shaft are present. Between them there is an angle of 90° or 120°. This is done in order to compare the model with the experimental test setup.

**Results trenching visualization**

In figure 3.8 three visualization images are shown for different traversing velocities and a constant rotational velocity ($\frac{v_{t,h} \cdot \frac{\pi}{\omega_{yc}}}{\frac{\pi}{\omega_{yc}}}$). The images show a cross-section of the clay block. All models are made with the same resolution and time step. The difference in wall structure is caused by the ratio between the vertical traversing velocity and the rotational velocity. In figure 3.8a the jet removes every rotation a layer with a thickness of 0.3 mm, while in figure 3.8c the layer thickness is increased to 5.6 mm for every rotation.

### 3.3.2. Draghead Visualization

In this module a clay block is modeled similar to the used clay blocks in the experiments. In this module no cross-section is needed to visualize the process. The process can be seen from the outside of the block. For the module that simulates the application of rotating jets on a draghead the nozzle has a certain Stand Off Distance and moves horizontally. Every time step the jet experience an angular rotation and a horizontal displacement. Again the location of the jet depends on the rotational and horizontal traversing velocity and the dimensions of the jet are taken from the results of the calculation module.

**Results draghead visualization**

In this model the traversing velocities are much higher than in the trenching module. The ratio between horizontal traversing velocity and rotational velocity is much higher than in the trenching module. An example of the visualization model is given in figure . In figure 3.9 the visualized cavity is shown for a low horizontal traversing velocity. It can be seen that the cavity shape is constant over the length of the block while in figure 3.10 the effect of the higher $\frac{v_{t,h}}{\frac{\pi}{\omega_{yc}}}$-ratio due to the high traversing velocity can clearly be seen.

It has to be noted that the simplification of modeling the jet as a cone has to be taken into account. Because the traversing velocities are much higher some excavation will take place by breaking out of larger blocks of clay. The modeled cone will therefore give an underestimation of the excavation production. However it is found to be very hard to model whether a chunk of clay will tear off or not, because many variables are influencing the failure mechanism of tearing off chunks of clay. Processes as preference failure planes, plastic deformations, shear strength varieties due to deformations are influencing the failure mechanisms, but are not taken into account in this model.
Figure 3.8: Visualization for three different vertical traversing velocities

(a) $v_{t,v} = 4 \text{ mm/s}, p_j/su = 25, \omega_{yc} = 400 \text{ rpm}, \alpha_n = 45^\circ$

(b) $v_{t,v} = 30 \text{ mm/s}, p_j/su = 25, \omega_{yc} = 400 \text{ rpm}, \alpha_n = 45^\circ$

(c) $v_{t,v} = 75 \text{ mm/s}, p_j/su = 25, \omega_{yc} = 400 \text{ rpm}, \alpha_n = 45^\circ$

Figure 3.9: Example of draghead visualization low horizontal traversing velocity

Figure 3.10: Example of draghead visualization large horizontal traversing velocity
3.3. MODELING JETTING PATTERN

Removal of thin layers  Because the jet is modeled as a cone, thin layers can be present that are still attached and located at the original location even while only attached to a very small area (see figure 3.10). It is likely that such attached chunks are teared off in reality. In the present module also floating chunks of clay are still present in the visualization. These layers are not counted as “excavated” but are counted as “non-removed”. In reality, chunks of clay that are not attached to anything, will be sucked up by the draghead. Also thin layers will be removed because it is likely that a thin layer does have a largely reduced bearing capacity. In order to improve the visualization module, a script is written that is able to remove layers smaller than a certain thickness. This is done after running the normal visualization. Layers in the traversing direction smaller than a threshold value are removed. In figure 3.11 an example is shown of the visualization before and after the removal of thin layers in the traversing direction.

Figure 3.11: Comparison between visualization before and after the removal of thin layers smaller than 10 mm
4

EXPERIMENTAL SETUP

4.1. INTRODUCTION

Two test setups are designed in order to validate the developed models. In this chapter the design choices of both designs are discussed. Also information about the pump, motors and sensors is described. The trenching setup was designed and tested first. It has to be noted that this setup will not be a wanted design on an actual trencher or draghead. Probably the revolutions in a possible design using rotating jets will be flow driven. For the experimental test setup however, different parameters have to be known and be varied. This cannot be done with a flow driven test setup. The results of this study could be used for a design of a trencher or draghead with rotating jets though.

4.2. SETUP TRENCHING

Swivel  A swivel is a device that is able to connect a rigid part to a rotating part. In this setup a swivel is needed to connect the water hose from the pump to the rotating jet shaft. The swivel has a two inch input hole for the water inlet. Inside the swivel there are special seals that seals the swivel to the jet shaft. These kind of swivels can either handle high rotational velocities and low pressures, either low rotational velocities and high pressures. The higher the pressure the higher the friction forces between seals and jet shaft. It becomes harder and harder to turn the jet shaft. As a result the setup is limited by the swivel and therefore the swivel had to be selected first before making any other design decisions. For this application a swivel was found which is able to withstand a maximum pressure of 12 bars and a maximum rotational velocity of 600 rpm.

As already mentioned in section 3.2.1 the choice for modeling a horizontal trencher like the BSS-II in a vertical orientation was made because using a test setup in a vertical orientation would be much more convenient. It is assumed that moving a vertical jet vertically through the soil gives the same results as a horizontal jet moving horizontally through the soil. The main parameters of the setup are chosen close to the characteristic parameters of the BSS-II. A setup had to be designed that would be able to vary the following items:

• pump pressure (8-12 bars)
4. EXPERIMENTAL SETUP

Figure 4.1: Manufactured nozzle head

- rotational velocity (0-600 rpm)
- vertical traversing velocity (trenching velocity) (0-5 m/min)
- two nozzle angles (45° / 60°)

Pump pressure  A centrifugal pump was selected that could produce a flow of around $5 \, m^3/h$ at approximately 12 bars. The pump pressure can be adjusted using a frequency controller.

Rotational velocity  A pneumatic air drill was chosen to drive the jet shaft. The choice for an air drill was made mainly for safety reasons. An air drill stops automatically when it’s being overloaded and there is no danger for electrocution caused by interaction between electricity and water. The rotational velocity can be adjusted by varying the air pressure.

Vertical traversing velocity  A linear actuator was needed to provide the vertical motion of the system. A suitable actuator was already available in the hydrodynamic labatory, but couldn’t be disassembled out of its structure. To be able to use the current spindle, a system of a steel wire and pulleys was constructed. Using a frequency controller the velocity of the actuator can be adjusted.

Nozzle  Two nozzle angles are tested. For this test setup a nozzle head with two outlets is chosen. Firstly, the jet shaft will be balanced using two nozzle outlets in opposite direction. Secondly, the jet shaft has to make twice as less revolutions per minute using two outlets. Also the combined jet velocity will be lowered, because of the reduction of $\omega_{cy}$. The jet shaft and nozzle have to be smaller in diameter than the cavity that will be created. Nozzle heads with two the required number of outlets, angle’s of outlets and nozzle head diameter didn’t exist. The required nozzle heads are made personally in the faculty workshop at the Delft University (see figure 4.1).
4.2 Setup Trenching

Next to the design choices for the test-variables some other design choices had to be made:

• Jet shaft
• Construction
• Assembly

Jet shaft A jet shaft with small shaft tolerances had to be designed. The jet shaft had to fit exactly in the selected swivel. This shaft is designed and produced personally because there are no custom shafts like this in stock on the market.

Construction In order of easy re-use most of the setup is assembled in a small construction which can easily be dismounted and assembled to the draghead test setup. This construction is attached to a vertical guiding rail.

Total assembly The jet-construction mounted on the guide rail is assembled to a support construction in a large box filled with water. This box has an overflow to another container to maintain the correct water level during jetting. An overview of the experimental setup can be seen in figure 4.2.

Sensors Sensors are placed in order to measure all relevant data. All sensors are connected to a data-log program developed by Boskalis. This program is able to log all data at 10 hertz. The sensors used are:

• flow sensor
• pressure sensor
• rotation sensor
• displacement sensors

A flow sensor is used to measure the flow. This parameter is important in order to calculate the jet pressure at the nozzle outlet. The jet pressure cannot be measured with a pressure sensor because it is a moving rotating part. To calculate the jet pressure the discharge coefficient of the nozzle has to be determined. The determination of the discharge coefficient is done with a test and will be discussed in section 4.4. A pressure sensor is placed at the swivel inlet to measure the pump pressure. The pressure drop due to friction will be limited from the pump outlet to the pressure sensor because of the low flow velocity. The flow velocity through this hose is low because of the relatively large diameter of the hose. The pressure drop over the swivel/jetting section can be estimated using the pump/swivel pressure and calculated jet pressure. A displacement sensor is used to measure the vertical location at every time step. Using the displacement and corresponding elapsed time, the vertical traversing velocity can be easily be calculated.

4.3. Setup Draghead

For this test setup an old test setup is partly re-used. In 2014 A.P. van Gurp conducted plough tests during his graduation project at Boskalis. The setup consists of a main frame and a rail frame containing an electrical motor, spindle and guiding rails.

The main parameters of this setup are again chosen close to the characteristic parameters of a jet on a draghead. Fortunately the required pump pressure was similar to the trenching pump pressure. This meant that the same pump could be used. The setup is designed using parameters:

• pump pressure (8-12 bars)
• rotational velocity (0-600 rpm)
• horizontal traversing velocity (0-1800 m/h)
• two nozzle angles (45° / 60°)

Rotational velocity Instead of using an air drill this setup will use a closed loop stepper motor. An air drill turned out to be not that constant in rotational velocity. For the trench setup the varying of the velocity wasn’t influencing the results that much. Because the traversing velocity is much higher in the draghead setup, the influence of the rotational velocity will be larger. A closed loop stepper motor will give a constant rpm independent of the load. The rotational velocity can be adjusted with a software program connected to a driver.

horizontal traversing velocity The horizontal translation of the jetting system is conducted by a horizontal spindle system driven by an electric motor. The motor is adjustable up to 0.5 m/s using a feedback loop regulator. The feedback loop regulator provides a constant rotational velocity of the spindle independent of the load. The spindle is attached to a special made cart rolling between two guiding rails.

Layout test setup

The whole jet construction is mounted to a special made cart (see figure 4.3). This cart is moving between two rails and is driven by the spindle system. An overflow is created in the main construction to maintain a constant water level. The whole test setup can be seen in figure 4.4.


4.4. EXPERIMENTAL DETERMINATION OF THE DISCHARGE COEFFICIENT

The discharge coefficient $\mu_n$ of a nozzle could vary between 0.6 and 1.0 depending on the geometry (White, 2009). A nozzle with a really bad geometry could have a discharge coefficient down to 0.6. For the experiments a personally manufactured nozzle head is used. Due to the maximum required dimensions of the nozzle head it wasn’t possible to produce a nozzle with a discharge coefficient close to 1.0. Especially the nozzle inflow had a really bad geometry. On a milling machine the openings were drilled at the correct angle. This resulted in a very sharp edge at the inflow area of the nozzle, causing a high pressure drop. To reduce the pressure drop, the inflow area was reamed with a drill. The pressure drop was reduced but the nozzle still has a bad geometry. In the left part of figure 4.5 the sharp edges at the nozzle inflow can be seen straight after manufacturing the nozzle head. At the right the reamed inflow is shown.

The discharge coefficient is determined by executing tests with low flow rates. The pressure drop is mainly
dependent on the flow velocity. By very low flow velocities the pressure drop can be neglected. When the pressure drop is assumed to be negligible the discharge coefficient can be calculated using:

$$\mu_n = \frac{Q_0}{n \cdot A_n \cdot u_0} \quad (4.1)$$

The flow rate is measured at the pump outlet giving a value for $Q_0$. At the swivel inlet the pressure is measured with a pressure sensor. Substituting the swivel pressure for the jet pressure and rewrite the equation gives an equation for the initial jet velocity at the nozzle’s exit:

$$u_0 = \sqrt{\frac{2p_{swivel}}{\rho_w}} \quad (4.2)$$

The nozzle outlet area is given by:

$$A_n = \frac{\pi D_n^2}{4} \quad (4.3)$$

Using equation 4.1 the fictitious nozzle area can now be calculated:

$$A_{n,f} = \mu_n \cdot A_n \quad (4.4)$$

It is assumed that the discharge coefficient is constant for a jet pressure for a range of 1 - 10 bar. The discharge coefficient found for both $45^\circ$ and $60^\circ$ nozzles was 0.87. The same test procedure was done for a standard professional manufactured 7 mm Woma nozzle. The determined discharge coefficient found of the Woma nozzle was 0.97. (Nobel, 2013) also conducted tests to determine the discharge coefficient of this Woma nozzle using another test procedure and found a value for the discharge coefficient between 0.94 and 0.98.

The initial jet velocity at the nozzle’s outlet can be calculated using the measured value of the flow rate:

$$u_0 = \frac{Q_0}{n \cdot A_{n,f}} \quad (4.5)$$

Finally the jet pressure corrected for the discharge coefficient becomes:

$$p_{jet} = 0.5 \cdot \rho_w \cdot u_0^2 \quad (4.6)$$
4.5. CLAY BLOCKS

Blocks of clay were selected based on:

• Undrained shear strength

The undrained shear strength of the clay is an important value. The stagnation ratio is an important parameter in this study. In this study a penetrating jet is considered. For a penetrating jet the $P_{stag}/su$-ratio has to be larger than 12. The required pump pressure to achieve a certain jet pressure is limited by the selected swivel. The support parts for the seals in the swivel are designed to withstand a pressure up to 12 bars. This resulted in selection criteria for the required pump. A pump was selected that could provide a maximum pump pressure of approximately 12 bar. A frequency controller was connected in order to adjust the pump pressure. Assuming a pressure drop in the whole jetting system of about 30% resulted in a theoretically maximum jet pressure of 8.4 bar. The maximum undrained shear strength to satisfy a minimum stagnation ratio of 12 is 70 kPa. The selected clay had an undrained shear strength $su$ in a range of 30 to 40 kPa.

• Geometry of block

Every side of the block has to be large enough to enable sufficient distance from the cavity to the exterior surface of the clay block. When a cavity is jetted too close to the exterior surface, the cavity will be affected by preference planes that are present due to the manufacturing process (see figure 4.6). Besides, the resistance of the soil is lower when the cavity wall is close to the outside wall of the block. The selected clay block has dimensions: (15.5 cm x 16 cm x 20.5 cm).

• Homogeneity

It is important that the characteristics of the clay are constant over the whole block. High deviations in undrained shear strength, consistency etc. are not wanted. Furthermore it is important that there are no large differences between different clay blocks in order to be able to compare the results accurately. Manufactured clay of Ginjaar-clay-factory was selected. The bricks are made of river-clay and have a high homogeneity in and over the clay blocks.

Figure 4.6: Failure along present preference planes at the outer walls of the clay block

The properties of the clay are tested at the Dolman laboratory and shown in table 4.1:
Table 4.1: Laboratory results of two clay samples

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Sample 1</th>
<th>Sample 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content</td>
<td>%</td>
<td>32.3</td>
<td>31.8</td>
</tr>
<tr>
<td>Dry matter content</td>
<td>%</td>
<td>75.6</td>
<td>75.8</td>
</tr>
<tr>
<td>Density (Situ)</td>
<td>kg/m$^3$</td>
<td>1907</td>
<td>1904</td>
</tr>
<tr>
<td>Density (Specific)</td>
<td>kg/m$^3$</td>
<td>2630</td>
<td>262</td>
</tr>
<tr>
<td>Density (Dry)</td>
<td>kg/m$^3$</td>
<td>1442</td>
<td>1444</td>
</tr>
<tr>
<td>Shear strength (torvane)</td>
<td>kPa</td>
<td>33</td>
<td>35</td>
</tr>
<tr>
<td>Plastic limit</td>
<td>%</td>
<td>21</td>
<td>18</td>
</tr>
<tr>
<td>Liquid limit</td>
<td>%</td>
<td>49</td>
<td>51</td>
</tr>
<tr>
<td>Plasticity index</td>
<td>%</td>
<td>28</td>
<td>32</td>
</tr>
<tr>
<td>D50</td>
<td>$\mu_m$</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>

A grain distribution of two clay samples is shown in appendix A.3.
5.1. INTRODUCTION

In total more than 100 tests are conducted. To achieve a high repeatability a test procedure was followed every test. In this chapter the test procedure is explained. Furthermore the determination of the results is discussed. Finally the results are plotted and evaluated.

5.2. TEST MATRIX

The main parameter varied is the vertical traversing velocity in the trenching experiments and the horizontal traversing velocity in the draghead tests. Besides varying the traversing velocities, most tests are conducted with two nozzle angles. To study the effect of the rotational velocity some tests are carried out with different rotational velocities. For the draghead tests also tests are conducted with two different Stand Off Distances. Finally some tests with different stagnation ratio's ($p_{stag}/su$) are conducted.

For the trenching setup over 30 tests are executed. The complete test matrix can be seen in A.1.1.

In the draghead setup the Stand Off Distance turned out to be of an importance after finishing first tests (see 6.2.2). Therefore the SOD is implemented as an extra variable in the test matrix (see A.1.2). In total more than 60 tests are conducted with the draghead setup.

To compare these results with a traditional non-rotating nozzle as they are normally mounted on a draghead, also tests are conducted with a single vertical non-rotating nozzle. These tests are conducted with one 7 mm nozzle. The flow cross area of a 7 mm nozzle opening is very close to the combined flow area of the two 5 mm nozzle’s from the rotating jet experiments. The experiments are done with the same jet pressure and over the same range of traversing velocities as the rotational jets (see A.1.2).

In table 5.1 the range of test parameters is shown for the different experimental setups:
Table 5.1: Range of test variables for the trenching and draghead experimental setup

<table>
<thead>
<tr>
<th></th>
<th>Trenching rotating</th>
<th>Draghead rotating</th>
<th>Draghead non-rotating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traverse velocity $v_t$</td>
<td>0.004 - 0.070 m/s</td>
<td>0.01 - 1.80 m/s</td>
<td>0.05 - 0.5 m/s</td>
</tr>
<tr>
<td>Jet pressure $p_j$</td>
<td>$6.4 \cdot 10^2$ kPa</td>
<td>$8.8 \cdot 10^2$ kPa</td>
<td>$8.7 \cdot 10^2$ kPa</td>
</tr>
<tr>
<td>Nozzle diameter $D_n$</td>
<td>5 mm</td>
<td>5 mm</td>
<td>7 mm</td>
</tr>
<tr>
<td>Undrained shear strength $s_u$</td>
<td>35 - 40 kPa</td>
<td>35 - 90 kPa</td>
<td>35 kPa</td>
</tr>
<tr>
<td>Stagnation ratio $p_j/s_u$</td>
<td>17.7 / 25</td>
<td>22 - 26 / 10</td>
<td>22 - 10</td>
</tr>
<tr>
<td>Stand Off Distance SOD</td>
<td>- mm</td>
<td>5 - 10 mm</td>
<td>10 mm</td>
</tr>
<tr>
<td>Rotational velocity $\omega$</td>
<td>200 - 600 rpm</td>
<td>200 - 600 rpm</td>
<td>0 rpm</td>
</tr>
<tr>
<td>Nozzle angle $\alpha_n$</td>
<td>45 / 60 deg</td>
<td>45 / 60 deg</td>
<td>0 deg</td>
</tr>
</tbody>
</table>

5.3. TEST PROCEDURE

A single test consists of many steps. A complete test cycle could be divided in three parts. Firstly every test has to be prepared, than the test is executed and finally the results of the tested sample have to be collected. To ensure a high repeatability of the test program a test procedure is followed every test. Furthermore a good comparison of the results can only be made when every experiment is executed the same way.

5.3.1. TRENCHING SETUP

Two persons are required in order to execute tests for the trenching setup. One person operates the pump, vertical displacement of the nozzle head. The second person operates the air drill that is responsible for the revolutions.

One test cycle took approximately 30 minutes, while the actual jetting part of the test was less than a minute. A detailed test procedure for the trenching experiments is given in appendix A.2.1.

Determination of undrained shear strength   The undrained shear strength was measured with a hand torvane. Some tests are performed before jetting and after jetting. There was no deviation found between the results before and after testing. This is probably because of the very limited time the clay block is submerged in water. This submerged time is that limited because the block is only inserted minutes before a tests and taken out of the water immediately after a test. Because there is no difference in undrained shear strength before and after a test, the choice was made to measure the undrained shear strength after each test. After a test the clay block is cut in half and the strength can now be determined at the "inside" of the block. The used clay block are produced in a clay factory. They are formed using an extruder. This process results in non-homogeneous spots and preference planes at the outer walls of the block. Furthermore the clay block will be dried out a bit at the surfaces. Besides the jet is moving through the block and will experience the strength of the inside of the block rather than the strength at the outer sides of the block. Therefore determining the undrained shear strength should preferably be done at the inside of the block after making a cross-section.

Measuring excavation production   The excavation production is determined after measuring the minimum cavity diameter with a ruler. This is done in the upper, middle an lower part of the cross section. A disadvantage of this method is that it is important to cut block at the correct location. The clay has to be cut over a straight line over the middle of the "circle" (cavity). However a small offset from the middle hasn’t a large influence on the measured minimum cavity diameter. This can be seen in figure 5.1.
Errors because of an offset less than 20% \((y/ r_c)\) are considered acceptable. The averaged value is taken as the minimum cavity diameter. The cross-sectional area can now be calculated using:

\[
A_c = \frac{\pi D_c^2}{4}
\]  

(5.1)

The vertical traversing velocity is determined using the location sensor. The excavation production can now be calculated by multiplying the velocity with the excavated cross-sectional area (eq. 5.1):

\[
\dot{M}_{ex} = v_{t,v} \cdot A_c
\]  

(5.2)

**TEST REPORT**

A typical figure showing the test parameters can be seen in figure 5.2. This figure shows a whole trenching test. A start up behavior of the flow sensor can clearly be seen in the beginning of the flow rate graph and the jet pressure graph. This is a result of the start up output of the flow sensor and does not represent the real flow. After this start up behavior the sensor starts to give reliable results. When the nozzle isn’t penetrating the clay the height of the nozzle in the graph is shown as a negative value. The nozzle starts penetrating the clay at height 0 mm and stops at height 140 mm. When the nozzle is located at the highest position the nozzle head is 200 mm away from the top surface of the clay block (-200 mm). For every test one single value for every parameter is obtained using the averaged value of the data in the range where the nozzle is penetrating the clay (see figure 5.3).

The filtered values in the graph for the vertical traversing velocities are calculated over a period of half a second and the filtered values for the rotational velocity over one second. The averaged value for the vertical traversing velocity that is taken for the whole test is determined by dividing the penetration distance (height) by the time it took (time). This will give the most accurate averaged value for the traversing vertical velocity.

For every test a test report is made (see Appendix B.1). A report includes some graph’s from the sensors, some pictures and the collected test data. A typical test report can be seen in figure 5.4.
Figure 5.2: Sensor data of a whole test, nozzle start penetrating the soil at Time=14 s

Figure 5.3: Parameters of actual penetrating part of a trenching experiment (Time: 14 - 16.5 s)
5.3. TEST PROCEDURE

<table>
<thead>
<tr>
<th>Date</th>
<th>20-11-2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Testnr</td>
<td>1</td>
</tr>
<tr>
<td>SU tests [kPa]</td>
<td>X X X X X</td>
</tr>
<tr>
<td>SU avg [kPa]</td>
<td>X</td>
</tr>
<tr>
<td>Nozzle angle [deg]</td>
<td>X</td>
</tr>
<tr>
<td>p_jet [bar]</td>
<td>X</td>
</tr>
<tr>
<td>v_t,v [m/s]</td>
<td>X</td>
</tr>
<tr>
<td>v_t,v avg</td>
<td>X</td>
</tr>
<tr>
<td>Dc [mm]</td>
<td>X</td>
</tr>
<tr>
<td>Area [mm²]</td>
<td>X</td>
</tr>
<tr>
<td>Production [m³/h]</td>
<td>X</td>
</tr>
</tbody>
</table>

Figure 5.4: Test report test 20151120test1
5.3.2. Draghead setup

Experiments with the setup for the draghead application have to be executed by two persons. One person operates the pump and rotational revolutions while the second person operates the horizontal traversing velocity.

The setup assembly can be divided into two sections. A lower and upper section. The lower section consists of the main tank where the clay blocks can be inserted. The upper section consists of a structure where the whole jetting system is attached to. This upper section has to be craned away before and after a test to be able to insert and recover the clay blocks. After a test the tank has to be emptied and cleaned before inserting a new block. These necessary steps resulted in a large cycle time for a single test. In order to reduce the total number of cycles, two tests are done in one cycle. Two blocks can be inserted in the tank with sufficient distance between them. The motor that drives the spindle system has a very large acceleration, resulting in a very limited acceleration time before achieving the required horizontal velocity. Because the whole jetting system can achieve the correct velocity almost immediately two tests with different settings can be done in one cycle.

A detailed procedure of a single test cycle can be seen in appendix A.2.2.

One test cycle took approximately 1.5 hours. Two tests can be conducted during one test cycle. For several tests also movies are recorded using a submerged Go-Pro camera placed just in front of the nozzle-head.

Determination of undrained shear strength

Like the determination of the su in the trenching experiments the strength is measured at the inner side of the blocks. After the block is inserted in the support structure the upper part is sliced to create a flat clean service at the correct height. Approximately a layer of 5 cm is sliced off, the sliced plane is the sample surface for the undrained shear strength measurements. This surface isn't dried out yet and is most close to the cavity that will be created by the jets.

Measuring excavation production

As already discussed in section 5.3.1 the excavated area has to be determined. In contrast to the trenching experiments, the results of the draghead experiments aren’t shaped in a nice circle, but more like a triangle shape. Because the traversing velocities are much higher in the draghead experiments the ratio between traversing velocity and rotational velocity \( \frac{v_t h}{R \cdot \omega_{yc}} \) is much larger than the draghead experiments. This means that the shape isn’t constant over the whole length of the block. Measuring the dimensions at one cross-section won’t give a reliable result of the excavated area. A more accurate determination of the excavated area is to fill the cavity with water. The volume of water that went in the cavity can be divided by the length of the sample giving the averaged excavated area.

The first and last parts of the block are sliced off before determining the excavated volume to get rid of the “walk-in” and “walk-out” effect. The clean middle part of the block is taken as sample to measure the excavated volume. This middle part has to have a sufficient length in order to get a representative result. Two wooden shelf’s are clamped to both cut surfaces. It’s important to place the upside part of the shelf in line with the upper side of the block. The cavity is now filled with water using a small funnel till it just overflows the wooden shelf. The amount of water that went in the cavity is measured with an accurate scale by weighing the measuring cup before and after inserting water in the cavity. This filling and weighting procedure is executed multiple times to get an accurate averaged value. It's important to note that by very small cavities the measuring error became larger. By small excavated volumes the error caused by spilled water and surface tension has a larger influence than by large volumes. This effect was also seen during determination of the volume. At small excavated volumes the deviation between the multiple volume measurement per test was
found larger than the deviation found by large volumes. In order to increase the reliability of the measured results, more volume tests were performed when a large deviation between the different measurements was found.

![Image](image.png)

**Figure 5.5:** Wooden shelf clamped on clay sample in order to measure the excavation volume

**Definition excavation production**  The measurement procedure that was executed leads to the following definition of the excavation production: **The excavated production is the volume of clay that is removed out of its original position in a certain amount of time.** During jetting also a bit of clay is moved upwards but still attached to the clay block. The measured excavated volume includes a bit of clay what is pushed upwards above the original top surface of the clay block. Also some volume measurements were executed where the pushed up clay was pressed back under the original top surface. This led to a decay of the excavated volume up to 30% in some cases. Unfortunately this couldn't be done for every test, but it has to taken into account when comparing the results with the model results, because in the model the clay isn't pushed up.

**Test report**

A whole test cycle consisted of two tests. Again a test report is made for every test (see appendix B.2). The averaged values from the sensors are taken over a distance of approximately 500 mm. From 150 mm in front of a clay block till 150 mm behind the block, the clay block has a length of around 200 mm. The results of a test are collected together with some pictures and the test parameters in a test report. An example of a test report for a experiment of the draghead setup can be seen in figure 5.6.
Figure 5.6: Test report 20160322test3
6.1. INTRODUCTION

In this chapter the results of the experiments and the models are described. In section 6.2 the results of the experiments for both trenching and draghead experiments are explained. In the second part of this chapter (section 6.3) the modeled results are compared to the experimental results.

6.2. TEST RESULTS

Much data is collected during every test. First of all the real test parameters are being processed. These parameters consist of the actual jet pressure, swivel pressure, flow rate, rotational velocity and traversing velocity. Furthermore dimensions, shear strengths and excavated volumes are measured from the produced cavities. Finally photographs are made and together with all other data stored in an electronic map.

6.2.1. TRENCHING SETUP

Influence rotational velocity  Different experiments are executed with a constant vertical traversing velocity but with a different rotational velocity. It turned out that varying the revolutions from 200 to 600 rpm has no influence on the produced cavity diameter. In figure 6.1 it can be seen that varying the rotational velocity doesn't result in a significant change in the cavity diameter.

The small deviations present are too small to allocate them to a single varying parameter. These small deviations can probably be allocated to measurement errors and differences in clay strength.

At these relatively low vertical traversing velocities the ratio between vertical velocity and rotational velocity is rather small which yields that the “height” of soil that one jet has to blow away is relatively small. Because this in-dependency it wasn't an issue that the air drill could not provide a very constant and accurate rpm. However this problem was solved for the draghead setup because the traversing velocity over rotational velocity ratio was much larger in the draghead setup and an accurate constant rotation speeds is preferred in the higher traversing velocity range.
Influence of the vertical traversing velocity  Figure 6.2 shows the affect of the traversing velocity on the cavity diameter. All data-points shown in the graph's are conducted with an averaged rpm of approximately 400.

Observing figure 6.2 a clear trend can be seen. The shapes of the graph's follow a shape of a negative power function. The trend-lines are added in figure 6.3. When the cavity diameter drops below to 40 mm the maximum vertical traversing velocity is reached. This is because the nozzle head has a diameter of 40 mm. The corresponding values for the plotted diameters of 40 mm can be considered as too fast and are produced “mechanically” instead of “hydraulically”. The traversing velocities just above 40 mm can be considered as the maximum possible velocities.

Influence of the nozzle angle  Two nozzle angles are tested. At the lowest vertical traversing velocity the 60° nozzle produced a slightly larger cavity diameter than the 45° nozzle. Most results of the two nozzle angles are quite similar. The 45° nozzle can be considered as the better one, because its maximum traversing velocity is 50 mm/s at a stagnation ratio of 17.7 where the 60° nozzle has a maximum velocity of 35 mm/s. It can be possible that this has something to do with a blockage of the nozzle head. The 45° nozzle produces
a more vertically oriented jet. The soil underneath the nozzle head will be better cleared than the more horizontally oriented jets of the 60° nozzle. However, a blockage should be noticeable in the pressure sensor, but no deviation in pressure was found in the pressure measurements of this test. This suggests that another mechanism is responsible for the better achievements of the 45° nozzle.

### Stagnation ratio dependency

For the 45° nozzle head two test series at different stagnation ratios ($\frac{p_j}{p_{st}}$) are conducted. Lowering the stagnation ratio is done by decreasing the jet pressure. In literature empirical formula's suggest the penetration depth to be linearly dependent of the stagnation ratio for a vertical jet moving horizontally. It seems that the suggested correlation holds for rotating jets. Multiplying the cavity diameters from the $\frac{p_j}{p_{st}} = 25$ experiments with a factor $\frac{17.7}{25}$ gives linear dependent results for the cavity diameters of the $\frac{p_j}{p_{st}} = 17.7$ data-set. These empirical based values can be compared to an actual test data-set with a stagnation ratio of 17.7. Figure 6.4 shows the comparison between the actual test data and the empirically estimated values.

![Figure 6.4: Dependency of the stagnation ratio](image)

To get some insight in the reproducibility of the experiments some tests are performed multiple times to check whether the results are reproducible or not. In figure 6.2 it can be seen that the repeated test results are almost identical to each other. However it can also be seen that there are some deviations. Especially the red circle around point (40,40) is quite different than the repeated test that is located at (40,50). Probably there went something wrong during that test because it mechanically cut the cavity. It can be possible that an in-homogeneity in the clay was present. The logged sensor data don’t show any irregularities in the pressure, flow or revolutions, so a blockage isn’t likely. Fortunately, the results differs that much from the trend and the repeated test that is could be considered as a test error.

The other present deviations can probably be subscribed to measurement errors and differences in clay strength’s.

### Wall profile

The structure of the cavity-walls become more rough when traversing faster. In figure 6.7 several cavities are shown created with different test settings. For very low vertical traversing velocities a continual spiral shaped cavity is present (see figures 6.7a 6.7d and 6.7g). A straight clean surface would be expected, because the very limited thickness of the layer of clay that is being removed by the jet at those low velocities; the thickness of the layer that is removed by one jet each rotation is even smaller than 0.25 mm. It could be...
possible that the spiral is created by the waste water. The waste water will most likely be flowing upwards centrifugally. The centrifugal shape can be caused because the jet water is exerted with a certain angular velocity and the jet is acting like a paddle that is driving the centrifugal flow as well. This effect is amplified slightly because the cross-sectional flow area for the back-flow is narrowed because of the present jet axis. However after subtracting the jet axis cross-sectional area from the cross-sectional cavity area the available cross-sectional area is still significant. The resulting flow velocity exerted by the jet at the remaining cross-sectional area for the cavity shown in figure 6.7g will be around 1 m/s \( p_{stag} < 0.6 \text{ kPa} \). Adding a tangential velocity of 1.15 m/s (400 rpm) leads to a stagnation pressure smaller than 2.4 kPa. Such low stagnation pressures will not penetrate the clay. To get more insight in the pressure acting along the nozzle head, some tests were executed with an extra pressure sensor just besides the nozzle head (see figure 6.5). However, the pressure deviations found were negligible. Therefore the centrifugal back-flow probably doesn’t produce the spiral because of the stagnation pressures. It would be more assumable that the back-flow creates some surface erosion on the cavity walls because the back-flow is weakening the surface with a continuing spiral as a result.

Figure 6.5: Extra pressure measurement point located just beside the nozzle head

Another possible explanation could be the effect that can be seen in the deflection zone of a penetrating jet. In the deflection zone of the jet larger lumps of soil (stripes) are removed than in the non-deflection zone (see figure 6.6a). It could be possible that during multiple rotations the pressure behind a lump of soil rises and fails when a certain stress-hold is reached. This effect results in a larger lump that is removed at once (see figure 6.6b). When this occurs at several locations of one revolution a spiral shaped wall structure would be possible.
6.2. Test Results

(a) Non-deflection and deflection zone of a horizontally moving vertical penetrating jet (Nobel, 2013)

(b) Non-deflection and deflection zone of a vertically moving rotating penetrating jet (45°)

Figure 6.6
Figure 6.7: Wall profiles by different test parameters
6.2.**TEST RESULTS**

**Comparison with conventional non-rotating nozzle**  
As already discussed in section 2.3.3 the cavity width of a non-rotating jet is limited to 1-2 times the nozzle diameter. In order to compare the rotating tests to a conventional non-rotating nozzle a single nozzle was selected with a nozzle diameter of 7 mm. One nozzle with an outlet diameter of 7 mm has approximately a similar cross-sectional flow area as two outlets of 5 mm. The expected cavity diameter based on section 2.3.3 would have a maximum around 15 mm. This diameter is smaller than the nozzle head diameter of 40 mm. Therefore the nozzle could never travel through the soil. An experiment is conducted to verify whether the nozzle head could penetrate the soil and travel through the clay. As expected the nozzle wasn't able to jet a cavity wide enough to enable the nozzle head to travel any further. Unfortunately, no cavity dimensions could be measured because the nozzle head was obstructed by the clay, the stagnation pressure was raised and a hole was created with an arbitrary shape. The created hole still wasn't large enough enabling the nozzle head to travel any further.

The get more insight in the cavity created by a conventional non-rotating nozzle, experiments with the 7 mm non-rotating nozzle are also conducted for the draghead test setup. The maximum cavity diameter of the non-rotating jet at a horizontal traversing velocity of 11 mm/s and a $p_j/Su$ of 22.5, occurred to be 11 mm ($1.6D_n$). For a traversing velocity of 51 mm/s the cavity diameter decreased to 8 mm ($1.2D_n$). Comparing the maximum achieved production of the tested 45° nozzle head ($v_{t,h} = 211 m/h, p_j/Su = 25$) to the theoretical production of a non-rotating nozzle with a cavity diameter of $1.2D_n$ using the same stagnation ratio leads to a production increase of a factor 54. However the stagnation ratio for the non-rotating jet could be lowered to achieve the same cavity diameter. This means that jet pressure could be lowered and the nozzle diameter could be increased to use the same hydraulic power ($P_h = Q \cdot p_{jet}$). When a minimum stagnation ratio of 12 is considered (for a penetrating jet) the jet pressure could be lowered with a factor 2.1. When the same hydraulic power is used, the discharge can be increased with a factor 2.1 resulting in an increase in the cross-sectional flow area of the non-rotating nozzle of 2.1. The increase in production of the rotating jet compared to the theoretical production of a non-rotating nozzle decreases to a factor 26. Probably the stagnation-ratio (jet-ratio) could be decreased slightly more, because no large penetrating depth is required. However, the productions of jet-ratio’s lower than 12 are hard to estimated, therefore another orientation of the nozzle is suggested. The Trenchformer owned by VBMS makes use of vertical orientated jets while moving horizontally (see figure 1.2). Such an orientation will have a larger production in clay, because the penetration depth of the jet is used for the production as well.

When such an orientation is considered the productions could be compared to the executed draghead experiments, because those experiments consist of a horizontally moving vertical non-rotating jet.

![Jet cavities realized by a jet sword](image1)

**Figure 6.8:** (a) Jet cavities realized by a jet sword, (b) Frontal view of jet cavities, (c) Jet cavities realized by a jet sword after changing the orientation of the jets (d) Frontal view of jet cavities
For non-rotating jetting in clay such an orientation will achieve larger productions. When the orientation is changed to a vertical jet the production of the non-rotating jet can be obtained from the results of the non-rotating draghead experiments. In table 6.1 a production increase of a factor 6.9 is found compared to a vertical jet moving horizontally (draghead setup).

Table 6.1: Production comparison

<table>
<thead>
<tr>
<th></th>
<th>Rotating jet</th>
<th>Non-rotating jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traversing velocity $v_t$</td>
<td>49 mm/s</td>
<td>51 mm/s</td>
</tr>
<tr>
<td>Jet pressure $p_j$</td>
<td>8.8 bar</td>
<td>8.6 bar</td>
</tr>
<tr>
<td>Undrained shear strength $s_u$</td>
<td>36 kPa</td>
<td>39 kPa</td>
</tr>
<tr>
<td>Stagnation ratio $p_{stag}/s_u$</td>
<td>24.4</td>
<td>22</td>
</tr>
<tr>
<td>Nozzle diameter $D_n$</td>
<td>5 mm</td>
<td>7 mm</td>
</tr>
<tr>
<td>Number of nozzle outlets $n$</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Discharge coefficient $\mu_n$</td>
<td>0.87</td>
<td>0.97</td>
</tr>
<tr>
<td>Hydraulic power $P_h$</td>
<td>1.23 kW</td>
<td>1.34 kW</td>
</tr>
<tr>
<td>Stand Off Distance $SOD$</td>
<td>X</td>
<td>10 mm</td>
</tr>
<tr>
<td>Rotational velocity $\omega_{cyc}$</td>
<td>370 rpm</td>
<td>0 rpm</td>
</tr>
<tr>
<td>Cavity width $W_c$</td>
<td>X</td>
<td>X mm</td>
</tr>
<tr>
<td>Minimum cavity diameter $D_c$</td>
<td>X</td>
<td>X mm</td>
</tr>
<tr>
<td>Cavity depth $Z_c$</td>
<td>X</td>
<td>X mm</td>
</tr>
<tr>
<td>Cavity area $A_c$</td>
<td>X</td>
<td>X mm²</td>
</tr>
<tr>
<td>Production $M_{ex}$</td>
<td>X</td>
<td>X m³/h</td>
</tr>
<tr>
<td><strong>Production increase</strong></td>
<td><strong>6.9</strong></td>
<td>-</td>
</tr>
<tr>
<td><strong>Specific energy decrease</strong></td>
<td><strong>7.4</strong></td>
<td>-</td>
</tr>
</tbody>
</table>

Unfortunately the non-rotating draghead experiments are not executed for every single test parameter of the rotating trenching experiments, i.e. it isn’t possible to compare every rotating experimental value to a non-rotating experimental value. However the production of the non-rotating draghead experiment can be well described by an empirical model developed in-house by Boskalis. The results of this empirical model are close to the actual non-rotating draghead experiments (see figure 6.9).

In figure 6.10b it can be seen that the increase in excavation production of a 45° nozzle compared to the empirical modeled production of a non-rotating jet lies in a range between 6 and 7.
6.2. Test Results

(a) Comparison production of rotating jet and non-rotating jet

(b) Production increase for several traversing velocities

Figure 6.10: Comparison of rotating jet experiments and empirical non-rotating values

6.2.2. Draghead Setup

Influence rotational velocity A stepper motor is used to ensure accurate and constant rotation speeds. At higher horizontal traversing velocities the ratio becomes larger. So less rotations are exerted over the length of the clay block and the cavity dimensions get less constant. The effect of the rotational velocity can clearly be seen in the shape of the cavities and in the averaged excavated area. Figures 6.11 and 6.12 show the effect of lowering the rotation speeds results in larger excavated area’s. At very low traversing velocities lower rotation speeds result in larger excavation area’s. This effect only holds for very low traversing velocities. From slightly larger speeds the averaged excavated area increases significantly with increasing rotational velocity.

Influence of the horizontal traversing velocity The horizontal velocity is varied between 10 and 500 mm/s. In figure 6.13 all data-points are presented with a rotational velocity of 400 rpm and a stagnation ratio between 20 and 25. A clear trend can be seen in all data-sets. Trend lines are added in figure 6.14. Two points differ significantly from the “60 deg, 400 rpm, pj/su=25, SOD=5 mm” trend-line. Because of this large deviation these experiments are conducted again and the repeated test results are located on the expected line. The two deviating results can be rejected because it is likely the strong deviation is caused by a measurement error or weaknesses in the clay block.

It has to be noted that there is a significant difference in stagnation ratio between the 45° and 60° nozzles. This
difference is caused by a difference in undrained shear strength of the clay blocks of about 15%, resulting in a difference around 15% in the stagnation ratios.

Figure 6.13: Influence of the horizontal traversing velocity

Figure 6.14: Influence of the horizontal traversing velocity with trendlines
Influence of the nozzle angle  The influence of the nozzle angle in the draghead setup seems to be larger than in the trenching setup. Figure 6.14 shows the largest excavated area's when the 60° nozzle at a SOD of 5 mm is used. Note that there is a difference in stagnation ratio of 15% between the experiments with the two nozzle angles. When the test would be performed with the same stagnation ratio the lines will be slightly closer to each other.

The shapes of the cavities are rather different between the different nozzle angles combined with a certain Stand Off Distance. In figure 6.15 four combinations of nozzle angles and SOD's are showed for a mid-range horizontal traversing velocity (XXX mm/s). A clear difference in the shape of the cross-sectional area can be noted in the figures. The cavities are wider but less deep for the 60° nozzle compared to the 45° nozzle. Most experiments conducted with a 60° nozzle and a SOD of 10 mm resulted in a cavity that isn't shaped triangularly, but more as a rectangle.

![Figure 6.15: Cavity shapes for different nozzle angles and SOD](image)

**Stand Off Distance dependency**  A clear difference in averaged excavated area can be noted between the tests with varying the Stand Off Distance. For the 45° nozzle the excavated area is larger when a vertical Stand Off Distance (SOD) of 10 mm is used. The SOD is the vertical distance between the nozzle head and bed top surface. Because the jet is placed under an angle the Stand Off Distance along the center-line of the jet is \( SOD_c = \frac{SOD}{\alpha_n} \).

During experiments with a SOD of 5 mm interaction occurred between the bed and the nozzle head. In the movies made by a submerged Go-Pro camera it could be seen that the soil is pushed upwards. Because the
jet rotates it will also be pointed towards the clay that is still in front of the nozzle or to the side of the nozzle. When the jet is orientated in such direction it is hard to get rid of the waste water. The pressure will rise in the cavity and therefore the clay will be pushed upwards (see figure 6.16, 6.17 and 6.18). At low traversing speeds this effect is less present than at larger speeds.

The rectangular shaped cavity for the 60° nozzle with a SOD of 10 mm, is most likely caused by tearing away of the triangular lid. This isn’t happening for the 60° nozzle with a SOD of 5 mm, because the nozzle head obstructs the clay from moving more than 5 mm upwards. Furthermore the height of the lid is larger with a SOD of 5 mm than with a SOD of 10 mm, enabling the clay to withstand more forces before tearing away. The difference in height at the location where the lid is attached to the rest of the clay is clearly larger when a lower SOD is used. This can be seen in a schematic overview for a 60° nozzle for two different Stand Off Distances (see figure 6.19). The lid created with the larger SOD will tear off more easily than the lid created with the lower SOD. The same effect can be seen for the 45° nozzles. The top-view of figure 6.15b shows tearing of large chunks of the cavity-lid. In figure 6.15a the lid is still present because the lid was obstructed from tearing away by the nozzle head during jetting.

**Figure 6.16:** Clay pushed upwards in front of nozzle head  
**Figure 6.17:** Clay pushed upwards in front of nozzle head  
**Figure 6.18:** View of a sample where clay has been pushed up

**Figure 6.19:** Schematic overview of height cavity lid for a 60° nozzle at different SOD

**Stagnation ratio dependency**  In the trenching test setup the influence of the stagnation ratio \( \frac{p_{stag}}{p_{su}} \) on the penetration depth is tested by varying the jet pressure. In the draghead test setup the stagnation ratio is changed by executing a few experiments with a clay block that had a larger undrained shear strength. These “stronger” clay blocks had an undrained shear strength of approximately 88 kPa, resulting in a stagnation ratio of 10.
Figure 6.20: Dependency of the stagnation ratio, changing the undrained shear strength

Figure 6.20 shows three tests with the 60° nozzle at a SOD of 5 mm that are repeated. The difference in stagnation ratio is a factor 2.5, which would result in a decrease in averaged excavated area of $2.5^2 = 6.25$. However, the decrease in averaged excavated area appeared to be approximately a factor 2.5. This discrepancy is probably caused by the effect of water on the undrained shear strength of the clay blocks. The used 88 kPa blocks appeared to be not that constant in holding shear strength when being submerged in water. The undrained shear strength is measured dry just before inserting the clay block in the test tank and just after an experiment. Before the test the undrained shear strength was 88 kPa and just after the experiment the undrained shear strength at the surfaces decreased to 50-60 kPa. These bricks of clay are normally used for producing roof tiles and are made artificially. The blocks are a mixture of clay, cement, small stones and paint. When submerged in water the outer surfaces of the block softens fast. The penetration of the jet is exerted at the softened surface. Besides, the experiments with this clay were conducted at relatively low horizontal traversing velocities and therefore a lot of water has flowed over the affected surfaces and caused even more decrease in undrained shear strength. It isn’t possible to find the exact undrained shear strength of the affected clay at the moment of penetration. Considering an undrained shear strength of 55 kPa would result in the expected linear behavior of the stagnation ratio (see figure 6.20). Because of the large deviation of the undrained shear strength before and after an experiment (50-88 kPa), the linear dependency of the stagnation ratio on the penetration depth cannot be granted based on these experiments.

This large differences between undrained shear strength’s weren’t present testing the main clay blocks that are made out of river clay. These river clay blocks had the same strength before and after the tests.

Excavated volume versus fluidized volume The procedure to measure the excavation volume results in a measured volume of soil that is pushed away from the original dimensions of the clay block. In figure 6.18 the clay above the original top surface of the clay block is pushed up but not excavated. The attached clay above the black line is measured as “excavated” in the excavated volume measurements. In contrast to this measured excavated volume the model predicts the “fluidized” excavated volume, because it doesn’t encounter clay that is being pushed up.

To get an idea of the difference between the measured excavated volume and the fluidized excavated volume some extra volume determination tests are performed where the pushed up clay is being pushed back to its original position. This is done by clamping a wooden shelf on the top surface and pushing the clay back till the top surface is pushed back to the original top plane. Again the volume is measured. Figure 6.22 shows
that the differences in volume could be up to 30%. In figure 6.22 it can be seen that the part of clay that is counted as “excavated” increases with horizontal traversing velocity till a certain point. After this point little clay is pushed up because there isn’t much penetration at this very high horizontal traversing velocity. With this graph some knowledge can be obtained about the difference between the excavated volume and the fluidized volume. However, the chunks of clay that are teared off are as well counted as “excavated” while they aren’t fluidized. These deviations have to be taken into account when comparing the model to the test results.

![Figure 6.21: Comparison between averaged excavated area before and after pressing back clay to its original surface](image1)

![Figure 6.22: Fraction of excavated area of pressed back clay measurements compared to measurements before pressing back the pushed up clay](image2)
6.2. TEST RESULTS

Possible extra production When rotating jets would be used on a draghead, they will positioned next to each other. Because of the triangular shaped cavities, extra production could be achieved by a certain distance between the nozzles. An example of the possible extra excavation is shown in figure 6.23. It can clearly be seen that there could be extra excavation in the middle of two nozzles. The amount of possible extra production differs. There is a large extra excavation for the setup shown in figure 6.23a. The whole triangle in the middle won’t be attached to the clay block and will be removed. On the other hand, in figure 6.23d there is no extra excavation production. It is important to keep the possible extra excavation production in mind when reviewing the results.

![Figure 6.23: Possible extra excavation when two fictitious nozzle’s would be placed next to each other for different nozzle angles and SOD](image)

The possible extra production should be compared to the fluidized production. For the 60° nozzle the fluidized production is estimated by pressing back the pushed up clay. The maximum possible production is the production that is achievable when placing multiple jets at a certain distance (center to center) from each other. This production with the “free” excavated part is estimated by determining the maximum cavity width and the cavity depth. A rectangular area is calculated using the maximum width and depth. The difference between the fluidized production and the maximum possible production for the 60° nozzle at a SOD of 5 mm is shown in figures 6.24 and 6.25. It can be seen that the maximum production including the “free” production is about 1.5 times the “fluidized” production. It is important to note that for the higher traversing velocities ($v_{tr,h} > 1200 m/h$) the maximum possible production can be overestimated, because the cavity dimensions are not constant, but influenced by the $\frac{v_{tr,h}}{R_{cyyc}}$-ratio. On the other hand, it is likely that existing thin layers between two fictitious nozzles that are placed next to each other will be removed because thin clay layers won’t withstand much forces and will probably easily tear away.

Comparison to conventional non-rotating jet

Another experimental data-set is performed with a single conventional nozzle. A nozzle of 7 mm was selected to obtain approximately the same cross-sectional flow area as the combined area of the two 5 mm nozzle’s used for the rotating jet experiments. The used conventional nozzle is a professionally built standard nozzle. Off course there is a difference in the discharge coefficients of the standard nozzle and the personally manufactured nozzle head, respectively 0.97 and 0.87. The difference in fictitious cross-sectional flow area between one 7 mm conventional nozzle and two 5 mm personally built nozzles is approximately 10%. The choice was made to conduct the conventional nozzle experiments with the same jet pressure as the rotating jet exper-
In figure 6.28 the excavation production of different rotating jets can be compared to a conventional nozzle. At different horizontal traversing velocities the excavation production is determined. Figure 6.28 shows the highest production for the experiments using a 60° nozzle at a Stand Off Distance of 5 mm. For that setup an increase in production up to a factor 3.5 can be found. Note that the production shown in figure 6.28 is taken from the volume of clay that is removed out of the original geometry of the clay block, i.e. the measured volume before pressing back of the pushed up clay. Considering a fraction of 0.3 of pushed up clay, the fluidized production increase of a single nozzle will be around a factor 2.5.

When the maximum possible production is estimated based on the maximum geometry of the cavity the increase in production can be even up to a factor 4 (see figure 6.29). The graphs for the maximum possible excavation production have to be used as an estimation, because they are based on the largest dimensions of a single cavity.
Figure 6.28: Excavation production for several nozzle setups

Figure 6.29: Maximum possible excavation production based on maximum geometry of cavity for several nozzle setups
6.3. **MODEL RESULTS**

The models for both applications of a rotating jet are based on the same principle of entrainment of water and soil (see chapter 3). The trenching model is compared to the experiments based on the minimum excavated diameter. The draghead model is compared to the experiments using the averaged cross-sectional area. This area is calculated by dividing the created cavity volume by the length of the cavity.

### TRENCHING

The minimum diameter (see figure 3.2) is calculated gonometrically based on the jet diameter, penetration depth and the vertical displacement after one rotation. The minimum diameter is also obtained during the executed measurements after a test. At several locations the minimum diameter is measured and averaged to obtain one averaged value for the minimum diameter. In figures 6.30, 6.31 and 6.32 the predicted values for the minimum cavity diameter from the model can be compared to the experimental results. It stands out that the model predicts the cavity diameter quite well for the 45° nozzle experiments. For the 60° nozzle the model overestimates the cavity diameter compared to the corresponding test results. An explanation could be that the nozzle head can easily be blocked, because the jet is exerting quite horizontal when the 60° nozzle-head is mounted. The area just beneath the nozzle outlets cannot be cleared that well with the 60° nozzle compared to the 45° nozzle and the clay bed can easily start to block the nozzle outlets. However, no pressure peaks are found in the corresponding test data obtained from the pressure sensor and flow sensor. This would suggest that another mechanism is responsible for the lower performance of the 60° nozzle. The model therefore overestimates the production of the 60° nozzle.

The minimum excavation production can be calculated by calculating the minimum cross-sectional area of the cavity and multiplying this area with the vertical traversing velocity. The results are shown in figures 6.33, 6.34 and 6.35.
6.3. Model Results

Figure 6.32: Comparison between test results and model for a 60° nozzle and a stagnation ratio of 18

Figure 6.33: Comparison between excavation production of test results and model for a 45° nozzle and a stagnation ratio of 25

Figure 6.34: Comparison between excavation production of test results and model for a 45° nozzle and a stagnation ratio of 18

Figure 6.35: Comparison between excavation production of test results and model for a 60° nozzle and a stagnation ratio of 18
The averaged cross-sectional area is used as the value for comparing the model to the experimental results. This is done because the shape of the cavity varies depending on the ratio between horizontal traversing velocity and rotational velocity. Measuring the volume of the cavity and dividing it by the length of the cavity gives an averaged cross-sectional area, which can be used to compare the experimental results to the model. The same procedure for calculating the averaged area is used in the model.

For every experiment conducted the model is run in order to compare the model to the actual test results. In figures 6.36 and 6.37 the results of the model with a 45° nozzle and the actual results are shown. It can be seen that the model expects the highest averaged excavated area's with a vertical SOD of 5 mm. The experimental results show a higher averaged excavated area with a SOD of 10 mm in contrast to the model. An explanation for this mismatch can be the fact that during the experiments with a SOD of 5 mm the nozzle head prevents the clay to break out. In other words, the clay is being pushed up towards the nozzle head. Because the nozzle head blocks the clay from moving further upwards, the clay isn't removed. With a SOD of 10 mm, the nozzle head doesn't prevent the clay from breaking of and as a result the amount of excavation will be larger. Another effect is that the amount of clay that is pushed above the original top plane of the clay block is limited to 5 mm with a SOD of 5 mm. As explained in section 6.2.2 the clay that is pushed above the original top surface of the clay block is measured as “excavated”. With a SOD of 10 mm more clay can be pushed up and a higher excavation volume is measured. In figure 6.37 the model is underestimating the average excavated area. It has to be noted that the results of the experimental measurements will be significantly lower when only fluidized volume would be considered. Again the clay that is pushed up is measured as excavated volume. This extra measured volume can be up to 30%. Besides, the chunks of clay that are teared off aren't predicted in the model. When these consideration are taken into account the model and actual experimental results will level to each other.
Figures 6.36 and 6.37 show the results from the model for the 45° nozzle. It can be seen that the predicted values from the model are underestimating the experimental values. Again these deviations will be smaller when the difference between excavated and fluidized volume is taken into account.

Figures 6.38 and 6.39 show the results from the model for the 60° nozzle. It can be seen that the predicted values from the model are underestimating the experimental values. Again these deviations will be smaller when the difference between excavated and fluidized volume is taken into account.

For the dataset shown in figure 6.38 the excavated volume is also measured after pressing back the pushed up clay. The results can be seen in figure 6.40. The model results are now closer to the actual test results, but
it can also be noted that the measured values are spread more. This can be explained because it is harder to measure the excavated volume after pressing back of the pushed up clay. After pressing back, cracks are created, causing chunks of clay that fall completely in the cavity which result in measurements errors. Furthermore during the actual tests cracks are created and larger chunks of clay are teared off.

The excavation production can be calculated by multiplying the minimum excavated area by the vertical traversing velocity.

Figures 6.41 to 6.44 show that the model gives a good estimation of the experimental results for horizontal traversing velocity lower than 1000 m/h. For traversing velocities > 1000 m/h the model underestimates the experimental results significantly. An explanation for the underestimation could be that the visualization model uses only one jet geometry over the whole rotation of the jet while in reality the penetration depth of the jet will be different at every location at one rotation. In figure 3.6 the differences in penetration depth at three different points on one rotation are shown. In the visualization model only one jet geometry (penetration depth and jet diameter) can be used for the whole rotation. Figure 3.6 shows that for horizontal traversing velocities larger than 1000 m/h the used value for the penetration depth is probably lower than the averaged penetration depth for one rotation. An underestimated value for the averaged penetration depth over the whole rotation leads to a large underestimation of the excavation production in the visualization model. When a better approximation of the averaged penetration depth would be used, the model will prob-
ably give also better results for traversing velocities higher than 1000 m/h. Besides, at high horizontal traversing velocities other failure mechanisms are occurring. Larger chunks of clay are breaking out at once. This isn't taken into account in the visualization model.
In this chapter the main conclusions of this study are presented. The main objective of this study was to find the amount of possible increase in excavation production of clay with the use of a rotating jet instead of a conventional stationary jet. This is studied for two applications:

- A horizontal jet, moving in horizontal direction (trenching machine)
- A vertical jet, moving in horizontal direction (draghead)

The conclusions are subdivided in three sections: conclusion for the trenching setup, the draghead setup and finally some general conclusions are presented.

### 7.1. CONCLUSIONS TRENCHING MACHINE APPLICATION

The excavation production of clay using a rotating jet can be increased a factor between 6 and 7 compared to the empirical modeled excavation production of a non-rotating vertical jet moving horizontally. These results are obtained using a 45° nozzle at a traversing velocity range of 15-215 m/h and and a stagnation ratio \( \frac{p_j}{su} \) of 25.

The decrease in specific energy is the highest at the largest traversing velocities. At a traversing velocity of 180 m/h the decrease in specific energy of a rotating jet compared to a non-rotating jet is found to be a factor 7.4.

No optimum ratio between the traversing velocity and the rotational velocity \( \frac{v_t}{\omega c y c} \) of the nozzle at a certain stagnation ratio is found.

The ratio between traversing velocity (15 - 125 m/h) and rotational velocity (200 - 600 rpm) was varied with a factor 3, but didn't result in a significant change in cavity diameter. However it is expected that at higher traversing velocities the \( \frac{v_t}{\omega c y c} \) ratio becomes more important.

The optimum distance between the nozzles (center to center) has to be equal to the expected cavity diameter.

Considering the experiment that achieved the highest production the optimum distance between the centers of two nozzle heads is approximately XX mm for the tested 45° nozzle at a traversing velocity of 215 m/h and a stagnation ratio of 25.
One nozzle head consists of two nozzle outlets with a fictitious nozzle diameter of $D_{n,f} = \sqrt{n} \cdot D_n = 4.7\, mm$. The corresponding fictitious diameter of a single nozzle outlet with equal cross-sectional flow area is $D_{n,f,\text{total}} = \sqrt{2 \cdot (\sqrt{n} \cdot D_n)^2} = 6.6\, mm$ leading to $D_c/D_{n,f,\text{total}} = XX/6.6 \approx XX$

The jetting pattern becomes rougher by an increasing ratio between traversing velocity and rotational velocity. From medium to large vertical traversing velocities (>35 m/h) the edges of the rough cavity wall are pointing upwards. At very low traversing velocities (<35 m/h) and a rotational velocity in the range of 300 to 500 rpm, the wall profile of the cavity is shaped as a continuous spiral. This spiral could possibly be created by surface erosion due to the weakening of the wall surface created by the centrifugal back flow of the waste water. Another mechanism that could occur is the effect that happens in the deflecting zone; every rotation the pressure underneath a lump is increased till a certain tress-hold value is reached, then the whole lump is removed after which a new number of revolutions is needed to remove new lump of soil. When this occurs at several locations on a revolution a continuous spiral could be created. However, no conclusions can be drawn for sure for the mechanism that is responsible for the continuous spiral shaped wall structure.

A cavitation cone is noted during the jetting experiments. The calculation module considers a cavitating jet. A cavitating jet entrains less water in the mixing zone than a non-cavitating jet. If less water is entrained, the gradient of the increase in jet mixture density is smaller resulting in a lower decrease in stagnation pressure and a larger penetration depth, i.e. a cavitating jet has a larger penetration depth than a non-cavitating jet.

The developed model consists of a calculation module and a visualization module, the calculation module is able to produce a good estimation of the excavation production that can be achieved for the 45° nozzle. For the 60° nozzle the module overestimates the production compared to the experimental results. The over-estimation could be caused by the fact that the 60° nozzle couldn’t remove the area beneath the nozzle head that easily because the jets are orientated quite horizontally.

The visualization module is able to visualize a cross-section of the modeled cavity. The jet is modeled as a cone with dimensions used from the calculation module, therefore the visualized wall profile won’t be equal to the actual wall profile of the experiments. The visualization module will model a smooth surface over the path where the cone came by, while in reality the path surface will be not that smooth. However the visualization provides a good view of the effect of the combination of vertical traversing velocity and rotational velocity. It also gives a feeling about the maximum traversing velocity at a certain rotational velocity.

7.2. Conclusions Draghead Application

The fluidized excavation production of a single rotating jet clay can be increased up to a factor 2.5 compared with a single conventional non-rotating jet. When the amount of clay is taken into account that is moved out of the original clay bed but still attached as a pushed up curl the production increase can be up to a factor 3.5. Considering the “free” extra production using multiple jet besides each other an increase in total excavation production can be even up to a factor 4.

These increase factors are achieved with a 60° nozzle, a SOD of 5 mm and a rotational velocity of 400 rpm. It is assumable that the production could be increased even more if a higher rotational velocity is used.

No optimum ratio between the traversing velocity and the rotational velocity of the nozzle at a certain stagnation ratio is found. However it is found that from horizontal traversing velocities from 350 m/h the
excavation production increases with increasing rotational velocity, i.e. the production increases with a decreasing \( \frac{v_{t,h}}{\omega_{cyc}} \)-ratio from traversing velocities higher than 350 m/h.

The optimal distance between the nozzles (center to center) has to be equal to the maximum cavity width produced by one nozzle head, depending on the traversing velocity. For the highest increase in production the optimal distance center to center is XX cm for a 60° nozzle, SOD of 5 mm, 400 rpm and a horizontal traversing velocity of 1250 m/h.

The jetting pattern becomes much rougher by a high increase in ratio between traversing velocity and rotational velocity If the \( \frac{v_{t,h}}{\omega_{cyc}} \)-ratio becomes larger than the jet diameter, the jet isn’t able to affect all clay available, resulting in a even rougher surface. The exerted rotations of the jet could clearly be seen in the wall profile of the produced cavities.

The highest excavation productions are achieved using a 60° nozzle at a Stand Off Distance of 5 mm. The combination between nozzle angle and SOD turned out to be important for the excavation production. The shape of the cavities produced are quite different for these different combinations as well.

A cavitation cone is noted during the jetting experiments. The calculation module considers a cavitating jet. A cavitating jet entrains less water in the mixing zone than a non-cavitating jet. If less water is entrained, the gradient of the increase in jet mixture density is smaller resulting in a lower decrease in stagnation pressure and a larger penetration depth, i.e. a cavitating jet has a larger penetration depth than a non-cavitating jet.

Large plastic deformation are noted at the top layer of the clay bed. It is assumable that the shear strength of the clay is decreased by a previous passing of the jet.

The developed model consisting of a calculation module and a visualization module is able to give results that are close to the corresponding test results for horizontal traversing velocities lower than 1000 m/h. In order to compare these result accurately it has to taken into account that the model predicts a volume that is mostly fluidized where the volume that is measured during the experiments includes a volume that is pushed out the original clay bed but still attached as a curl to the clay block. This extra measured excavation can be up to 30% of the total measured excavation. When this is taken into account the model predicts the excavation productions pretty well.

The visualization module is able to give a good idea about the path the jet is traveling at a certain \( \frac{v_{t,h}}{\omega_{cyc}} \)-ratio and the cavity that is produced. Because the jet is modeled as a cone the produced cavities are much smoother than the cavities produced during the experiments. The model doesn’t take into account the pressed-up clay and any preference planes that are present in real clay for example. However, the model can be used to get an idea about the general shape of a certain cavity, depending on parameters such as: traversing velocity, rotational velocity, nozzle angle etc.

For horizontal traversing velocities larger than 1000 m/h the underestimation of the excavation productions starts to increase. This occurs because only one jet geometry can be used over the whole rotation of the jet, while in reality different jet geometries are present. The used value for the jet geometry over one rotation for traversing velocities larger than 1000 m/h is most likely too low compared to the real averaged jet geometry over one rotation.
In reality the optimal center to center distance between nozzles will depend on the required excavation. If a nice flat trench surface is needed a lower traversing velocity is probably preferable with consequential optimal nozzle to nozzle distance. If just high clay reclamation is requested a higher traversing velocity and a smaller optimal distance is needed. Furthermore, if a deeper trench is required, the 45° nozzle at a SOD of 10 mm gives best results. Therefore the optimum setup parameters will strongly depend on the required dredge application. However this study can be used as a guideline for the design of a rotating jet for a certain excavation application.

7.3. **GENERAL CONCLUSION ROTATING JETS IN CLAY**

The use of a rotating jet on a jetting sword or draghead is very promising. This study shows a significant increase in excavation production of clay compared to the excavation production of a non-rotating jet in clay. The specific energy of jetting clay can therefore be significantly reduced as well. However, it has to be taken into account that the specific energy of rotational jetting of clay is still much higher than the specific energy of cutting clay. Whether a rotating jet is preferable over cutting clay depends on many parameters and should always be studied before making a decision.
8

RECOMMENDATIONS

The results from this study are very promising and further research in rotating jets is recommended. In this chapter some recommendations are presented. This is done for the trenching application as well for the draghead application.

8.1. RESEARCH RECOMMENDATIONS

Recommendations research

Further research should be done in the strain-rate dependency of the shear strength of cohesive soil during jetting processes. At high strain-rates the shear strength of clay tends to increase. Furthermore, the effect on the shear strength after multiple passes of the jet should be studied. The shear strength will decrease after plastic deformations caused by a previous jet pass. This will probably have a large effect at the draghead application, because the jetting take place at the top surface of the clay bed. At the top surface the clay can deform more easily than more inside. This research should include a study to the bearing capacity of clay when being jetted by a rotating nozzle.

Research in the responsible mechanism for the production of the continuous spiral shaped wall structure at very low traversing velocities would be very interesting also.

8.2. RECOMMENDATIONS TRENCHING APPLICATION

Recommendations trenching experimental setup

Some improvements on the experimental setup could be performed. Also some extra experiments will be very interesting to execute. Some recommendations considering the experimental setup are listed beneath:

- Use of a stepper motor to provide the revolutions instead of an air drill to ensure a constant rotation velocity. The influence of the ratio between traversing velocity and rotational velocity can be studied more accurately. Besides, the repeatability of the experiments would be improved as well.

- Execute more experiments over another range of $p_j/su$ to get more knowledge about the scaling to stronger clay’s.

- Perform experiments with another nozzle design, for example another number of nozzle outlets on one nozzle head. Also two nozzle angles on one nozzle head could be interesting to study. One jet can be
placed more vertically to ensure better clearance of the area in front of the nozzle, the other jet could be placed more horizontally to get a wider cavity.

- An experimental setup with at least three nozzle heads placed next to each other will be interesting to study. The optimal distance between the nozzle heads (center to center) can then be studied better.

- In addition to the standard cavity diameter measurements, an averaged diameter could be obtained by measuring the volume of water of the jetted cavity and divide that volume by the length of the sample.

- To investigate the effect of cavitation some experiments should be performed at larger water depth or in a pressure vessel to be able to perform tests without cavitation.

**Recommendations model** The developed model is based on the entrainment of soil and water and is founded on the 1D-approach of Nobel (2013). The model is a simplification of the reality. The jetting process consists of many sub-processes that are not taken into account in this study. Many assumptions are made. Further research in the different failure mechanisms of jetting in clay would be necessary to get more knowledge about the sub-processes. It would be interesting to use a more advanced calculation module for the jet penetration (Nobel, 2013) as a basis for the rotating jet calculation module. The visualization module could become more accurate when using a more accurate calculation module. To improve the modeled cavity wall profile the jet shouldn’t probably be modeled as a cone. However, for the application this module is used for, a very accurate wall profile is not that important so improving the calculation module for more accurate cavity dimensions will have priority.

**Recommendations design** In order to use a rotating jet actually on a trenching machine, the whole design has to be changed. No rotating parts will be wanted on such a tool. The rotary movement should be driven hydraulically instead of mechanically. However, this study could provide some required information for certain design parameters.

### 8.3. **Recommendations Draghead Application**

**Recommendations draghead experimental setup** For this setup some additional experiments can be interesting to execute. Some ideas for extra experimental research is noted beneath:

- Execute more experiments with different $p_j/su$-ratio’s.

- Execute experiments with another nozzle design. It could be interesting to design a nozzle with two outlets not close to each other in the center but located more at the outer ring of the nozzle head. At higher traversing velocities the ratio between traversing velocity and rotational velocity becomes more important. Better results are expected with a lower ratio. To lower the ratio, either the rotational velocity should be increase or extra nozzle outlets have to be placed.

- An experimental setup with at least three nozzle heads placed next to each other will be interesting to study. The amount of “free” production as well of the optimal distance between the two nozzle head can than be studied better.

- The effect of cavitation should be studied by performing some test without cavitation. This can be realized by increasing the water depth or executing the tests in a pressurized vessel.
8.3. **Recommendations draghead application**

**Recommendations model**  Because the calculation module of the draghead setup is almost identical to the calculation module of the trenching setup the same recommendations are valid. In addition to these recommendations extra research is needed to the jetting processes at these large traversing velocities. The visualization module can be improved by implementing a position depended jet geometry. Because the combined velocity \( v_{\text{drag}, k} \) varies during one rotation, the corresponding penetration depth varies as well. The calculation module calculates the minimum, median and maximum combined velocity. However for the visualization module and finally the determination of the excavated volume the median combined velocity with corresponding jet geometry is used as a constant value over the whole rotation in the visualization module. It would be more accurate if the jet geometry could also be varied in the visualization module. It would especially increase the accuracy for the horizontal traversing velocities larger than 1000 m/h. Furthermore it would be nice to implement a module that models the plastic deformations of the soil, in order to model the pushed up clay. Unfortunately this will require a far more advanced calculation module and a new visualization module.

**Recommendations design**  As already mentioned at section 8.2 research should be done in the way how a rotating jet could be implemented on an actual draghead, preferably without moving parts.


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Appendices
A.1. Test matrices

A.1.1. Test matrix trenching setup

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A.1.2. Test matrix draghead setup

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A.2. Test procedures

A.2.1. Trenching setup

This test has to be executed by two persons. One person operates the air drill and the second person operates the pump and spindle.

1. Preparations
   
   (a) fill main test tank with water near overflow level
   
   (b) fill water supply tank with fresh water
   
   (c) empty waste water tank
   
   (d) insert clay block in support frame in the main test tank
   
   (e) connect water hose from pump to swivel
   
   (f) power on all devices
   
   (g) ensure that nozzle is located at starting point
   
   (h) setting up the correct settings for pump pressure, vertical velocity and rotational velocity of the concerned test
2. Test
   (a) start data-logging program
   (b) start air drill
   (c) start pump
   (d) check actual data from sensor
   (e) wait till sensors are giving constant signals
   (f) start traversing vertically till it automatically stops
   (g) switch off pump, air drill
   (h) stop data-logging
   (i) move nozzle up to starting point
   (j) power off all devices
   (k) collect clay block out

3. Collect results
   (a) make photographs of sample
   (b) cut clay block in half
   (c) make photographs of cross section
   (d) measure minimum cavity diameter at three location using a ruler
   (e) measure undrained shear strength at three locations on the cross section
   (f) save all collected data and photo's

A.2.2. Draghead setup

1. Preparations
   (a) switch off power spindle
   (b) crane off upper section (lid)
   (c) empty main test tank (lower section) and waste water tanks
   (d) clean main test tank
   (e) fill water supply tank with fresh water
   (f) insert clay blocks in support frame in the main test tank
   (g) slice clay blocks at correct height
   (h) measure undrained shear strength at three locations
   (i) crane back upper section on main test tank
   (j) power on all devices
   (k) check Stand Of Distance
A.2. **TEST PROCEDURES**

1. **Test Procedures**
   - (l) ensure that nozzle is located at starting point (left)
   - (m) connect pump-hose to swivel
   - (n) fill test tank till overflow level
   - (o) setting up the correct settings for pump pressure, horizontal velocity and rotational velocity of the concerned test

2. **Test**
   - (a) start data-logging program
   - (b) start recording submerged Go-Pro camera
   - (c) start pump
   - (d) start stepper motor for the rotational velocity
   - (e) measure rotating speed with hand laser tachometer
   - (f) check actual data from sensor
   - (g) wait till sensors are giving constant signals
   - (h) start traversing horizontally till midpoint of rails (middle between the two blocks)
   - (i) switch off pump, stepper motor
   - (j) stop data-logging
   - (k) setting up new setting for the second test
   - (l) start data-logging program
   - (m) start recording submerged Go-Pro camera
   - (n) start pump
   - (o) start stepper motor for the rotational velocity
   - (p) check actual data from sensor
   - (q) wait till sensors are giving constant signals
   - (r) start traversing horizontally till end point of rails
   - (s) switch off pump, stepper motor
   - (t) stop data-logging
   - (u) stop recording submerged camera
   - (v) move jetting system to the middle point
   - (w) power off all devices
   - (x) crane off upper section
   - (y) empty main test tank
   - (z) collect clay block out

3. **Collect results**
(a) make photographs of sample
(b) cut entry and end part of the block
(c) make photographs of cross section
(d) measure dimensions
(e) measure excavated volume
(f) save all collected data and photo's
A.3. CLAY CHARACTERISTICS

Figure A.1: Laboratory results clay
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<th>Grain Size Distribution</th>
<th>Clay P.</th>
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*Note: The table above shows the grain size distribution for clay particles.*
Figure A.3: Grain size distribution clay p.2
B.1. **TEST REPORTS TRENCHING SETUP**  
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B.2. **TEST REPORTS DRAGHEAD SETUP**  
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C.1. **Render of Trenching Assembly**

Figure C.1: Solidworks 3D render of total trenching setup
C.2. DRAWINGS

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