Adhesion factor and reduction methods for subsea cable ploughing in clay

An experimental study

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Challenge the future

Adhesion factor and reduction methods for subsea cable ploughing in clay

An experimental study

by

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Abstract

Context

The shift to green energy offers a need for offshore wind farms. The transition from a relatively cheap energy production from carbohydrates, to a young offshore wind energy industry needs innovations to lower the cost. Increasing the efficiency of wind turbines and lowering the installation cost of a wind farm, will eventually make wind energy cheaper then energy produced by coal. A part of the installation process is the burial of the submerged power cables. The fragile power cables have to be buried a couple meters below the seabed, to be protected from anchors, fallen objects, and fishing activity.

Problem definition

To submerge the power cable into the seabed, a trench have to be made. The soil of the seabed can consist of sand, silt, clay, rock or any combination of them. This research focuses on the trenching though clay. Clay has a very low permeability compared to sand, and clay has cohesive strength. For trenching in clay, a narrow plough is mostly used. These ploughs have a small frontal area and are build to cope with the high ploughing forces. A prediction of ploughing forces and velocities are made by models in preparation of cable burial projects. With accurate predictions, the best equipment can be chosen and a planning of the trenching operation can be made. The prediction models take into account the geometry of the plough and the soil characteristics. A reduction in pulling force results in an increase in ploughing velocity and therefore lowering the time and cost of cable installation.

Approach

A large part of the pulling force in clay is caused by the adhesive force on the sides of the plough sliding through the clay. The adhesive force is therefore the main focus of this research. There are two main goals: the first goal is to investigate the adhesion force in relation to the strength of the clay; the second goal is to investigate ways to reduce the force caused by the adhesion.

The adhesion factor is a parameter that is included in the prediction models. In literature of construction and agricultural engineering, predictions of adhesion factors and ways to reduce the adhesive force can be found. However, the circumstances during subsea ploughing are vastly different then in the other fields of engineering. Therefore, the approach of this study is to use small scale ploughing experiments with different strengths of clay to investigate the two goals under subsea ploughing conditions.

For the experiments, a test setup is used. In this setup, a block of clay of a meter long can be hold into place in a water tank and be submerged. On top of the water tank, an electric motor can pull a cart over rails. A small scale plough can be bolted underneath the cart. During an experiment, the plough is pulled through the clay and the velocity and pulling forces are measured with sensors.

Results and conclusions

The adhesion factors of three types of clay are found. The softest clay with a undrained shear strength of 25 kPa has a adhesion factor of 0.43. Literature shows that the adhesion force is about 1.0 at 25 kPa. This low adhesion factor could be the result of the frontal cutting that disrupt the clay. The residual shear strength is lower then the undisturbed clay. For the medium (80 kPa) and hard (131 kPa) clay the adhesion factor is respectively 0.68 and 0.53. These values are on the higher side of what literature reports. This could have to do with the relative high velocity during ploughing. The downward trend of adhesion factor with increasing clay strength does correspond to literature.

To research the possibility of reducing the adhesion force, three small scale ploughs with modified adhesion surfaces are tested. The Alpha plough, which uses vertical gaps, reduced the adhesion force by 52 percent in both soft and hard clay. The Bravo plough, which uses convex shapes, reduced the adhesion force 39, 72 and 54 percent in respectively soft, medium and hard clay. The Charlie plough, which uses water nozzles at the adhesion surface, reduced the adhesion force by 70 percent in soft clay and 63 percent in hard clay.

This experimental study obtained valuable knowledge of the adhesion factor and possibilities to reduce the adhesion force.

Contents

1
Introduction

1.1. Introduction to offshore electric cable burial

Mankind is relying on carbohydrates as main source for there energy consumption for decades. Scientists concluded that burning carbohydrates for example gasoline, natural gas and coal, have an impact on the climate. Countries across the world have made agreements to increase the percentage of green energy and thereby reducing the emissions of using carbohydrates. Green energy is produced using inexhaustible sources nature is providing which do not pollute the environment. Think of solar energy collected by solar panels, hydroelectricity produced by turbines at dams or tidal turbines and wind energy collect by wind turbines. Wind turbine, are a great way of producing energy in areas where the weather is rough and the wind energy potential is thus high. These are mostly areas close to shore where the wind is not jet reduced by the land.

The majority of the worlds population is living close to shore. This has the advantage that the wind energy can be produced close to the user. However, in these densely populated areas there is a limited space for building large quantities of wind turbines. For this reason more wind farms are build offshore where the wind energy potential is higher and large areas are made available for construction. The challenges to go offshore are the installation of turbines, the foundations and the transportation of electricity to shore.

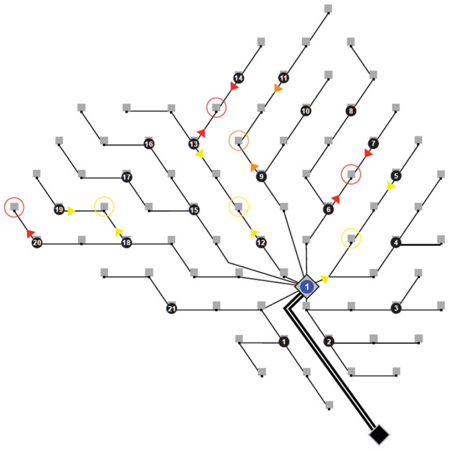
The energy collected is transported to shore by submerged electric power cables. These cables contain copper or aluminium cores to conduct the electricity and also contains data wires to monitor and control the wind farm. The fragile cable is buried up to several meters below the seabed to protect it from anchors, falling objects and fishing activities. A trench is made for the cable by ploughing, cutting or jetting depending on the soil type. The diameter of an electric cable is relative small in comparison to an offshore pipeline, therefore the common practise is to make a narrow shaped trench. These narrow trenches will collapse and therefore be back filled automatic over time and no need to close the trench after installing the cable. The burial process ensures that the cable is protected for it lifespan of 20 years or more.

1.1.1. Power cables infrastructure at offshore wind farms

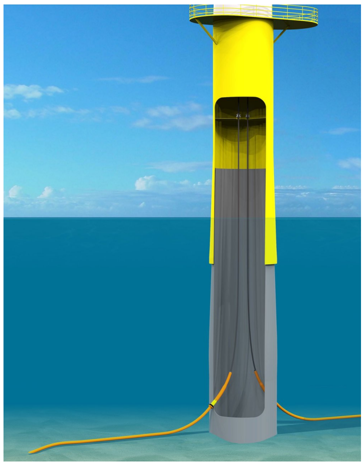
In offshore areas where wind farms are allowed to be built, energy companies try to maximise the output of energy. Besides an optimum of wind turbines placement in the designated area, the layout of the electric infrastructure has an influence of the efficiency and cost of an offshore wind farm. For most wind farms the turbines are placed in some sort of matrix formation (see fig. 1.1a). Rows of turbines are interconnected by submerged cables. A cable enters the wind turbine at the bottom of the foundation by a J-tube (see fig. 1.1b). The power of each array of turbines is collected at the substation near the centre of the wind farm. From the substation a export cable is installed to connect the wind farm to the power grid ashore. The export cable has a larger diameter relative to the interconnection cables.

1.1.2. Cable burial depth determination

When a subsea electric cable is damaged by an anchor or dropped object, the cost of the repair is just a fraction of the downtime cost of the offshore wind park. For this and other reasons cables are being



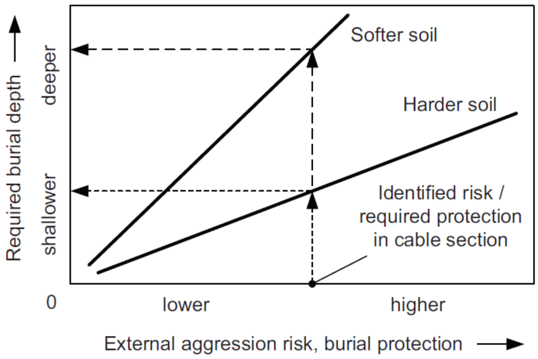
(a) Grid of an offshore wind farm



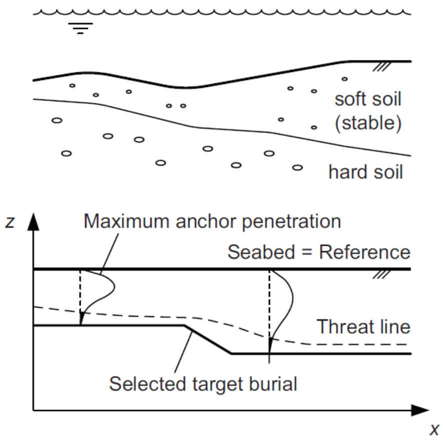
(b) Cross section of wind turbine foundation

Figure 1.1: Layout of offshore electric power cables

buried for protection. Det Norske Veritas (DNV) [1] have made a recommended practise for the burial depth of cables. The depth is mainly determined by the type of soil and the area in which the cable is laid, for instance shipping lanes and fishing areas. DNV has included the Burial Protection Index (BPI) method of Allen (1998) [2] (see fig. 1.2a). The required burial depth will increase with softer soil and when the external risk of damage increases. For each part of the cable route the threat line is determined under which the target burial depth is selected (see fig. 1.2b). The threat line is the depth of penetration of a hazardous activity into the seabed.



(a) Burial protection index



(b) Threat line

Figure 1.2: Det Norske Veritas principles of risk based burial assesment.

1.1.3. Cable burial methods in different soil types

The offshore wind farms may encounter many types of seabed conditions. Therefore the power cables have to be buried in different soil types. These types can be roughly categorised in sand, rock and clay. In practise a combination of these types can be found. Because each soil type has distinctive aspects the optimal method of burying a cable are diverse.

Sand

The distinctive properties of sand are that it contains particles with pores in between and the particles do not cohere with each other. When an object is forced through sand the particles move out of there

settled formation. This will enlarge the pore volume. When sand in submerged these pores contain water. The increase in pore volume have to be filled with water from the surrounding area. A large force is needed to accommodate the displacement of water through the sand.
To reduce the forces of this process water jets in front of the plough are used. There will be an overpressure created instead of an under pressure. Because the sand particles, made out of quartz, do not cohere the soil near the jets is fluidised. The fluidization prevents the force by a great deal and is the preferred trenching method in sand.

Rock

The main property of rock when looking for a burial method is that is has a high compressive strength. A great deal of cutting energy has to be put into a rock seabed to make a trench. A chain cutter with the width of the power cable is used to chip off pieces of rock. Rock has a Unconfined Compression Strength (UCS) of around 10 to 100 Mpa. A rule of thumb to calculate the specific energy in J/kg needed to cut through rock is to multiple the UCS by a value between 0.25 to 0.50.

Clay

In comparison to sand, clay consist out of minerals that in contradiction to sand cohere to each other. Another property is that clay has a low permeability of water. Fluidization of clay is less effective then with cohesionless sand. Clay has a large range of composition of particles. The strength of clay can differ highly, from soft clay that can be washed away by jets to firm clay that can be challenging for chain cutters. For the clay types in between there has been found a practical solution. Most clay types will behave plastic when a stump object is forced though it. When the force exerted on the clay exceeds the bearing capacity, the clay will be pushed aside. The shape of the object will have influence on the forces. The plough itself has to transfer the pulling forces into the deformation of the clay. For most clay trenching operations a rigid plough with optimised cutting shape is a practical option for cable burial.

1.2. VBMS

Volkerwessels Boskalis Marine Solutions (VBMS) started in the late 2000's with an idea of Visser & Smit Hannab. Visser & Smit Hannab is part of the Volkerwessels networks and is specialised in the installation of pipelines and cables on land. The idea for an offshore cable installation company came with the growth in sustainable offshore energy. Visser & Smit Marine Solutions (VSMC) started in 2007 as a subsidiary of Volkerwessels. Boskalis joined forces with VSMC in 2013 by acquiring 50 % of the stakes. Boskalis is a large dredging and offshore installation company. With the expertise of both companies VSMC could fulfill large contracts for installing infield and export cables of offshore wind farms. In 2014 the name was changed to VBMS. In the summer of 2016 Boskalis took over the remaing 50% of the shares of Volkervessel, making VBMS a full Boskalis company. While writing this report, VBMS has been integrated into the Boskalis company.

1.3. Cable burial ploughs of VBMS

VBMS has multiple tools to bury power cables for specific operations. VBMS has two narrow ploughs for cable burial. The sea Stallion 4 and Heavy Duty 3 ploughs are able to plough in sand and clay.

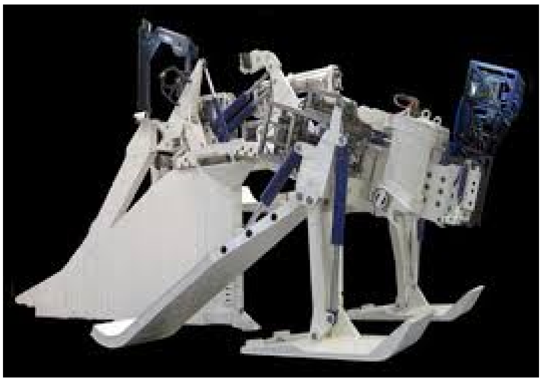
Sea Stallion 4

The Sea Stallion 4 (SS4) is a narrow plough designed to withstand rough soil conditions (see fig. 1.3a). The SS4 can withstand 120 ton constant pulling force, with peak loads of 150 ton. The teeth at the front of the plough are designed to dig into the soil to a depth of 3 meter. An export cable with a maximum diameter of 280mm and a minimum bending radius of 3.6 meter can pass through the plough.

Heavy Duty 3

As the name suggest the Heavy Duty 3 plough (HD3) is build for hard soil conditions (see fig. 1.3b). The plough chassis is build to withstand a constant pulling force of 150 ton. The HD3 can bury cables up to a diameter of 300mm with a minimum bending radius of 5 meter. The depressor ensures that the cable is installed at the desired depth of maximum 3.3 meter. At the cutting knife of the plough jets are installed. In contradiction with the SS4 plough the HD3 plough has only 1 tooth at the lowest part of the cutting blade to dig itself into the ground.

(a) Sea Stallion 4



(b) Heavy Duty 3

Figure 1.3: Pulled trenchers

1.4. Problem definition

To connect offshore wind turbines to the onshore power grid, power cables between the turbines and to the onshore grid have to be installed. These cables are very vulnerable to damage by anchors, dropped objects and fishing activity. Therefore these cables are buried underneath the seabed. To bury a cable, a option is to use a narrow shaped plough to make a trench. When pulling a plough trough clay large forces occur. When the pulling forces exceeds the operational limits in clay, the target depth cannot be guaranteed. The target depth is the depth at which the cable has a small risk of being damaged. The target depth is determined based on the soil type.

In previous research of Van Gurp(2014) [3] it was concluded that the ploughing forces in clay consist of a frontal force and an adhesive shearing force. The adhesive force was the larger part during the experiments of scale models of the SS4 and HD3 for one type of clay. The adhesive force of clay depends on the strength of clay. There is still little known about the adhesion of clay during trenching on the seabed. Predicting the adhesive shearing force between clay and the plough is vital to predict the total pulling force and the achievable burial depth.

In order to lower the risk of not reaching the target depth two solutions will be looked at in this research. The first is to increase the prediction accuracy of the adhesive shear force during trenching in clay. The second is to find solutions to decrease the adhesive shear force.

1.5. Objectives of this research

Ploughing through clay has numerous challenges. To improve the plough force prediction capability and lower the risks, this research will investigate a couple of these challenges. The challenges that this research wants to tackle are formulated in two separated main objectives. This division will be found throughout this thesis. For each of the two main objectives, sub objectives has been made to support the main objective.

1.5.1. Main objectives

The first objective of this research is to find the possible relationship of the undrained shear strength on the adhesive force during subsea trenching.

The second objective is to investigate practical designs to reduce the adhesion force along the sides of the plough.

1.5.2. Sub objectives

The sub objectives can also be divided into the two topics. The first topic is focused on the aspects of clay strength on the predicting of the plough pulling force. The second topic is focused on how the adhesion force of the plough can be reduced.

Adhesive force prediction

- Find clay with different undrained shear strength to conduct experiments.
- Build an experimental setup to simulate the subsea ploughing process on scale.
- Find the dependency of the clay undrained shear strength on the adhesion factor of a plough.

Adhesion reduction

- Will there be an effect on the adhesion force due to the ridges along the side of the plough? As found on the HD3 plough.
- Will there be an effect on the adhesion force if the adhesion surface is made non-smooth?
- Will there be an effect on the adhesion force if the adhesion force is lubricated with water?
- Determine which of the adhesion reduction designs has the highest reduction of adhesion force and is practical to apply.

1.6. Research approach

Small scale experimental research was chosen to achieve the objectives. The small scale has the advantage to do many test at low cost. The choice of experimental research instead of an Finite Element Method (FEM) or Discrete Element Method (DEM) had two arguments. First the FEM and DEM are not jet fully developed for soil-tool interaction and secondly, the soil parameters for example strain rate and adhesion factor have to be given as input. The soil parameters are not clear enough for subsea ploughing. Therefore the small scale experiments provide a way to carry out multiple tests with low cost and close to real subsea trenching operation conditions.
To determine how the experiments have to be executed literature has been studied. The cutting and adhesion characteristics of clay are being discussed. Models for ploughing on land and seabed are looked at. Also research for adhesion reduction for other industries is studied to find ways to incorporate there findings in this research.
While the literature study is performed, the test setup is made. There was a setup available which has been used for previous research, but it must be adjusted to the specifications for this research. Especially the construction has to be reinforced to withstand the higher expected forces for the hard clay.
At the same time, suitable types of clay have to be found. For comparing the results of the different tests, clay blocks with consistent properties have to be arranged. Clay types with different shear strength for the comparison of cutting force and adhesion factor are needed.
When a test plan can be made on the basis of the literature study, small scale plough have to be designed and made. While the setup is being designed and the types of clay are arranged, the shape and sizes of the scale ploughs are established.
The tests can be carried out after the test setup is prepared and the plan is made. The results of the test will be analysed and a report will be written. The clay characteristics found in this research, together with recommended prediction parameters and adhesion reduction methods will be presented in the conclusions of the report.

1.7. Boundary conditions and limitations for the experiments

Limited time and money is available for this research. The variables of soil and plough configurations are endless. Therefore choices have to be made to answer the objectives as best as with limited amount of experiments. Boundary conditions and limitations have been made with knowledge of ploughing

operations by VBMS and for the adhesion reduction methods looking at practical application of the designs.
The experiments will only be executed at small scale in clay. For both objectives only narrow ploughs are taken into account to simulate the power cable burial method.

Adhesive force prediction

- Three different types of clay are used during this research. To investigate the differences in adhesion.
- Depth and width of the scale models are constant during all tests, they will be respectively 94mm and 10mm. This is a 1/35 scale of the ploughing dimensions of the SS4 and DH3 ploughs.
- A velocity of about 100 m/h is chosen for all tests.

Adhesion reduction

- The solutions of the adhesion reduction have to be practical for subsea ploughing. This means no moving parts, no electrical components and no pollution from lubricants for example.
- S355 steel is used to make the ploughs. This steel type is used for the SS4 and DH3 plough. Different materials and coatings have already been tested by Tong et al [4].
- The amount of scale ploughs to test adhesion reduction is limited to three.

1.8. Layout of this report

This report consist out of seven chapters. In the first chapter an introduction to offshore cable burial and the research is given. The research introduction includes the problem definition, objectives, approach and boundary conditions for this study.

In the second chapter soil and clay properties are explained. First general soil properties and thereafter specific clay properties, as this study is specifically interested in ploughing in clay. To finish the chapter a summation of the important information is stated in the conclusion of the soil and clay properties.

The third chapter includes the literature study. The literature is split into multiple parts. In the first part the adhesion factor of clay is discussed, in the second part the frontal ploughing force and in the third part the velocity influence. These three parameters of the ploughing force are needed to estimate the pulling force needed to trench. In the fourth part the different models to predict the pulling force are discussed. The last subject of the literature study is ways to reduce the adhesion force.

In chapter four the experimental materials and methods are explained. This includes the setup, types of clay and the small scale ploughs used. Also the measurement equipment and test procedures as discussed. Thereafter, the order in which the experiments are explained follows the order of the literature study. First the adhesion and frontal forces, secondly velocity influence, thereafter verification of the plough pulling force model, and finish with the adhesion reduction experiments

The results of the experiments are shown in chapter five. In chapter six the conclusions are stated. A separation between estimating pulling forces and reducing pulling forces is made. In the final chapter recommendation are made for future experiments, estimating pulling forces, and reducing the adhesion forces.

2
Soil and clay properties

2.1. General soil properties and soil mechanics

The soil characteristics have a large influence on the ploughing process and forces. The soil properties and soil mechanics that are essential for the ploughing process are explained in this chapter. In the final paragraph the important conclusions are summed up.

2.1.1. Particle size classification

The properties of the soil depend highly on the size of the particles. To obtain the particle sizes of a soil sample, the soil is sieved. The classification system used in this study is the British Soil Classification System (BSCS) (see table 2.1) [5].

Table 2.1: BSCS grain size classification

Soil	Grain size	Plasticity	Material
Boulder	>200 mm	Non plastic	Quartz
Cobbles	60 - 200 mm	Non plastic	Quartz
Gravel	2 - 60 mm	Non plastic	Quartz
Sand	0.06 - 2 mm	Non plastic	Quartz
Silt	0.002 - 0.06 mm	Slightly plastic	Quartz
Clay	<0.002 mm	Plastic 9	Minerals
Peat	Varies	Varies	Organic

2.1.2. Porosity

The porosity of the soil is the percentage of volume between the soil particles. The volume of the pores is divided by the volume of the total sample volume. The volume of these pores is filled with liquids, gasses or a combinations of both.

$$n = \frac{V_p}{V_t} \tag{2.1}$$

n	Porosity	[-]
V_p	Volume of pores	$[m^3]$
V_t	Volume of the soil	$[m^3]$

2.1.3. Void ratio

The void ratio is the ratio of the volume of voids over the volume of the solids. The void ratio is dependent of the porosity and vice versa.

$$e = \frac{V_p}{V_s} = \frac{n}{1-n} \tag{2.2}$$

e	Void ratio	[-]
V_s	Volume of soilds	$[m^3]$

2.1.4. Density

The density of the dry solids is determined by dividing the mass by the volume of the soil. The volume includes the pore volume and the volume of the solids.

$$\rho_t = \frac{M_t}{V_t} \tag{2.3}$$

ρ_t	Density of the soil	$[kg/m^3]$
M_t	Mass of the soil	$[kg]$
V_t	Volume of the soil	$[m^3]$

For fully saturated solids the density of the whole volume is an addition of the density of the solids and of the water in the pores.

$$\rho_{in-situ} = \rho_w \cdot n + \rho_s \cdot (1 - n) \tag{2.4}$$

$\rho_{in-situ}$	Density of fully saturated soil	$[kg/m^3]$
ρ_w	Density of water	$[kg/m^3]$
ρ_s	Density of solids	$[kg/m^3]$

2.1.5. Unit weight

The unit weight is the force that gravity exerts per cubic meter of soil. The force differs when the soil is dry or saturated. For dry unit weight the force per cubic meter is only the mass of the solids times the gravitational constant.

$$\gamma_{dry} = \frac{M_t \cdot g}{V_t} = \rho_t \cdot g \tag{2.5}$$

γ_{dry}	Unit weight of dry soil	$[N/m^3]$

For the unit weight of fully saturated soil the weight of the water is also taken into account.

$$\gamma_{in-situ} = n \cdot \rho_w \cdot g + (1 - n) \cdot \rho_s \cdot g = \rho_{in-situ} \cdot g \tag{2.6}$$

$\gamma_{in-situ}$	Unit weight of saturated soil	$[N/m^3]$

During cable burial on the seabed the soil is fully saturated and submerged. The submerged unit weight is the saturated unit weight of soil minus the unit weight of water. The unit weight for submerged soil is lower then of equal soil in dry situation on land. Lifting soil under water will therefor cost less force then in air.

$$\gamma\prime = \gamma_{in-situ} - \gamma_w \tag{2.7}$$

$\gamma\prime$	Unit weight of submerged soil	$[N/m^3]$

2.1.6. Moisture content

The moisture content is the percentage of the mass of water over the mass of the solids (see eq. 2.8).

$$w = \frac{M_w}{M_s} \cdot 100\% \tag{2.8}$$

w	Moisture content	[%]
M_w	Mass of water	$[Kg]$
M_s	Mass of solids	$[Kg]$

2.1.7. Permeability

Soil permeability, the ability of fluid to flow though soil, is dependent of the type of the soil and the particle diameter. With Darcy's law (see eq 2.9) the discharge can be described. The velocity at which a fluid can flow though soil is dependent of the permeability of the soil. During ploughing operations, permeability velocity of sand is in the range of cm/s, with clay this will be in the range of mm/h. At the ploughing velocity of about 100 m/h the fluid in the clay pores will not be able to redistribute to low pressure areas during the ploughing process. This makes the ploughing process in most clays an undrained process.

$$Q = -\frac{\kappa A(p_b - p_a)}{\mu L} \tag{2.9}$$

Q	Total discharge	$[m^3/s]$
κ	Permeability of soil	$[m^2]$
$p_b - p_a$	Pressure drop	$[Pa]$
L	Length or depth of the soil	$[m]$

2.1.8. Mohr circle

The Mohr circle is a tool to transform 2 dimensional stress tensors within an infinitesimal small point in the soil. The objective is to calculate the normal stress and shear stress with there angle relative to the coordinate system. The forces on each point in the soil can written as 2 perpendicular forces, σ_1 acting on surface A-C and σ_2 acing on surface A-B (see fig. 2.1). If the angle α is changed, the normal force σ_N acting on surface B-C and the shear force τ changes.

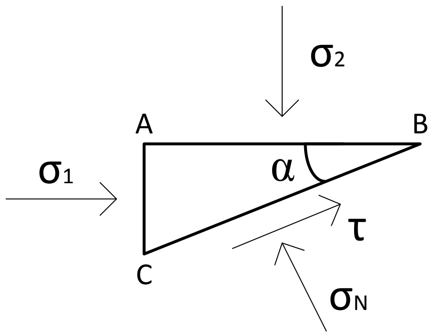


Figure 2.1: Stresses in 2D soil element

To formulate a force equilibrium the stress tensors have to be multiplied by the surface, or length in 2-D. Consider that the length of B-C has a length unit of 1. The tensor σ_2 have to be multiplied by $cos(\alpha)$ which is the length of A-B. The normal and shear stress has to be separated into horizontal and vertical stresses. In equation 2.10 the equilibrium of forces in vertical direction is shown, where both the normal and the shear force counteract the force created by the σ_2 tensor. In equation 2.11 the the equilibrium of forces in horizontal direction is shown.

$$\sigma_2 \cdot cos(\alpha) = \sigma_N \cdot cos(\alpha) + \tau \cdot sin(\alpha) \tag{2.10}$$

$$\sigma_1 \cdot sin(\alpha) = \sigma_N \cdot sin(\alpha) - \tau \cdot cos(\alpha) \tag{2.11}$$

Combining both equations results in a separate formula for the normal and shear force at an specific angle.

$$\sigma_N = \left(\frac{\sigma_2 + \sigma_1}{2}\right) + \left(\frac{\sigma_2 - \sigma_1}{2}\right) \cdot cos(2\alpha) \tag{2.12}$$

$$\tau = \left(\frac{\sigma_2 - \sigma_1}{2}\right) \cdot sin(2\alpha) \tag{2.13}$$

The relation of the normal and shear force of each angle of α can be made visible by combining both equation into a circle equation by summing up the square of both equations (see eq. 2.14). The highest value of τ is calculated when the first part of the equation the zero. The maximum and minimum of the normal force can not exceed the maximum and minimum values of σ_1 and σ_2.

$$\left(\sigma_N - \left(\frac{\sigma_2 + \sigma_1}{2}\right)\right)^2 + \tau^2 = \left(\frac{\sigma_2 - \sigma_1}{2}\right)^2 \quad (2.14)$$

2.1.9. Mohr-Coulomb failure criterion

Soil can handle a limited amount of stress before failure. The amount of stress depends on the normal forces applied to the soil and the characteristics of the soil. When a soil sample is loaded to failure at different normal stresses, multiple Mohr circles can be drawn (see fig. 2.2). As result the equation of the failure line can be made for a specific soil sample (see eq. 2.15). The soil will fail when the Mohr circle will exceed the failure line. From the failure line the internal friction angle and the cohesion of the soil can be determined.

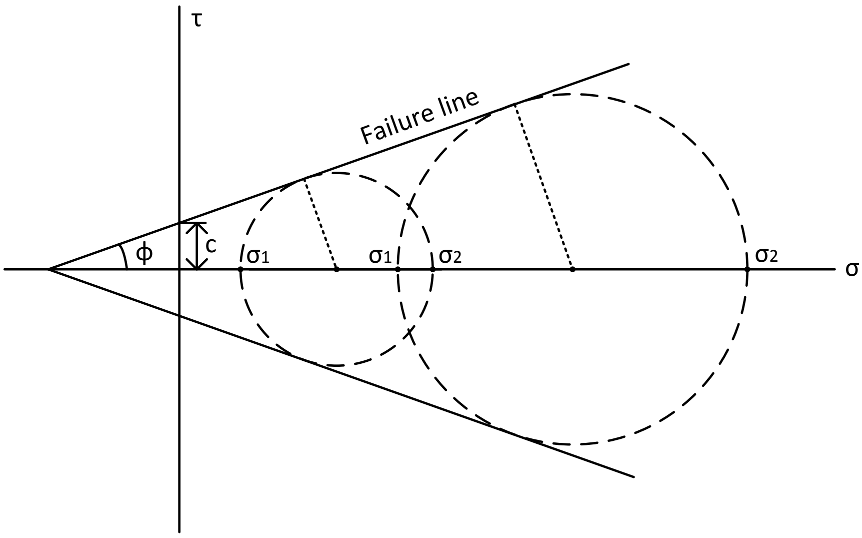


Figure 2.2: Mohr-Coulomb failure criterion

$$\tau_f = c + \sigma_N \cdot tan(\phi) \quad (2.15)$$

τ_f	Shear strength at failure	$[Pa]$
σ_N	Normal stress	$[Pa]$
c	Cohesion	$[Pa]$
ϕ	Internal friction angle	$[°]$

2.1.10. Undrained soil failure

During a quick soil loading process undrained soil failure occurs, where the water in the pores is not able to drain from the loaded soil. This process occurs in soil with a low permeability, such as clay. The load applied on the soil in distributed trough the water inside the pores, not though the particle structure. The effective stress on the soil particles is independent of the stress enforced on the soil. The failure line of the undrained failure of soil is in theory horizontal (see figure 2.3). The stress soil can withstand before failure is dependant on the undrained shear strength (see equation 2.16). The undrained shear stress is half of the diameter of the Mohr circle. Clay failure under fast loading is independent of the internal friction angle. The friction will therefore not increase with increasing normal force, often referred as the $\phi = 0$ failure principle.

$$S_u = \left(\frac{\sigma_2 - \sigma_1}{2}\right) = \frac{C_u}{2} \quad (2.16)$$

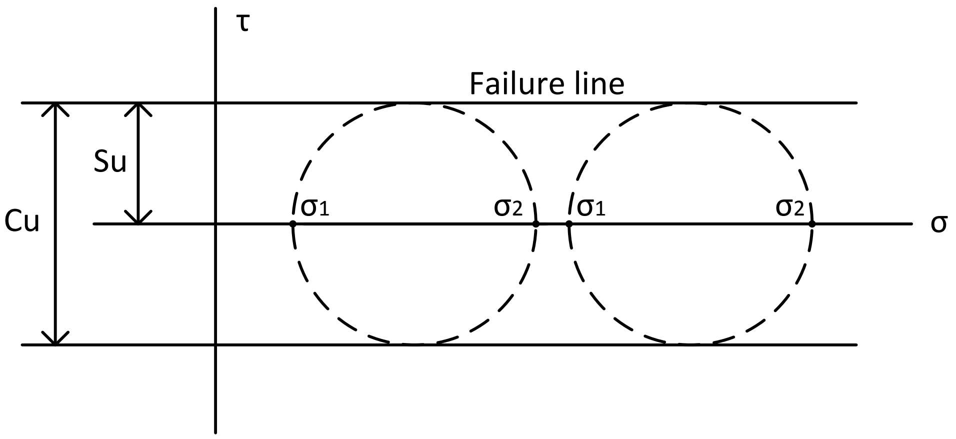


Figure 2.3: Undrained soil failure

S_u	Undrained shear strength	$[Pa]$
C_u	Unconfined compressive strength (UCS)	$[Pa]$

2.1.11. Cohesion, adhesion and adhesion factor

Cohesion, adhesion and adhesion factor will be repeatedly used is this report to indicate strength values of clay.

Cohesion

Cohesion is a force per area that holds the clay particles together. In this report cohesion is the internal shear strength, not the internal tensile strength of clay. The cohesion can be measured during failure experiments. These experiments can be drained or undrained, depending on the purpose of the information. The cohesion for quick loading process is equal to the undrained shear strength.

Adhesion

Adhesion is a force per area which is needed for two materials to be separated. In this report by adhesion the external shear strength is meant, not the external tensile strength. Clay adheres to materials for example metals, plastics and wood. The same cohesive soil can have different adhesive strength for different materials.

Adhesion factor

The adhesion factor gives the fraction of adhesion over undrained shear strength. The adhesion factor differs for varying materials and clay strength. A general assumption is that the adhesion factor decreases when the shear strength increases. More comprehensive information from literature is given in chapter 3.1.

$$\alpha_A = \frac{\alpha}{S_u} \tag{2.17}$$

α_A	Adhesion factor	$[-]$
α	Adhesion	$[Pa]$

2.2. Soil mechanics of clay

This research is focused on the ploughing of a clay seabed. Clay has many parameters that can differ. To make predictions of the behaviour of clay these parameters have to be tested. In this chapter the definition and characteristics of clay are explained. The final paragraph contains a conclusion that sums up the essential information of this chapter.

2.2.1. Classification of clay

In the previous chapter, the grain size classification table (see table 2.1) shows that clay particles are smaller then 0.002 mm. In nature, clay soils have a dispersion of particle sizes including sand and silt particles. The ratio of these particle sizes has influence on the behaviour of the soil.
The United States Department of Agriculture (USDA) [6] has made a soil texture triangle (see fig. 2.4) that classifies the soil type based on the percentage of sand, silt and clay particles.
In 100% sand or silt soils the voids are filled with air or water. When clay particles are added, they fill up the voids between the sand or silt. If the voids are fully filled with clay particles, the soil will behave as clay. Meaning that the soil has cohesion characteristics and low permeability. From the USDA triangle it can be concluded that a soil consisting of 40% or more clay particles is considered a clay.
Another way of classifying clay is the British standard. The British standard is used with soil with a clay particle content of over 35%. The plasticity of the clay can be categorised after the Atterberg limits are measured. The plasticity and Atterberg limits are discussed in further detail later on in this chapter.

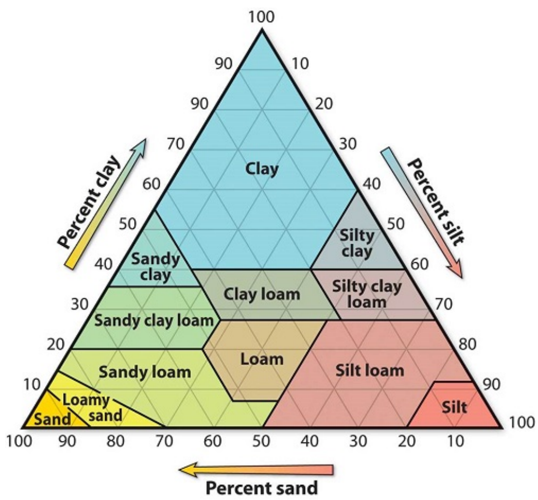
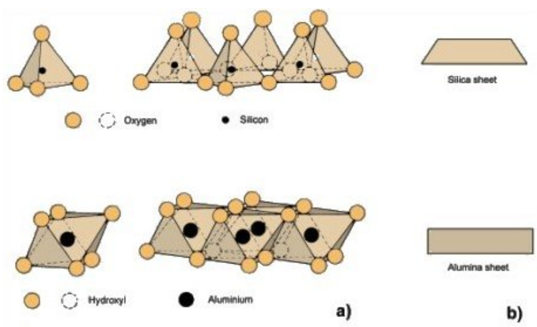


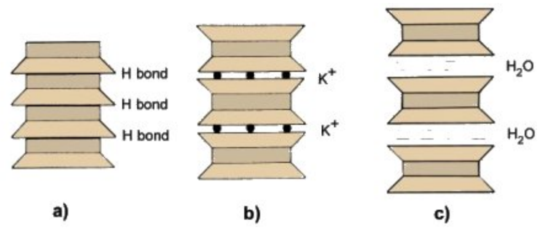
Figure 2.4: USDA Soil texture triangle

2.2.2. Composition of clay

Clay minerals are differently shaped then sand particles. Sheets of silica and alumina are stacked to build the basic structure of clay minerals. The silica sheets are represented as a trapezium shape, alumina sheets as rectangles (see fig 2.5a). These sheets are bonded together by electric charges. The most common clay structures are shown in figure 2.5b. The basic structures are joined by different bonds. In greater or lesser extent, each clay structure has a negative charge. The negative charge has influence on the cohesive and adhesive characteristics of a clay sample.



(a) Basic units of clay minerals



(b) Structure of main clay minerals. (left:kaolinite|middle:Illite|right:Montmorillonite)

Figure 2.5: Composition of clay

2.2.3. Undrained shear strength testers

The undrained shear strength is the value for cohesion in quick processes where the moisture is not drained form the soil. There are varies ways to test the undrained shear strength. Two hand held devices are used during this research: the portable shear vane tester (see fig. 2.6a) and the pocket vane shear tester (see fig. 2.6b). These testers are also named field vane and hand vane, respectively. These names will be used in this report.
Both devices use the same principle to measure the strength of the soil. The vanes of the testers are pressed down in soil. The field vane is inserted deep into the soil, whereas the hand vane only penetrates the soil by 1 cm. The handles of the testers are turned at a rate of about one rotation every minute. When rotating the handle, the part of the device inserted into the clay stays in place and a calibrated spring in loaded. When the clay fails under the pressure the spring will be unloaded and a indicator points at the maximum shear forces reached.
After the clay has sheared the residual shear strength could be measured. The indicator must be set to zero and the device rotated a second time. The strength read form the indicator is the steady shear strength of clay shearing over clay after failure of the clay.

(a) Portable shear vane tester

(b) Pocket vane shear tester

Figure 2.6: Devices to determine the undrained shear strength of clay

2.2.4. Atterberg limits

The shear strength of clay is highly depended on the percentage of water within the clay. The Atterberg limits defines the state a fine grained soil in relation to the water contents. There are four states a soil can be categorised in: solid, semi-solid, plastic and liquid (see fig. 2.7).
These states are separated by three limits. At the transition from solid to semi-solid the shrinkage limit (W_s) indicates at what moisture content the volume starts increasing when water is added. The plastic limit (W_p) indicates the transition from semi-solid to plastic state. Clay in the plastic state can be remoulded, in the semi-solid state clay is brittle. The limit between the plastic and liquid state is the liquid limit (W_l). In the liquid state the clay behaves like a viscous liquid.

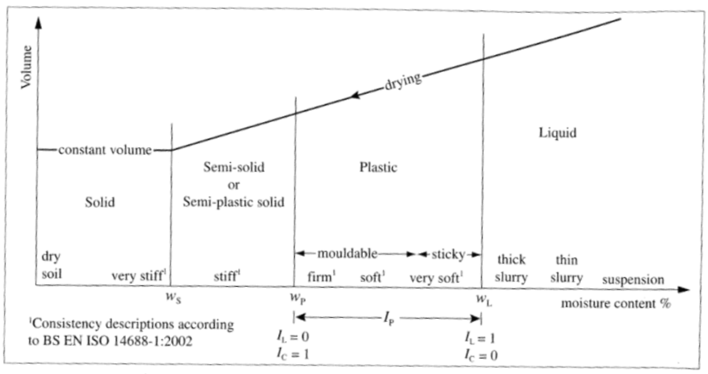


Figure 2.7: Atterberg limits

The plasticity index determines the size of the range at which the clay has plastic behaviour (see eq. 2.18). Clay with a small amount of sand and silt particles can absorb more moisture and have a large plasticity index compared to a clay with a larger amount of sand and silt.

$$I_p = w_l - w_p \tag{2.18}$$

I_p	Plasticity Index	[%]
w_l	Liquid limit	[%]
w_p	Plastic limit	[%]

The behaviour of clay can be indicated by the percentage of moisture content relative to the plastic range by the liquidity index. The liquidity index is the percentage of moisture content of a soil sample minus the plastic limit of that soil divided by the plasticity index (see eq. 2.19). Very stiff clays have a low liquidity index or zero if the moisture content is equal to the plastic limit. Clay with a negative liquidity index are semi-solid and therefore could have brittle behaviour. Clay with high liquidity index are very plastic. Above a liquidity index of 100% the clay is considered a viscous fluid. The fluid clay will become less viscous with increasing liquidity index.

$$I_l = \frac{w - w_p}{I_p} \tag{2.19}$$

I_l	Liquidity Index	[%]
w	Water content	[%]

2.2.5. Plasticity chart

Clay and silt types can be categorised in levels of plasticity on the basis of the proportion of plasticity index and the liquid limit (see fig. 2.8). Clay soils are indicated in the plasticity chart between the A- and the B-line. Plasticity of clay and silt increases with higher liquid limits. Soils below the A-line and with a liquid limit higher than are considered silt or organic soil. In the bottom left corner sand can be found, having no plasticity and not able to retain liquid.

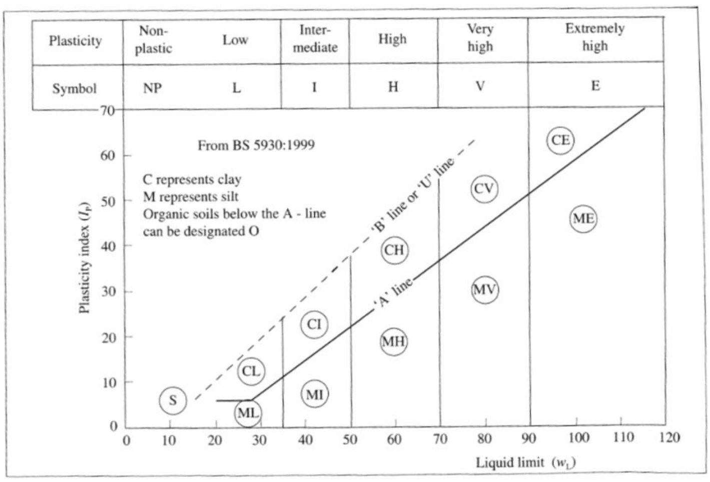


Figure 2.8: Plasticity chart

2.3. Conclusion soil and clay properties

Conclusion soil properties

Soil consist of various particles, where the clay particles are the smallest with an diameter of maximum 0.002 mm. Sands is made of quartz and clay from minerals. Voids filled with water or air exists in all types of soil. The voids determine partly the permeability of a soil. Water can exits the voids of water relative quick when a pressure drop over the soil in created. Clay has a low permeability. Forces on the soil can be transformed to a maximum shear and normal force at failure. The clay failure experiments can be tested over long periods of time during a drained test or with quick tests determining the undrained shear strength. Adhesion is the force at which the clay is attached onto another material. The adhesion factor is the adhesion divided by the cohesion, also known as the undrained shear strength. Adhesion and cohesion is caused by the mineral composition found only in clay particles. The adhesion factor is predicted to decrease when the undrained shear strength of clay increases.

Conclusion clay properties

Soil consisting of al least 40% or more clay particles is classified as clay. Clay particles are build up of silica and alumina sheets. Combinations of these sheets are stacked to form the clay structure. The type of bonds between the sheets has influence on the cohesive strength and plasticity. The cohesive strength can be measured as the undrained shear strength for quick loading processes. The undrained shear strength for each experiment is measured by two hand held devices.
The state at which a soil is currently in can be determined with the moisture content in relation with the Atterberg limits for that soil. Clay and silt have plastic behaviour for a range of moisture content. The level of plasticity can be determined by the proportion of plasticity index and liquid limit.

3
Literature

3.1. Literature study on adhesion factor clay

With the adhesion factor the amount of adhesion force can be predicted when the undrained shear strength of a clay is known. The adhesion force is a significant part of the pulling forces for ploughing in clay. The adhesion factor changes with the clay strength and the material the clay is adhering to. There has been no research that looked into the adhesion factor of clay types with different shear strength that adhered to steel at ploughing velocities. To obtain an indication of the adhesion factor trends, literature of concrete pile foundations have been studied. A study of clay to steel adhesion gives an insight of the shearing process.

3.1.1. Adhesion factor of pile foundation

An industry where the adhesion of clay to solids also plays a significant role is the foundations of buildings and civil structures. There has been many researches to find a relation between the cohesion and adhesion. McClelland (1974) [7] provided a summary of researches done about the adhesion ratio to undrained shear strength. In the graph 3.1 the adhesion factors are plotted of Tomlinson (1957, 1970), Peck (1958), Woodward et al.(1961), Kerisel (1965). These are the result of pile-loading test of concrete piles in undrained clay conditions.
What can be seen is that the adhesion factor between the 25 and 50 kPa is 1. When the adhesion is larger than the undrained shear strength, the clay will slide over a layer of clay stuck to the pile. The theoretical force needed for clay to shear is the undrained shear strength times the shear area, therefore the adhesion factor can never be higher then 1. Furthermore the ratio decrease for increasing undrained shear strength found by Peck is linear between the 60 and 170 kPa. Others conclude an decrease in adhesion factor inversely proportional to the undrained shear strength. The factor at about an undrained shear strength of 150 kPa is around the 0.3 for Kerisel, Woodward and Tomlinson. All the proposed trends are a result of numerous tests. With empirical research scatter occurs due to small deviations in for example soil, skin surface, measurement devices and method. The results these researches are showing are trends with a bandwidth above or below the trend line.
It is still unclear what the adhesion factor will be for higher undrained cohesion. Rock has no adhesive strength, this means that there has to be a transition zone where the the adhesion factor reaches zero at high strength of rock.

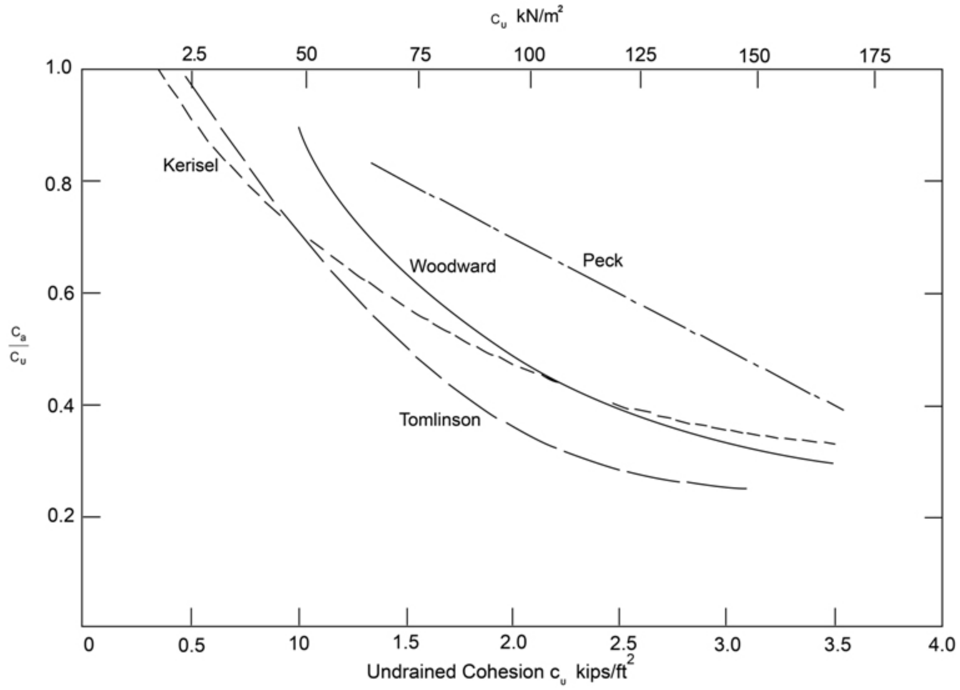


Figure 3.1: Summary of adhesion factor research for driven piles

3.1.2. Littleton (1976)

Littleton [8] executed multiple researches in his paper about strength parameters for the shearing resistance of clay and smooth steel surfaces. One of the shearbox tests with an illite clay obtained form a brickworks gives an insight in the normal stress influence (see fig. 3.2). This is the result of a "quick" undrained shearbox test with the maximum velocity of 0.592 mm/min. During trenching operations velocity ranges between 800 and 13000 mm/min. Two conclusions can be made looking at this graph. First an increase in normal stress has no significant impact on the shear stress. The internal friction angle found by Littleton is 1%. Secondly the adhesion factor is approximately 0.8 at a undrained shear strength of circa 25 kPa. This is in accordance with the adhesion factor trends of Kerisel and Tomlinson (see fig. 3.1).

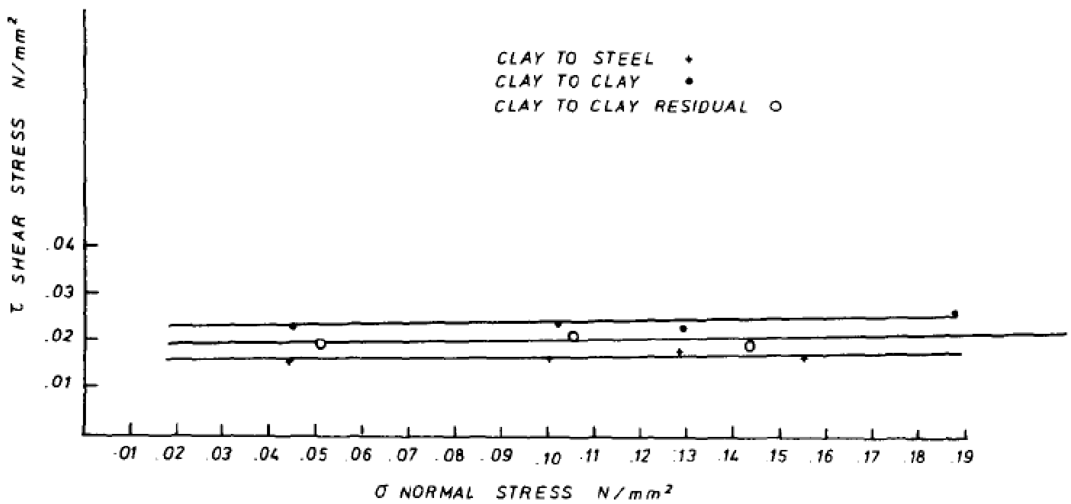


Figure 3.2: Results shear box test with a velocity of 0.592 mm/min

3.1.3. Van Gurp (2014)

Van Gurp [3] made a plough pulling force model by the information gathered from experiments. One of the variables of the model was the adhesion factor. The adhesion factor is determined by three ploughing tests in the same clay. Each test is performed by a unique plough with the same frontal surface, but increasing length of 20mm, 44mm and 90mm. The cutting force of the ploughs has to be the same. The horizontal force increases linear with the increasing adhesion area, as can be seen in figure 3.3. If the three point are linear interpolated to zero the cutting force of 224N is found. The inclination angle determines the adhesion force per area. For each mm^2 adhesion area 0.0194N is added to the pulling force. This result in a adhesion of 19.4 kPa. Dividing the adhesion with the undrained shear strength of 30 kPa, results in an adhesion factor of 0.65.

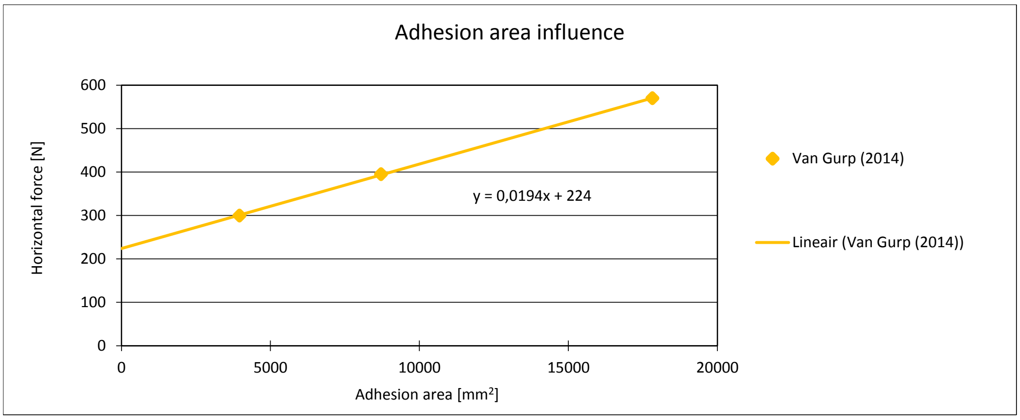


Figure 3.3: Measured horizontal loads of various adhesion area ($S_u = 30kPa, \alpha_a = 0.65, depth = 94mm, v = 28mm/s$)

3.1.4. Combe (2015)

Combe (2015) [9] studied the influence of adhesion on dredging with a clamshell. During loading and unloading of the clamshell the adhesion of clay has influence on the production. The hypothesis of his paper is that with increasing clay strength the adhesion decreases to zero. To find out if this hypothesis was correct he build an experimental setup to test the adhesion of clay (see fig. 3.4). This setup pulled a horizontal metal plate, by the use of a constant speed actuator, though two blocks of clay. One underneath the metal plate and one above. The pulling force is measured by a load cell in combination with an amplifier and recording software.
In figure 3.5 the forces are shown schematically. When the plated is pulled, the adhesion and possibly the shear force will appear in opposite direction. With the option to vary the weight on top of the upper clay box, the normal force on the plate could be varied. The adhesion would be constant with increasing normal force, but the shear force component would then increase linear.
Multiple test were carried out with three different type of clay (see table 3.1). Two velocities were tested, 8 mm/s and 0.4 mm/s. The results of the experiments can be seen in graph 3.6. For an increase in normal stress the shear stress increased. This would imply that an internal friction angle exist between the clay and the plate. In table 3.2 the calculated internal friction angles can be seen. Also included are the adhesion factors of each clay. The adhesion factor is calculated to be under 0.1 for all, except the Freeport Grey clay. This clay has a adhesion factor of 0.29.

Table 3.1: Clay used by Combe (2015)

Clay	Liquid Limit [%]	Plastic Limit [%]	Specific gravity [kg/m3]	Undrained shear strength [kPa]
Delaware, Philadelphia	30.5	19.1	1837	12
Freeport Grey, Texas	61.5	23.6	1952	17
Freeport Red, Texas	60.5	18.2	2160	89

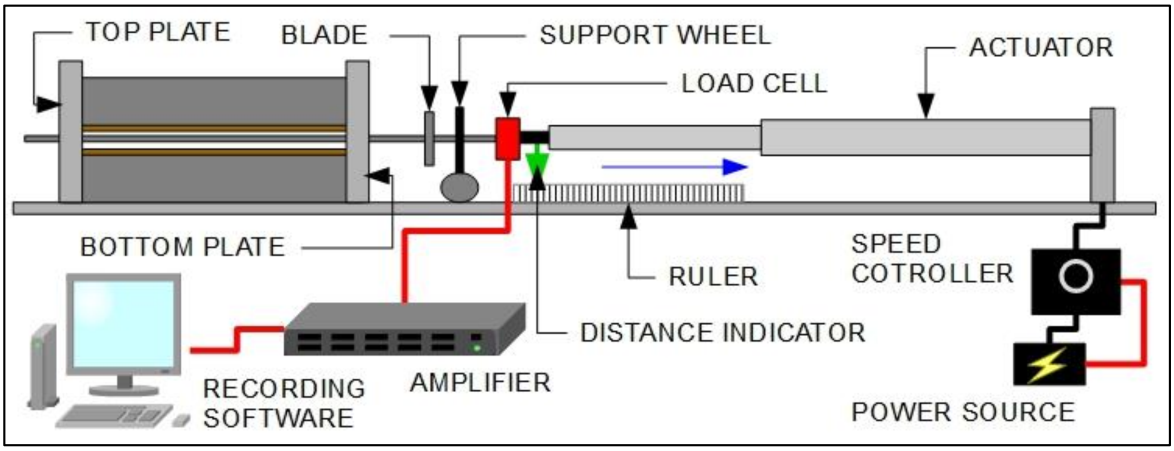


Figure 3.4: Setup used by Combe (2015)

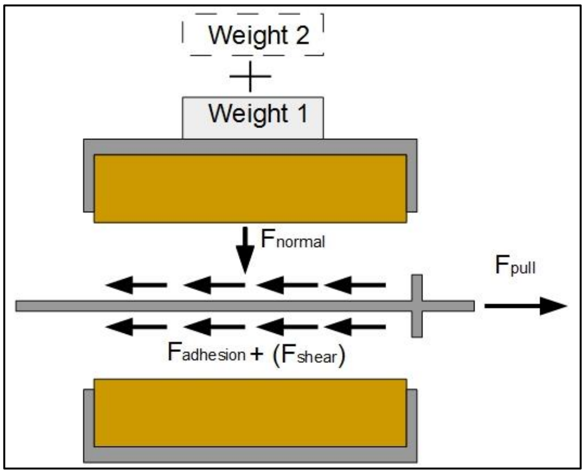


Figure 3.5: Forces on the clay

Table 3.2: Results of experiments Combe (2015)

Clay	Pulling speed [mm/s]	Undrained shear strength [kPa]	Adhesion [kPa]	Adhesion factor [-]	Internal friction angle [degree]
Delaware	0.4	11.5	0.70	0.061	4.0
	8	10.1	0.90	0.089	2.17
Freeport Grey	0.4	25.9	1.74	0.067	16.34
	8	17.3	5.00	0.29	1.42
Freeport Red	0.4	102.1	1.22	0.012	4.75
	8	89.0	2.79	0.031	15.35

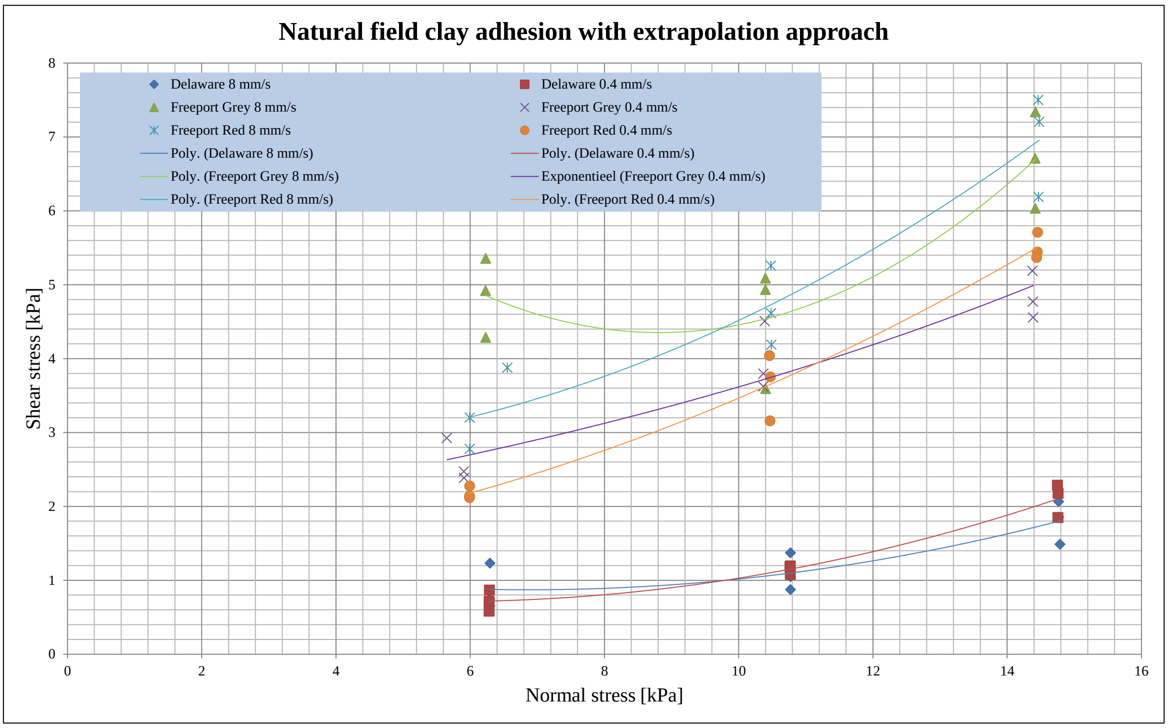


Figure 3.6: Results of experiments

3.1.5. Chen (2019)

The goal of Chen (2019) [10] was to find a way to determine the relation of adhesion and cohesion of cohesive soils. With the results the cutting of clay can be optimised and increase the production of dredging operation. The test setup Chen used was similar of that Combe (2015), seen in figures 3.4 and 3.5. Chen used two types of clay to perform test under five different vertical loads. The results where a linear fit for increasing normal stress, like expected in a Mohr-Coulomb failure criterion. The cohesion factor in relation to the dimensionless cohesion has a polynomial fit. At low dimensionless cohesion the cohesion factor tends to go to a factor of one. At a dimensionless cohesion number of three the factor drops to 0.2 and between five and ten the factor is around 0.1. This test is a way to determine the cohesion factor of a cohesive soil, which can be used to optimise the dredging operation. To generate a material database a lot more soil types with different moisture content must be done.

3.2. Literature study on frontal ploughing force

Soil can withstand a certain amount of pressure before shearing occurs. The pressure at which the soil is moved is called the ultimate bearing capacity. This capacity varies for each soil. The dimensions of the object that applies the pressure to the soil also has influence on the bearing capacity. The theories of the bearing capacities are discussed in this chapter. These theories are based on the vertical pressure of a foundation. In the final paragraph the usable information of these theories for the ploughing operation are stated.

3.2.1. Terzaghi (1943)

The Austrian civil and geotechnical engineer Karl von Terzaghi presented a theory for the ultimate bearing capacity of rough shallow soil [11]. During the second world war he had a post at the Harvard University and was a consultant for subway and port constructions. Terzaghi suggested a method for determining the bearing capacity for the failure of soil under a foundation. He used the failure zones discovered by Rankine (1857) and Prandtl (1920) (see fig. 3.7). In the figure the foundation is vertically loaded and an active Rankine zone is pushing down into the soil. This force creates the Prandtl zone on both sides of a strip foundation or all around a square or circular foundation. At failure this Prandtl zone will slide over the underlying soil and pushes up the passive Rankine zone. The force needed to push the passive zone upwards depends on the overburden pressure.

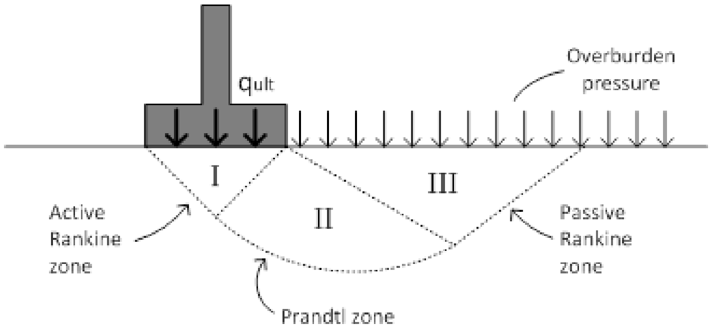


Figure 3.7: Ultimate bearing capacity failure zones

Terzaghi developed multiple theories for different foundation dimensions. For this research into narrow ploughs, the continuous foundation or strip foundation theory is most suitable (see eq. 3.1). The ultimate bearing capacity is dependent on the cohesion and unit weight of the soil and the width of the foundation. For a foundation resting on the soil surface the overburden weight is zero. The equation of Terzaghi is valid for a ratio of foundation depth divided by the width of maximum 1. The bearing capacity factors of N_c, N_q, N_y depend on the soil internal friction factor (see eq. 3.2, 3.3, 3.4, 3.5).

$$q_{ult} = c \cdot N_c + q \cdot N_q + 0.5 \cdot y \cdot B \cdot N_y \tag{3.1}$$

c	Cohesion	$[Pa]$
q	Surcharge pressure	$[Pa]$
y	Unit weight	$[N/m^3]$
B	Width of foundation	$[m]$
N_c, N_q, N_y	Bearing capacity factors	$[-]$

$$N_c = 5.14 \quad for \quad \phi = 0 \tag{3.2}$$

$$N_c = \frac{N_q - 1}{tan(\phi)} \quad for \quad \phi > 0 \tag{3.3}$$

$$N_q = \frac{e^{(2\pi(0.75-\phi/360)tan(\phi)}}{2cos^2(45+\phi/2)} \tag{3.4}$$

$$N_y = \frac{2(N_q+1)tan(\phi)}{1+0.4sin(4\phi)} \tag{3.5}$$

3.2.2. Meyerhof (1951)

Meyerhof [12] continued the research of Terzaghi, he focused on the bearing capacity of deep foundations (see fig 3.8). Meyerhof also used a strip foundation, where there is only interaction between soil and foundation at the bottom of the foundation strip. There is a small difference in ultimate bearing capacity for smooth and rough surface of the foundation.

For the ultimate bearing capacity in purely cohesive soil Meyerhof found the following equation 3.6.

$$q_{ult} = c \cdot N_c + y \cdot D \tag{3.6}$$

The factor N_c for a perfectly smooth pile is $N_c = 2 \cdot \pi + 2 = 8.28$, and for a rough foundation pile $N_c = frac5\pi2 + 1 = 8.85$. Meyerhof found a linear dependency of the the depth of the foundation on the ultimate bearing capacity.

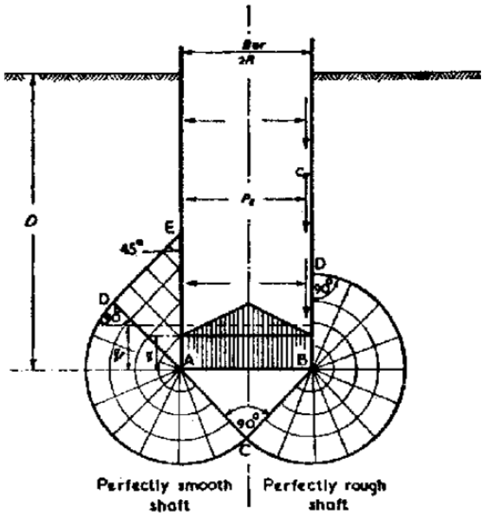


Figure 3.8: Deep foundation theory by Meyerhof (1951)

3.2.3. Hansen (1961)

Following up the ultimate bearing capacity of Terzaghi, Hansen (1961) [13] empirical research found shape and depth factors. The theory of Terzaghi assumes an infinite long strip. Hansen included an end effect (S_x) and depth factors (d_x) of finite shapes to the equation of Terzaghi (see eq. 3.7).

$$q_{ult} = c \cdot N_c \cdot S_c \cdot d_c + q \cdot N_q \cdot S_q \cdot d_q + 0.5 \cdot y \cdot B \cdot N_y \cdot S_y \cdot d_y \tag{3.7}$$

For rectangles the shape factors are determined by the following formula, which are highly dependent on the width over length ratio:

$$S_c = 1 + 0.2 \cdot \frac{B}{L} \cdot \frac{N_q}{N_c} \tag{3.8}$$

$$S_q = 1 + \frac{B}{L} \cdot sin(\phi) \tag{3.9}$$

$$S_y = 1 - 0.3 \cdot \frac{B}{L} \tag{3.10}$$

The depth factors Hansen proposed depends on the depth over width ratio:

$$d_c = 1 + 0.4 \cdot arctan\left(\frac{B}{L}\right) \tag{3.11}$$

$$d_q = 1 + 2 \cdot tan(\phi) \cdot (1 - sin(\phi))^2 \cdot arctan\left(\frac{D}{B}\right) \tag{3.12}$$

$$d_y = 1 \tag{3.13}$$

3.2.4. Cutting force of horizontal ploughing in clay

Ploughing horizontally has similarities with vertical foundation piles. One of the differences is that when a pile is driven into the soil the bearing capacity increases due to the increasing overburden pressure. Horizontal ploughing has a fixed depth for a length of trench. There will not be any overburden pressure, because when rotating the failure zones 90 degrees, the soil will not be pushed upwards only sideways. The failure zones are assumed to have the same dimensions for a flat rectangular horizontal moving plough and the vertical foundation. Together with the knowledge that clay has an internal friction angle of zero, the formula for the bearing capacity can be reduced.

The formula for bearing capacity of Meyerhof can be reduced to only the cohesion times the bearing capacity factor for cohesion (see eq. 3.14). The soil does not have to be pushed upward, therefore the depth factor has no influence on the bearing capacity.

$$q_{ult} = c \cdot N_c \tag{3.14}$$

The formula of Hansen can also be reduced for horizontal ploughing in clay (see eq. 3.15). Hansen uses the bearing capacity factor for cohesion of Terzaghi in combination with end and depth effects. These effects depend on the dimensions of the plough.

$$q_{ult} = c \cdot N_c \cdot S_c \cdot d_c \tag{3.15}$$

The cutting force of a plough is the multiplication the the ultimate bearing capacity times the front surface of the plough (see eq. 3.16).

$$F_c = q_{ult} \cdot D \cdot B \tag{3.16}$$

3.2.5. Geometry of soil failure with narrow ploughs on land

Three dimensional narrow plough soil failure models were first made for agricultural purposes. These models where used to predict the pulling forces of tillage tools. Similarities with the soil failure shape of the bearing capacities can be seen as sideways failure. Besides the sideways failure, these vertical plough models also take into account the crescent failure at the surface. A number of the models are phenomenologically discussed in this chapter to give an insight of theoretical ways to simulate the geometry of soil during ploughing on land.

Hettiaratchi & Reece (1967)

Hettiaratchi & Reece [14] made a model to provide a solution to symmetrical three dimensional soil failure problems by trigonometrical factors. Others have described the soil failure process by complex solutions, the trigonometric factors provide a rapid way to find the solution.
In figure 3.9 the evolution of a wedge in front of the plough is shown. For a plough with a large relative width (a), the soil is pushed forward and up. The depth at which a full wedge is created (b) is called the critical depth. The critical depth depends on the soil characteristics. Below this critical depth a full wedge is created (c).
Below the critical depth, the soil fails sideways (see fig. 3.10). The wedge will be pushed forward in front of the plough. The soil slides sideways around the wedge and the plough.
Above the critical depth the soil will fail upwards (see fig. 3.11). Hettiaratchi & Reece provided a simplified solution for the accurate logarithmic spiral method, shown as dotted line in the figure. The solution the a linear line between points AC.

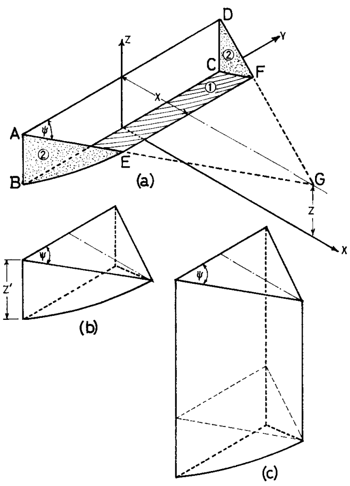


Figure 3.9: Evolution of three dimensional soil wedge

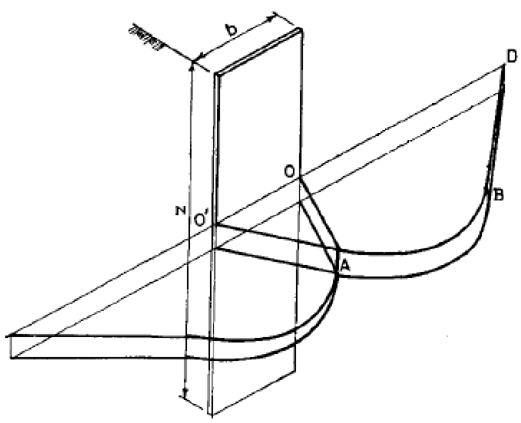


Figure 3.10: Sideways soil failure

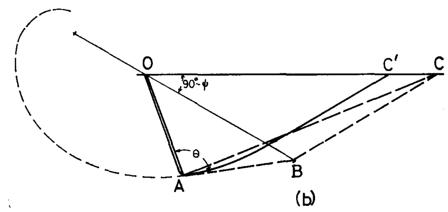


Figure 3.11: Forward failure regime

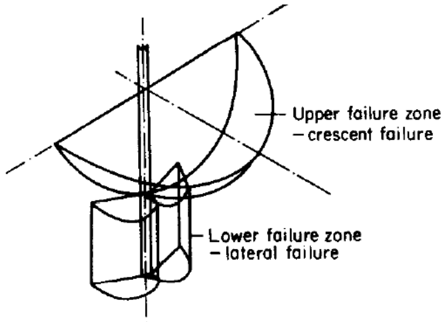


Figure 3.12: Sideways and crescent failure

Godwin & Spoor (1977)

Godwin & Spoor [15] found a soil failure model for agricultural tines. They focused an finding the geometry of the soil for tines with a large width over depth ratio (see fig. 3.12). The model consist of two failure zones, an upper and lower failure zone. At the upper failure zone crescent failure occurs, where the soil has an upward movement. At the lower failure zone only lateral movement of the soil occurs. The transition between the upper and lower zone is the critical depth.
The lateral failure zone shows the same failure mechanism as with vertical foundation piles.
The upper failure zone is proposed as a circular zone with radius that decreases with depth.

3.3. Literature study on velocity influence

The velocity at which an object moves through clay has influence on the strength of the clay. The ultimate bearing capacity assumes a static pressure until failure. During ploughing a continues failure of soil takes place. Three studies have made a prediction of the velocity influence on the shear strength. Each model uses a constant value. The upper and lower limits of these values are determined empirically.

3.3.1. Wismer & Luth (1972)

Wismer & Luth (1972) [16] discuss the formula of a successful treatment of the shear rate effect for saturated clay (see eq. 3.17). After cone penetration test with various velocities ranging from 2 m/h up to 15500 m/h the exponent 'm' was determined to lay between 0.091 and 0.109. If, in this theory, the velocity nears zero the undrained shear strength is decreasing to zero as well. In reality there will always be a force needed to shear the clay even at low velocities.

$$S_u(v) = S_{u_{ref}} \cdot \left[\frac{v}{v_{ref}}\right]^m \tag{3.17}$$

S_u	Undrained shear strength dependant of velocity	[kPa]
$S_{u_{ref}}$	Undrained shear strength at reference velocity	[kPa]
v	Velocity	[m/s]
V_{ref}	Reference velocity	[m/s]
m	Constant (material property)	[-]

3.3.2. Dayal & Allen (1975)

Dayal & Allen (1975) [17] have done an empirical study on the penetration rate effect on the strength of clay and sand. They performed tests with various moisture contents and velocities up to 81.14 cm/s. Experimental results showed an insignificant velocity effect for the penetration test in sand. Whereas for cohesive soils a logarithmic relation was found (see eq. 3.18). The constant value of λ had a range between 0.03 and 0.25 according to Dayal & Allen. At very low velocities the logarithm becomes a negative number, eventually resulting in a negative undrained shear strength. In practice this will not be possible.

$$S_u(v) = S_{u_{ref}} \cdot \left(1 + \lambda \cdot log\left[\frac{v}{v_{ref}}\right]\right) \tag{3.18}$$

λ	Constant (material property)	[-]

3.3.3. Miedema (1992)

Miedema (1992) [18] proposed an solution for the yield stress going to zero or minus infinity and which does not contradict with previous theories (see eq. 3.19).

$$S_u(v) = S_{u_y} + S_{u_o} \cdot ln\left[1 + \frac{v}{v_{ref}}\right] \quad (3.19)$$

S_{u_y}	Yield strength (material property)	[kPa]
S_{u_o}	Dynamic shearing resistance strength (material property)	[kPa]

3.3.4. Velocity influence measured by Van Gurp (2014)

The velocity has influence on the undrained shear strength. The pulling force of a plough increases with increasing velocity. In chapter 3.3 velocity models are discussed. Van Gurp has verified two models during his experiments. Three experiments at different velocities are carried out with the small plough. In figure 3.13 the measured horizontal force of the three experiments are shown as the yellow dots. The exponential model of Wismer & Luth (1972) is fitted to the measured values. The value of m is 0.12, which is higher then the range proposed by Wismer & Luth (1972) of m ranging from 0.091 to 0.109. A curve fit of the logarithmic model by Dayal & Allan (1975) found a value for λ of 0.32. The value of the measured forces is higher then the proposed value for λ ranging from 0.03 to 0.25. The logarithmic model of Dayal & Allan (1975) is used in the plough pulling force model.

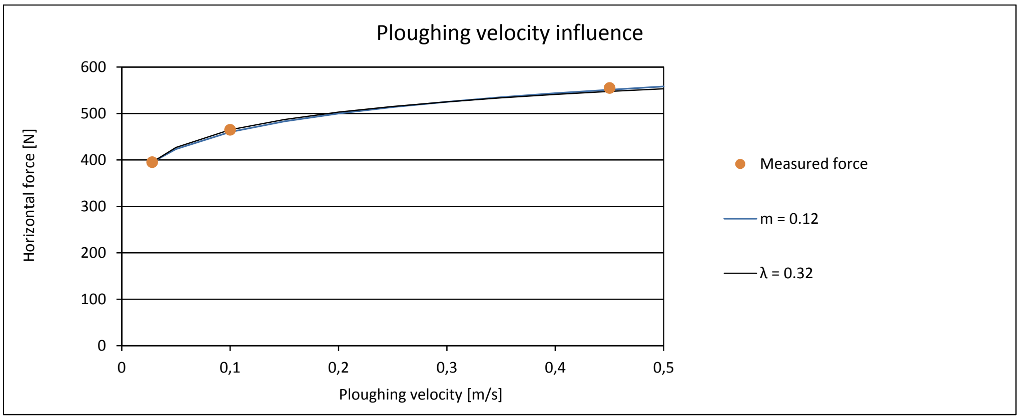


Figure 3.13: Measured horizontal loads at various velocities ($S_u = 30kPa, \alpha_a = 0.65, depth = 94mm$)

3.4. Literature of plough pulling force models

The first submerged plough pulling force model was made by Reece & Grinsted in 1986. Later companies like IHC and Primo Marine made models to calculate the pulling force for subsea ploughs. Van Gurp (2014) researched many parameters that influence the pulling force of the plough and made a model from his results. With these models the pulling force can be predicted.

3.4.1. Reece & Grinsted (1986)

Reece & Grinsted [19] used a plough configuration that pushed the clay upwards (see fig. 3.14). By using this configuration the horizontal pulling force is quadratic with depth. When the depth is increased, the area of the sliding surface is increased. The volume of clay that is pushed upwards is increased with depth. The model (see eq. 3.20) of Reece & Grinsted shows that the depth is quadratic and that a dimensionless coefficient is used depending on the geometry of the plough.

$$F_c = K_3 \cdot c \cdot z^2 \quad (3.20)$$

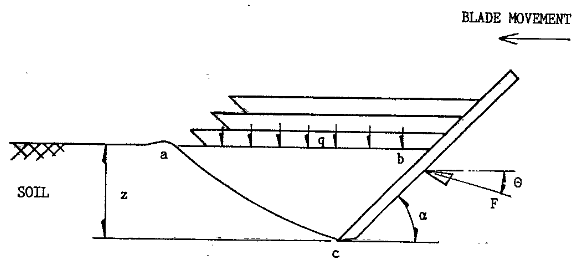


Figure 3.14: Plough configuration used by Reece and Grinsted

F_c	Horizontal plough pulling force	$[N]$
K_3	dimensionless coefficient depending on the machine geometry	$[-]$
c	Cohesion of the clay	$[kPa]$
z	Ploughing depth	$[m]$

3.4.2. IHC Engineering Business

IHC is the builder of the Sea Stallion ploughs. With there experience of building ploughs, they also have knowledge of the pulling forces to predict. In the model of IHC (see eq. 3.21) the forces of the skids and the velocity influence are included. The pulling force of the skids is calculated with a coefficient of friction of the clay multiplied by the submerged weight of the plough. The velocity influence is linear, for every meter per second half a percent of ploughing force is added. The ploughing depth influence is controlled by a depth coefficient between the 1.5 and 2.0.

$$F_{pull,clay} = C_{w,clay} \cdot Wplough, subm + (C_1 + C_2 \cdot v) \cdot c \cdot z^n \tag{3.21}$$

$F_{pull,clay}$	Horizontal plough pulling force in clay	$[N]$
$C_{w,clay}$	Coefficient for the friction of the skids on clay	$[-]$
$Wplough, subm$	Submerged weight of the plough	$[kg]$
C_1	Coefficient for ploughing in clay of 0.1	$[-]$
C_2	Coefficient for ploughing in clay of 0.0005	$[-]$
v	The speed of the plough	$[m/s]$
c	Cohesion of the clay	$[kPa]$
z	Ploughing depth	$[m]$
n	Depth coefficient between 1.5 2.0	$[-]$

3.4.3. Primo Marine

Primo Marine, a company with knowledge of offshore trenching, has a rule of thumb to estimate the pulling force in clay soils. This rule (see eq. 3.22) describes that the pressure on the clay soil to make a trench has to be 9 times the amount of cohesion of the clay. The number 9 can be compared by the N_c value described in section 4.5.2. This formula does only include the frontal plough force needed, the adhesion on the side or the skids of the plough are not included.

$$\sigma_h = 9 \cdot C_u \tag{3.22}$$

σ_h	Horizontal soil pressure	$[kPa]$
C_u	Cohesion	$[kPa]$

3.4.4. The plough pulling force model of Van Gurp (2014)

In the first section, the model is explained. In further sections the different variables are further clarified and the results of the empirical research is shown. The last section gives a conclusion and summarises the important values for the this research.

Plough pulling force model

Van Gurp has done experimental research on the influence of plough variables on the pulling force (see fig. 3.15). The multiple experiments isolated each of the variables and each individual impact on the

pulling force was formulated in an equation (see eq. 3.23).
Van Gurp used pottery clay with a average shear strength of 30 kPa. Further information of the clay can be found in chapter 4.2. The cutting force of a flat rectangular cutting blade perpendicular to the clay surface was found to be 224N. The width of the plough is 10mm and the depth 94mm, resulting in a N_c of 7.9.

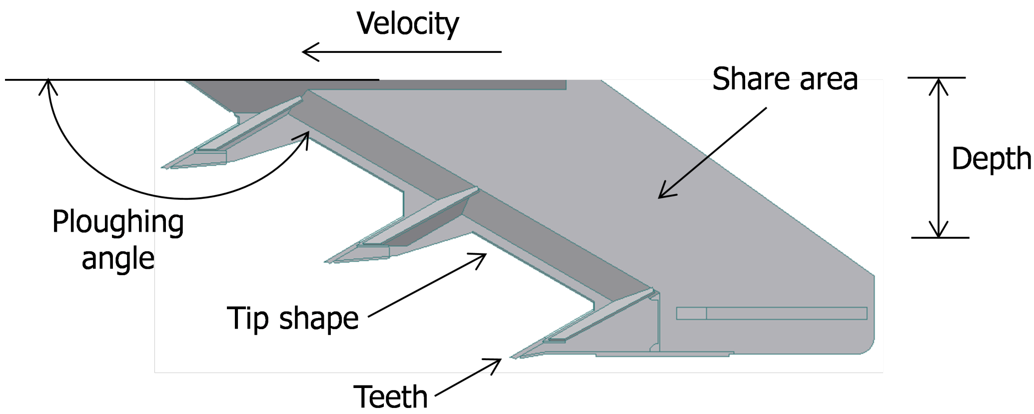


Figure 3.15: Plough variables tested by Van Gurp (2014)

$$F_h = S_u(v) \cdot \alpha_{depth}(d) \cdot (\alpha_{tip} \cdot b \cdot d \cdot N_c + \alpha_a \cdot A_{adh}) + F_{cable} + F_{skids} \tag{3.23}$$

F_h	Horizontal plough pulling force	$[N]$
$S_u(v)$	Shear strength dependant of velocity	$[kPa]$
α_{depth}	Depth influence	$[-]$
α_{tip}	Tip shape factor	$[-]$
α_a	Adhesion factor	$[-]$
A_{adh}	Adhesion area	$[m^2]$

Tip shape

The front of the plough has influence on the pulling forces needed to make a trench in the clay. As mentioned before Van Gurp (2014) carried out experiments with different dimensions of the plough, one of the topics is the tip shape of the plough. The pulling force of the varying shapes of the tips are measured during the experiments. The cutting force is isolated from the adhesion force. The cutting forces of the varying tip shapes are compared with the rectangular tip shape (see table 3.3). The full dimensions of the ploughs can be found in appendix II. Three ploughs have been tested with a sharp edge with different tip angles. The plough with a circular tip has a radius of half the width of 10 mm. The tip shape factor is the cutting force of a specific tip divided by the cutting force of the rectangular. The ploughs with sharp edges and circular tip reduce the cutting force up to 25%. Both the scale models of the SS4 and HD3 reduce the cutting force by 40%, having a tip shape factor of 0.6.

Table 3.3: Tip shape factors by Van Gurp (2014) ($S_u = 30kPa, d = 9.4cm, v = 2.8cm/s$)

Tip shape	Tip shape factor
Rectangular	1.0
90° sharp edged tip	0.93
60° sharp edged tip	0.86
30° sharp edged tip	0.75
Circular tip	0.87
SS4	0.6
HD3	0.6

3.5. Literature study on reduction methods of adhesion force

Numerous researches have been performed to reduce the adhesion force of various applications. During most of these researches, the concepts of adhesion reduction were found looking at soil-burrowing animals, like beetles, ants and worms. Feasible options for the adhesion reduction tests, in this experimental study, are clarified in the conclusion at the end of this chapter.

3.5.1. Non-smooth surface

In this section different researches on non-smooth surfaces are reviewed. These researches found design to reduce the adhesive force by changing the geometry of the adhesion surface.

Ren *et al.* (1995)

Ren et al. (1995) [20] carried out experiments with scaled bulldozing plates moving through clay. To reduce the sliding resistance of the clay over the bulldozing plate, they looked at the bionic unsmoothed surface of the dung beetle. The body surface of a beetle, which has contact with the soil, is covered by convex bulges as shown in fig. 3.16.
The objective of the research was to divine the arrangement and size of the convexes at which the sliding resistance is the least. The bulldozer plate was held in a constant angle and depth and moved through the same soil condition at an unknown constant speed. The soil had a moisture content of 27.8% and the particle distributing (see table 3.4) shows 37.16% particles in the range of 0.001 mm and smaller. The base diameter, amount and arrangement of the convexes where varied.
The optimum dimensions of the convex during these experiments had a base diameter of 25 mm and a height of 7 mm. The parallelogram configuration (see fig. 3.17) has the most reduction of sliding resistance. This unsmoothed surface reduced the sliding resistance by 18.09%.

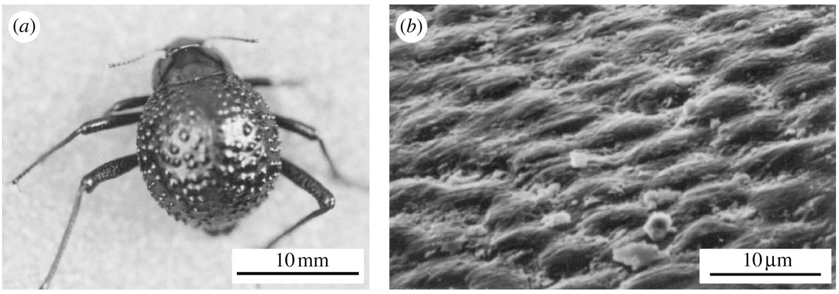
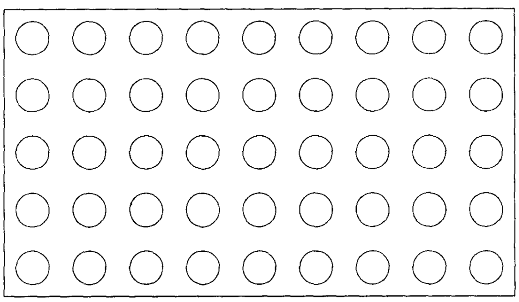


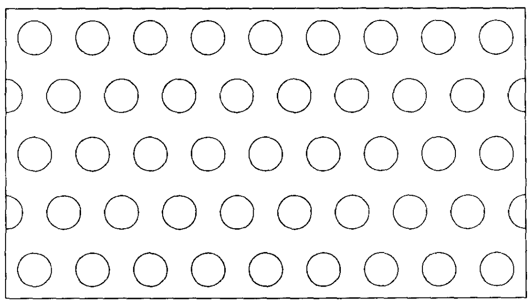
Figure 3.16: Convex bulges on a beetle skin

Table 3.4: Soil distribution of soil used by Ren et al. 1995

Size [mm]	>0.05	0.05 - 0.01	0.01 - 0.005	0.005 - 0.001	<0.001
Percentage of total soil	20.94	18.18	7.91	15.81	37.16



(a) Rectangle convex configuration



(b) Parallelogram convex configuration

Figure 3.17: Arrangement of convex shape on bulldozing plate surface.

Qaisrani *et al.* (2010)

Qaisrani et al. [21] carried out experiments to prevent adhesion on bulldozing plates and mouldboard plough by the mechanism of bionic unsmoothed surface. Qaisrani also looked at the surface morphology of beetles. The convexes, for both the bulldozing plate and the mouldboard plough, are made of Ultra High Molecular Weight Polyethylene (UHMW-PE). The plate or plough at which the convexes are glued on are made of steel 45. The diameter of the convexes is 20 mm, the height is unknown. The soil that is used for both experiments is black clay with a moisture content of 30.38%.

Bionical modified bulldozing plate experiment To compare the draft forces for a smooth and non-smoothed bulldozing surface, two different plates where made. The plates had a width of 250 mm and a length of 130 mm. An angle of 35ř to the horizon and a depth of 15 mm into the soil stayed constant for all experiments. On one plate three rows of twelve convexes are placed. The two bulldozing plates are pushed through the clay at three different velocities. In table 3.5 the drafts of the six experiments are shown. The draft with the convexes has a reduction of just over a quarter of the total draft force for all the velocities.

Table 3.5: Drafts of bionically modified and conventional plates at three working speeds (Soil moisture content of 30.38%, cutting depth of 15 mm, bulldozing angle to the horizon of 35ř)

Plate	Speed [m/s]	Draft [kN]	Relative draft
Conventional bulldozing plate	0.01	0.80	1.00
	0.02	0.85	1.00
	0.06	0.97	1.00
Bionically modified bulldozing plate using UHMW-PE convexes	0.01	0.58	0.73
	0.02	0.62	0.73
	0.06	0.69	0.71

Bionical modified mouldboard plough experiment A mouldboard plough is used to make a trench by cutting a layer of soil and move the soil up and to the side of the trench. In figure 3.18 the outline of the used plough is shown with the rows of convexes. The figure is a front view of the plough. On the underside the cutting of the soil takes place. The plough has an angle with the vertical and horizon, therefore the soil will slide up and to the left. The line with an angle of 62° is the path the soil follows over the surface.
To measure the relative draft between a smooth and non-smooth mouldboard plough, two ploughs are tested with the same dimension. On one of the ploughs rows of convexes with a diameter of 20 mm are placed. The centerline of the rows are separated by 40 mm. The average draft force is measured at a velocity of 3.6 and 5.0 km/h. The results shows a reduction of the draft by 26% at a velocity of 3.6 km/h and 30% at a velocity of 5.0 km/h.

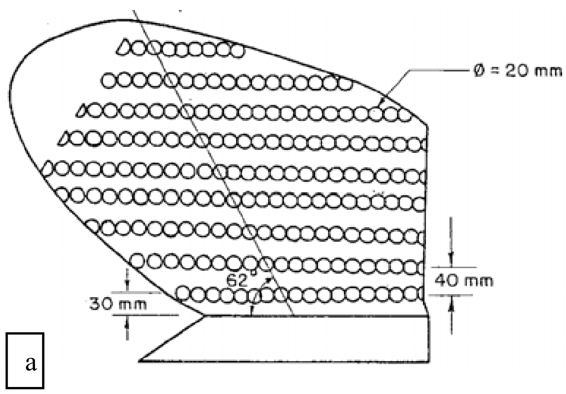


Figure 3.18: Mouldboard surface with convexes inspired by unsmoothed beetle morphology.

Table 3.6: Average draft of ploughs at two working speeds (3.6 km/h and 5 km/h)

Ploughs	Average draft [kN]		Relative draft to conventional plough	
	3.6 km/h	5.0 km/h	3.6km/h	5.0 km/h
Conventional	1.27	1.46	1.0	1.0
Bionically modified	0.95	1.02	0.74	0.70

Ridged surface HD3 plough

VBMS owns two ploughs for cable burial in clay, the Sea Stallion 4 and the Heavy Duty 3 (HD3). The Sea Stallion 4 has a smooth adhesion area. The HD3 however has a ridged surface, consisting of vertical steel strips of about 3 cm thick that are welded to the adhesion area. The strips where 10 cm wide and placed 18 cm apart. The reason why this is done is unknown. The effect of these strips is that clay builds up between the vertical strips. The effect in term of force reduction in comparison to a smooth steel adhesion area is not known.

3.5.2. Various other reduction methods

In literature, approaches to lower the adhesion force between machines and clay have been found, other then changing the geometry. In this section three approaches are discussed.

electric-osmosis

Ren 2001 [22] researched the adhesion of soils to shovels. The adhesive soils stick to the metal of loading and excavating machines, therefor the effectiveness of loading buckets was 30% less and the energy consumption up to 50 % more. To reduce the adhesion to the metal surface Ren experimented with a bionic electro-osmosis shovel (see fig. 3.19). On the shovel rows of convexes are places to create a bionic surface, similar to beetle skin. These convexes have a diameter of 30 mm and the height is 2 mm. The convexes are also used as the positive pole of an electric circuit. The electric circuit runs though the convexes, though the adhesive soil back to the metal plate surrounding the convexes. When electricity is running though this circuit electro-osmosis occurs. The result of electro-osmosis is that the moisture in the adhesive soil will flow to the metal surface of the shovel. The water that flows to the metal surface will create a lubrication layer between the metal and the clay. The result of the experiment was that the soil would not build up in the shovel after a number of cycles.

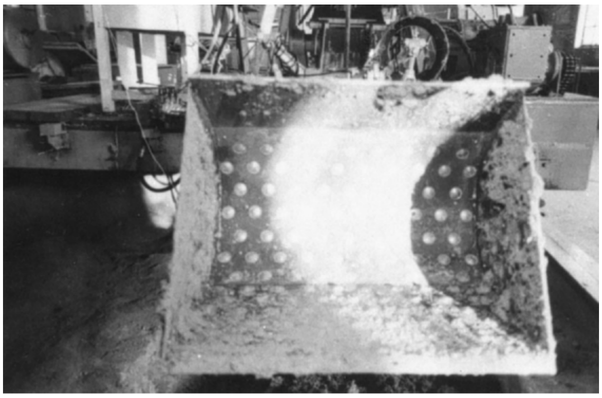


Figure 3.19: Shovel with bionic electric-osmosis surface.

Temperature

Azadegan (2012) [23] has done experiments to find the influence of temperature on adhesion of soil. Azadegan used a setup to measure the force needed to pull a metal plate of a clay surface (see fig. 3.20). To have consistent clay, dry clay particles where mixed with water. The temperature differs from 5 degrees Celsius to 30 degree Celsius with steps of 5 degrees per experiment. A fridge of oven was used to get a consistent temperature though out the clay. The result was a decrease of adhesion of 82%, when temperatures increased from 5 degree to 30 degree Celsius.

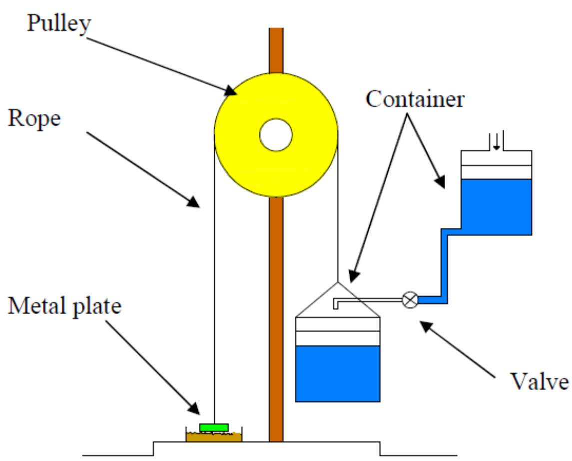


Figure 3.20: Setup for measurements used by Azadegan.

Materials

Jin Tong 1994 [4] researched the influence of different coatings on mouldboard ploughs on the pulling force. Jin Tong used thee mouldboard ploughs with coating and one conventional (d) (see fig. 3.21). The coatings used are Enamel coated (a), PES-PTFE coated (b), and iron base alloy-epoxy coated (c). The ploughs were pulled though adhesive soil and the drag of the mouldboard ploughs was measured. The drag of the PES-PTFE coated plough was 11% less then of the conventional, the Enamel coated was 8.3% less, and the iron base alloy-epoxy coated plough had 10.3% less drag.

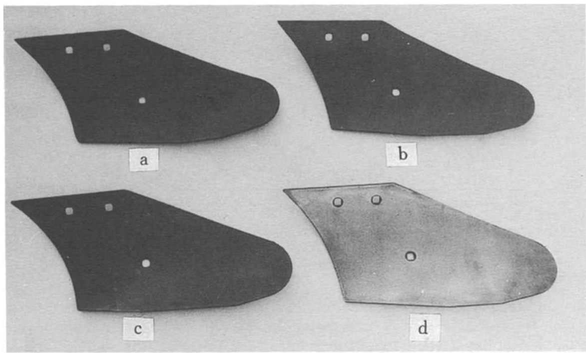


Figure 3.21: Mouldboard ploughs with different coatings.

3.6. Conclusions of literature study

Conclusions of adhesion literature

Multiple researchers, of concrete pile foundations, found that the adhesion factor would decrease with increasing undrained shear strength. Below an undrained shear strength of 25 kPa the adhesion factor would be 1. The adhesion factor will decrease to around 0.2 at a undrained shear strength of 175 kPa.

Littleton carried out experiments with a quick shearbox test with a clay shearing over a smooth steel surface. The internal friction of the clay was found to be 1% at a shearing velocity of 0.592 mm/min

Van Gurp (2014) found an adhesion factor of 0.65 using a clay with undrained shear strength of 30 kPa. Combe (2015) found an adhesion factor of 0.1 for a 12 kPa and 89 kPa undrained shear strength clay. Chen (2019) found a polynomial curve for the adhesion factor relative to the dimensionless cohesion. Combe and Chen have concluded a decrease in adhesion factor with increasing undrained shear strength of the clay.

Conclusions frontal ploughing force and velocity influence

The frontal ploughing force depends on the plough geometry and the ploughing velocity. Primo Marine made a simple equation to predict a frontal shear strength, they multiply the cohesion times 9. When multiplied by the frontal cutting surface area, a horizontal force is acquired. Van Gurp uses the N_c value multiplied by tip shape factors. The tip shape factor found for scale models of the SS4 and HD3 are both 0.6. Van Gurp then uses the frontal area and a velocity dependant undrained shear strength to predict the frontal ploughing force.

There a three formulas to predict the velocity influence on frontal pulling force. Wismer & Luth (1972) and Dayal & Allen (1975) make use of a reference velocity and a material constant. With there formula the frontal cutting force slowly increases with velocity, but when the velocity drops to zero the cutting force also drops to zero. In practice the frontal cutting force does not drop to zero. Miedema (1992) found a solution for this problem. Miedema uses a yield strength and adds a dynamic shearing resistance to it. When increasing the velocity, for all three methods, the frontal pulling force increases following a natural log function.

Conclusions literature submerged plough models

Van Gurp (2014) had the most complete model to predict the horizontal force for subsea narrow trenching operations in clay. The model includes factors for velocity, depth, tip shape, frontal area, frontal ploughing coefficient, adhesion factor, adhesion area, and also force factor for the cable and skids. Primo Marine uses a constant of 9 for the frontal ploughing coefficient to calculate the frontal pulling force needed. IHC includes a friction coefficient and weight of the plough to calculate the force on the skids. The IHC model includes a linear velocity influence of half a percent increase in ploughing force per meter per second increase in velocity.

Conclusions adhesion reduction literature

There are multiple ways to reduce the adhesion. Not all the options can be tested and can be implemented in the full scale ploughing operation. The option to test different materials is not tested in this experimental study because there are many different kinds of materials and clays. The influence of the materials can better be research with a smaller test set-up so that more experiments in a shorter time can be performed. The influence of temperature is also not going to be tested, because it will take a lot of energy and heating elements in the plough. The intention of VBMS is to keep the plough as simple as possible. Adding extra elements makes the risk higher of something to fail and therefor delays the ploughing operation. For that same reason the electric-osmosis is not going to be tested, it is a to complex system to make a water film between the plough and clay. A system of nozzles to create a water film will be tested. Nozzle systems are already used in the ploughing industry at the front of ploughs. Also the bionical modified surface, to replicate the skin of a beetle, shows great potential of reducing adhesion. Next to the water nozzle system and the bionical modified surface, the ridged surface of the HD3 plough is going to be tested in these experiments.

4

Experimental materials and methods

4.1. Experimental setup

The experiments are carried out in a setup where the ploughing condition could be set and the ploughing forces measured. The full drawings with the dimensions of the parts can be found in appendix II.

4.1.1. Overview

The setup has a couple of separate parts. The base of the setup is a water container (see fig. 4.1). The water container (2) support the topside (1) on the sides and the ends. The force that pulls the ploughs is generates by an electric motor. The electric motor is fixed to the end of the topside, in the figure the motor is coloured red. The topside is made of steel, and is designed to withstand the forces of the ploughing process. The electric motor is attached to a spindle that pulls a cart along the rails, which are also attached to the topside. The ploughs are bolted onto the cart and are thus interchangeable. To measure the forces of the ploughing procedure, three load sensors are fixed on the cart. The topside can be lifted of the water container, reviling the clay container. The clay container is hold in place by L-profiles, that are welded to the bottom of the water container. The clay container can be lifted out to replace the clay after an experiment.

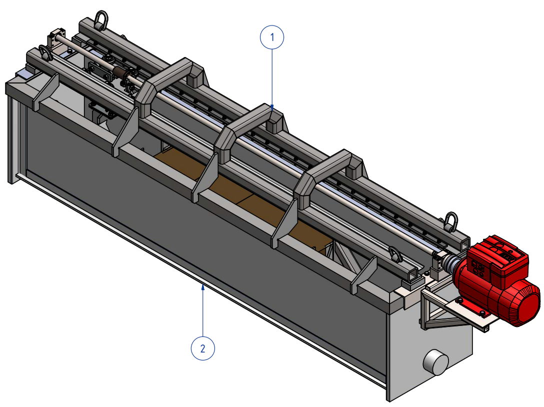


Figure 4.1: Main assembly. Height x width x length: 799 x 612 x 2987mm

4.1.2. Clay container

The purpose of the clay container (see fig. 4.2) is to hold the clay (1) in place when the plough is making a trench in the clay. The clay container is situated inside of the water container. The length of the clay string is 1016 mm and has a width of 200 mm. The maximum height of the clay is 170 mm, this can be adjusted by placing steel plates underneath the clay string. The container is hold in place by the steel L-profiles at each corner. The L-profiles are welded to the bottom of the water container.

The height of the container, and thus the depth of the trench, can be adjusted by the height of wooden blocks that support the clay container inside the water container. To be able to load and unload the clay container, one of the sides a loose plate (2). The loose side plate is hold in place by clamps (3). These four clamps are welded to the underside of the clay container and are equally spread over the length. At both ends a gap of 50 mm wide and 130 mm deep is made so the plough can pass though (6).

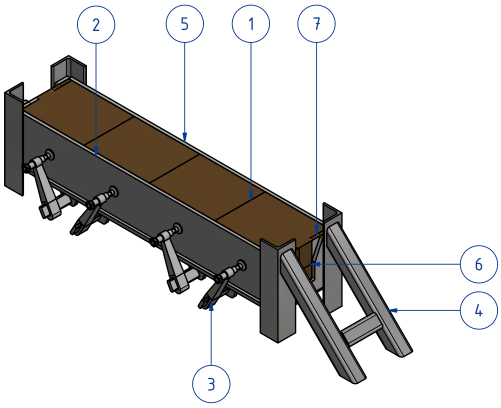


Figure 4.2: Clay container

4.1.3. Topside

The topside (see fig. 4.3) consist out of a frame where the rails, spindle and electric motor are connected to. When the topside is lifted onto the water container the rails and spindle will be above the centerline and parallel with the clay container. The electric motor has 3 MW of installed power and turns with constant speed at variable loads. The motor drives the spindle. On the spindle a ball screw converts the rotating motion of the spindle to a linear motion that drives the cart and thus the plough. The velocity of the plough could be adjusted in steps of 5 mm/s up to a maximum velocity of 500 mm/s.

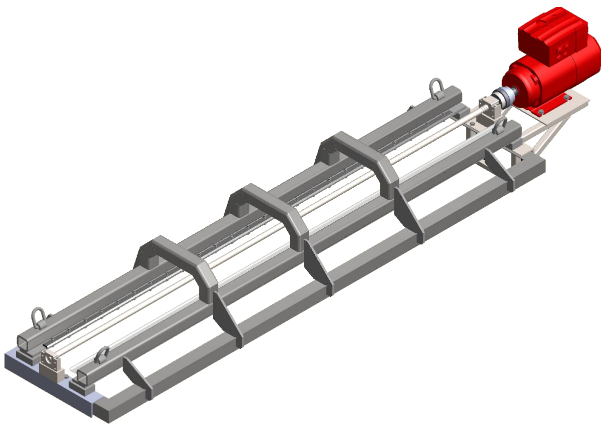
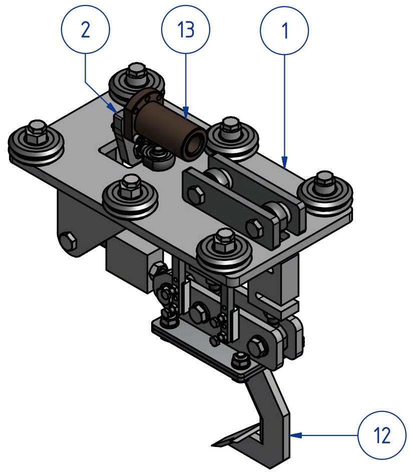


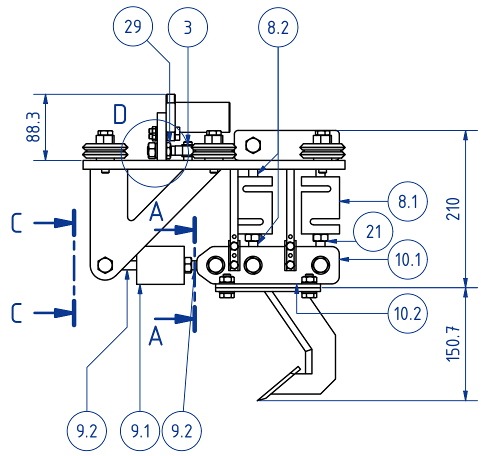
Figure 4.3: Top side including motor and spindle

4.1.4. Cart

The cart (see fig. 4.4) has the function of pulling the plough through the clay. The cart is split into two parts that are connected by the load sensors. The upper part has two rows of three wheels that roll over the rails. The wheels are attached to a base plate (2), where also the cart is pulled forward by the ball screw (13). There are three load sensors connecting the upper and lower part of the cart. All the sensors are connected on both ends with a rod end to the cart. These rod ends have spherical bearings, therefore the load sensors only transfers forces in the direction of the load sensor. One sensor is placed horizontal to measure the pulling forces (9.1). The vertical force is measure by two load sensors (8.2). With the three connections the lower part of the cart is not able to rotate in longitudinal direction. The sideways, roll and yaw movement of the lower part is restricted by pins that are attached to the upper part of the cart. There are four pins, two on each side, that prevent the lower part to move sideways without transferring horizontal or vertical forces. The lower part of the cart has an horizontal plate, with the same dimensions as the horizontal plate of the plough, where the plough (12) can be bolted on. With this design the ploughs can be easily changed and the forces on the plough are measured in horizontal and vertical direction.



(a) View of the cart from the back left



(b) Side view of the cart

Figure 4.4: Drawing of the cart

4.1.5. Sensors and calibration

To measure the forces on the plough, load cells are used (see table 4.1). The base plate, at which the plough is attached, is connected by three load cells to the upper part of the cart. A current runs trough the load cell, depending on the load the output current changes. The current is amplified and then measured. The data is send to TassVIEW, a piece of Boskalis software, which reads out the data and plots it.

Besides the load sensor, TassVIEW also reads out the distance meter. The distance meter that is used is a draw wire linear length encoder. The meter was fixed at the top side of the setup, next to the end of the spindle and the wire was attached to the cart. When the cart moved, the wire was pulled out of the encoder parallel to the spindle. TassVIEW logs the time, load cell and distance meter at a rate of 10 Hz.

Table 4.1: Sensors

Sensor location	Supplier	Type	Capacity
Horizontal load cell	AE Sensors	TS-0.5T-C2	500 kg
Vertical load cell front	AE Sensors	TS-1T-C2	1000 kg
Vertical load cell aft	AE Sensors	TS-1T-C2	-1000 kg

For the conversion of milliAmperes to forces in Newton, the load cell had to be calibrated. The calibration process consist out of two phases: the first phase is to get a linear relation from each load cells and distance meter and the second phase is to verify the three load cells under different angles by loading a plough. The result of the calibration process are linear calibration formulas for the censors (see table 4.2). These formulas are used to convert the amount of ampere from the sensor to a force or distance. Data and further information of the calibration process can be found in appendix I.

Table 4.2: Results of the first step of the calibration process, the linear relation of the sensors

Sensor location	Calibration formula
Horizontal load cell	N = 323.17 · mA - 1299.65
Vertical load cell front	N = 642.74 · mA - 2597.68
Vertical load cell aft	N = -975.29 · mA - 3821.59
Distance meter from start clay container	mm = 104.66 · mA - 560.58

4.2. Properties of the used types of clay

Three types of clay are used with increasing undrained shear strength, naming them Soft (S), Medium (M) and Hard (H) clay for distinction. Each of the clay types has been tested for composition of particle diameter and soil properties. Furthermore, test results are compared with the clay used by van Gurp (2014) (W).
In table 4.3 and figure 4.5 some of the tested properties are shown. The clay tests are performed by the Dolman laboratory, part of Boskalis Environmental. The full test reports can be found in appendix V.1. In the first column the clay type is stated. for each type of clay, the the Liquid Limit (LL), Plastic Limit (PL) and the Plasticity Index (PI) are displayed. The percentages of clay, silt and sand are measured using a sieving and hydrometer test for the clay particles. In the last column the average shear strength of each clay variety is shown.

Table 4.3: Properties of used types of clay

Clay	LL [%]	PL [%]	PI [%]	Moisture [%]	<2 μm [%]	>2, >63 μm [%]	>63 μm [%]	Shear strength [kPa]
W	57	23	34	35.0	-	-	-	30.0
S	41	16	25	27.2	62	36	2	25.0
M	36	16	20	17.2	43	29	28	80.8
H	44	15	29	19.5	43	44	13	131.0

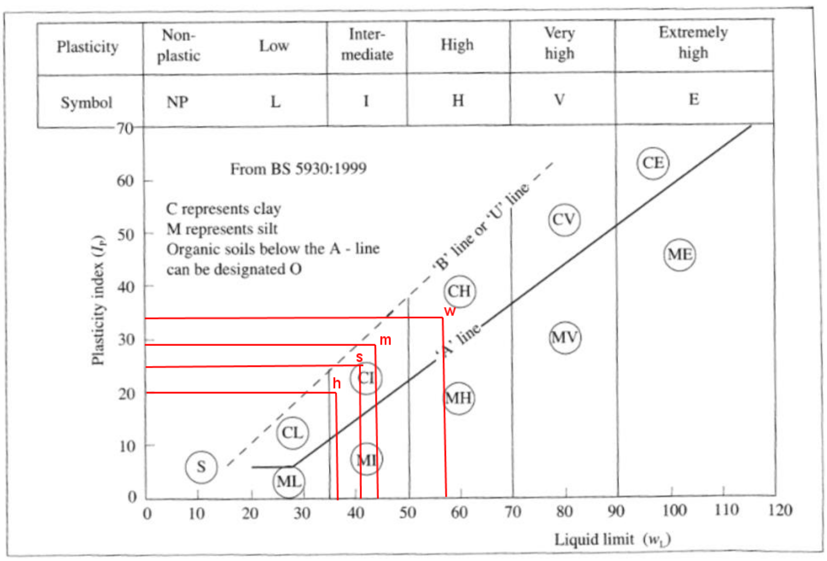


Figure 4.5: Data of the used types of clay plotted in the plasticity chart

Origin and dimensions of the soft clay

The softest clay used during this research has been bought at a wholesale for pottery clays. To prevent drying the clay was packed in plastics bags. The blocks of clay had a dimension of 300x150x150mm. Therefore the blocks had to be placed transverse into the clay container. For each experiment 8 blocks of clay are used. The depth of the clay was 140mm, due to the cutting of the top layer after clay container was filled.

Origin and dimensions of the medium clay

The medium clay is composed in a brick factory. A combination of clay, silt and sand is mixed for the purpose of making long lasting bricks. A string press forces the clay mixture out in a string of clay. A vacuum is created to extract all the air out of the clay. The mouth of the press had a dimension of 160x160 mm. The clay string was cut every 250 mm. To fill the whole clay container of the experimental setup, four blocks are needed.

Origin and dimensions of the hard clay

The hard clay also originates from a string press. In a roof tile factory a different composition of clay, silt and sand was used. The same process of mixing, pressing and vacuum was used to create a string of clay. The dimensions of the mouth of the string press are 21x14 cm. The string could be cut at a length of just over a meter. For the clay to fit in the clay container the side of the string had to be cut to 16 cm and a metal plate had to be placed underneath the clay. The metal plate was used to lift the clay up to just over the edge of the clay container, to be able to cut the top layer and create a flat surface.

Clay used by Van Gurp (2014)

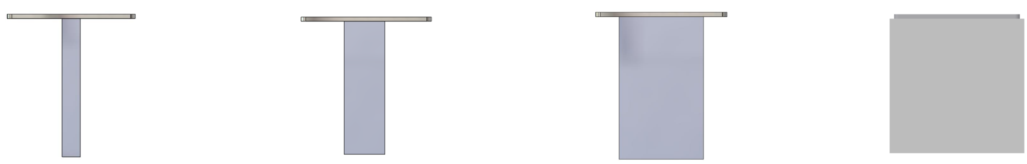
Van Gurp had used clay from a wholesale for pottery clay. The clay is sold in blocks with the dimensions of 210x160x150 mm.

4.3. Experimental ploughs used

For the experiments ploughs are made to provide information to fulfil the objectives. The adhesion factor can be determined by the adhesion area ploughs. The objective to reduce the adhesion force can be done the adhesion force reduction ploughs in comparison with a equal sized adhesion area plough. To verify the plough pulling model of Van Gurp, scale models of the SS4 and HD3 plough are used. All the plough are made from S235 steel.

4.3.1. Adhesion area ploughs

The objective of the adhesion area ploughs is to find the shearing adhesion force on the sides of the plough. This can be found when ploughs in similar conditions trench the same clay, but with a different adhesion area along the sides of the plough. During this research three ploughs with increasing adhesion area are used, namely the Small, Medium and Large ploughs (see table 4.4 and fig. 4.6). The Extra small plough was used by Van Gurp. The Ploughs are rectangular plates welded perpendicular onto a base plate that can be bolted to the cart. The plate of the plough is 10 mm thick, which is therefore also the trenching width. The depth has been set to 94 mm, because these ploughs then have the same depth over width ratio as the SS4 plough. The SS4 plough has a width of 0.35 m and a depth of 3.3 m. The length of the ploughs in longitudinal direction have increasing values, therefore increasing the adhesion area.



(a) Extra small plough (b) Small plough (c) Medium plough (d) Large plough

Figure 4.6: Adhesion area ploughs

Table 4.4: Dimensions of adhesion area ploughs

Plough	Width [mm]	Depth [mm]	Length [mm]	Adhesion area [mm^2]
Extra small (XS)	10	94	20	3960
Small (S)	10	94	44	8712
Medium (M)	10	94	90	17820
Large (L)	10	94	180	35640

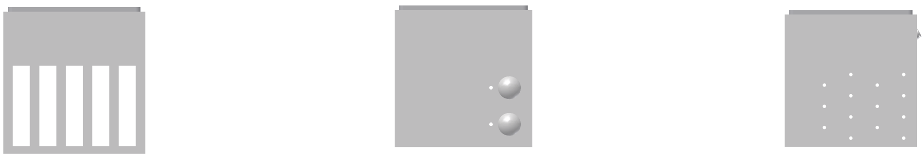
4.3.2. Adhesion force reduction ploughs

The objective of the adhesion force reduction ploughs are to find practical solutions to reduce the adhesion force that occurs on the sides of the ploughs. In this part the dimension of these ploughs are given. The outside dimensions of the three ploughs shown in figure 4.7 are the same as the large plough. The depth of the ploughs are also kept constant at 94 mm. To not interfere with the frontal cutting of the clay, the first 10 mm of the sides behind the leading edge of all the ploughs is kept unchanged in comparison with the large plough.

The ALPHA plough has five gaps, with a height of 85 mm and a length of 18 mm. The steel bars between the gaps have a length of 10 mm. The steel between the bottom and the gaps is 8 mm.

The BRAVO plough has four convexes, two on both sides. The centre of the convexes are 25 mm from the leading edge. The distance to the bottom of the plough are 25 mm and 65 mm. There are three sets of convexes made, each set with another height. The height of the convexes are 3 mm, 5 mm and 7 mm. The radius of the sphere, where the convexes are made of, are respectively 30 mm, 20 mm and 15 mm. The diameter of the convexes on the side of the plough are therefore about 26 mm, with a margin of less then 1 mm.

The CHARLIE plough has small holes, with a diameter of 4 mm, on both sides of the plough where water can flow out of. There are 4 rows of tubes that are connected by a tube on the inside of the plough. This inside tube has a diameter of 5 mm. The tube on the inside is closed at the bottom and is connected to a poly-flow tube with an inside diameter of 4 mm.



(a) ALPHA plough (b) BRAVO plough (c) CHARLIE plough

Figure 4.7: Adhesion force reduction ploughs, ploughing direction is to the right

4.3.3. Scale models SS4 & HD3 ploughs

VBMS owns two ploughs that are able to plough through clay, the Sea Stallion 4 and the Heavy Duty 3. Van Gurp has made small scale models of these ploughs (see fig. 4.8). These small scale models have the same width and depth as the adhesion area ploughs and the adhesion reduction, 10 mm by 94 mm.

(a) Sea Stallion 4 plough (b) Heavy Duty 3 plough

Figure 4.8: SS4 and HD3 scale model ploughs, ploughing direction is to the right

4.4. Scale influence

Small scale experiments are a fast and relative cheap way to carry out multiple tests. When applying the results of this report to full scale trenching operations, a couple of aspects need to be looked at.

The frontal cutting force of a full scale plough can differ from the small scale results multiplied by the increase in frontal surface. In the literature of Meyerhof (1951), the N_c value is between the 8.28 and 8.85. These values depend on the smoothness of the cutting surface. The small scale ploughs will be very smooth in comparison with the full size ploughs. The value of N_c of the full scale plough will probably be higher then the small scale experiments, in the range of up to 10%. The company of Primo Marine uses a standard value of 9 for there calculations.

The adhesion force on the sides of the plough could in theory be scaled from small scale experiments to full scale ploughs. The adhesion can be calculated by multiplying the adhesion surface area with the adhesion factor. The larger length of the contact area of the steel and clay could have effect on the adhesion factor. The clay could be disrupted even further, influencing the adhesion factor. This could be a subject for future studies.

When trenching at full scale, the depth of the trench can be up to 3.3 meter. The walls of the trench will collapse immediately after trenching when the clay is not able to hold the submerged weight of the clay. With the soft clay of 25 kPa shear strength a trench of 3.3 meters would probably collapse. At higher undrained shear strength of the medium (81 kPa) and hard clay (131 kPa) the trench would not collapse on its own.

A final issue when comparing small scale laboratory experiments with full scale ploughing are the different types of clay and sand layers. When trenching 3.3 meters deep, multiple layers of different clay strengths and possible sand layers can be stacked on top of each other. When predicting the pulling forces, a summation of the forces for each layer can be made. This method does not include the interaction between the layers. Making a model for the full scale trenching of different soil layers could be a topic for future studies.

4.5. Experimental methods

In this section the general test procedures and the test sequences are explained. For each experiment a test report is made. An overview of all the experiments can be found in appendix V. In the PDF version of this report all the test report are included. In the hard copy of the report the test reports are excluded to reduce the spillage of paper.

4.5.1. General test procedures

Preparing clay container

The blocks of clay have to put into the clay container. The hardest clay was made into strings that where the length of the clay container. For the other types of clay, the container had to be filled with multiple blocks of clay. Before the blocks where cut and put into the container, the undrained shear strength was measured with the hand vane. Based on three test the blocks are lined up in the ploughing direction from softest to hardest. Although the differences is strength are not significant, it will prevent that harder clay will be pushed against slightly softer clay.

The clay blocks are cut to length by a steel wire. The hardest block of the series is placed at the end of the clay container first. There after the second hardest block is pushed against the first block to decrease the gap between the blocks. After all the blocks are in place side of the clay container is installed and the clams are tightened. The last step is to cut the top of all the blocks by a steel wire to the height of the clay container.

Installation before an experiment

First the prepared clay container is lowered into the empty water container, between the four L-profiles. Wooden blocks on the bottom of the water container will determine the height of the clay container relative to the plough. When the clay container is in place a measuring tape is installed along the side of the container, to see the distance on the video.

The undrained shear strength measurements are taken when the top of the clay is cut and is installed in the water container. This gives the most reliable measurement. There are two devices with which the measurements are taken. The hand vane is used along the whole clay strip, because the hand vane only reaches a depth of about 5 mm. When this measurement takes place at the edges of the clay strip, this will not effect the ploughing process. The other device is the field vane, this vane reaches a depth of 80 mm. Because this depth will influence the ploughing process, only four measurements are taken from the first block at the start of the clay strip.

The plough used in the experiment is bolted underneath the cart and is railed to the starting position. Then the top side is lowered onto the water container. Two video cameras are installed on the cart. The final step before the experiment is to fill the water container with tap water. The water container is filled till the horizontal sensor is reached. This results in 69 mm of water on top of the clay when ploughed at a depth of 94 mm.

Running an experiment

When the water container is filled a couple steps has to be carried out to run the experiment. First the velocity of the spindle is set by the frequency controller of the electric motor. Next the data logging software, TassVIEW, has to be started. Thereafter the recording with the video cameras is started. The final step is to witch on the motor and let the plough make a trench.
After the trench is made, the water is drained and the topside with plough is hoisted of the water container. The shear strength measurements are repeated and picture of the clay are taken. The final step is to gather the raw data of the experiments and make a test report.

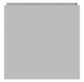
Reporting of the experiment

For each experiment a test report is made with the essential information. On page 44 and 45 the first two pages of test report number 12 are shown. The third and last page contains photo's of the plough and clay, during and after the test. All of the test reports can be found in the PDF version of this report.

TEST REPORT 12

General information

Test number:	12	Length of clay box:	1015 mm
Date of test:	11-11-2016	Water on top of clay:	69 mm
Time of test:	15:00	Depth of the plough:	94 mm
Test profile:	L	Set motor velocity:	-6 [-]
		Clay type:	Hard



General information about the test. Date and test profile that is used. Length of the clay box is the distance from start to end of trench. When the clay was submerged during testing the water depth was 69 mm. The trenching depth is the depth from the surface of the untrenched clay to the depth the plough was set to trench. The velocity could be adjusted by the setting of the electric motor. Finally the clay type is mentioned.

Particular during test

Particulars of the clay block:
0

Particular events during the test:
0

In this part of the test report particulars of the test are mentioned. This can be deviations of the clay or non normal events during testing.

Material properties of the clay

	Before	After	
Average shear strength:	114,5	116,3	kPa
Average residual shear strength:	63,0	55,7	kPa

Field vane clay strength tests

	Before		After	
	Shear	Residual	Shear	Residual
Left 1	102	48	106	62
Left 2	108	84	109	62
Left 3	No test	No test	107	56
Right 1	122	50	128	50
Right 2	126	70	123	50
Right 3	No test	No test	125	54

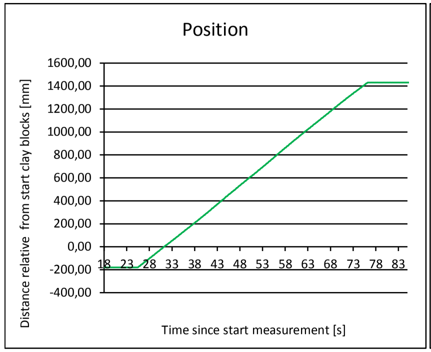
The undrained shear strength test results are summarized here. Tests have been done before the clay was submerged and after the test was carried out. Strength test where performed on the left and right side of the trench. The average of all the field vane tests before the test determined the clay strength of that particular test.

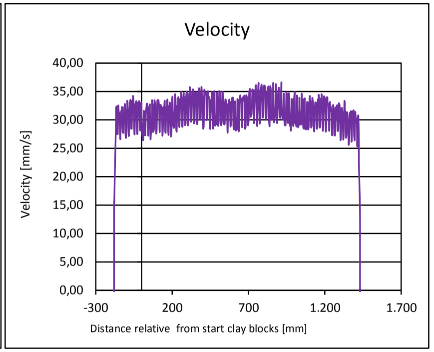
Averages in measuring length

Start measuring length	351,4	mm
End measurement length	971,5	mm
Total length	620,1	mm
Average speed	32,7	mm/s
Average speed	117,9	m/h
Horizontal load cell	3537,2	N
Total Vertical load	-112,7	N
Total force	3539,0	N
Angle of total force	-1,8	Degree

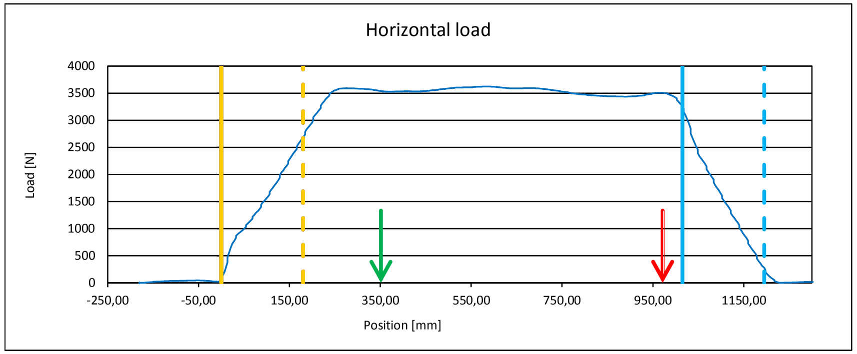
The average of the forces is measured between a start end point. These points are determined by eye within an area where the forces are relative constant. Within this measurement length the average velocity, horizontal and vertical force are calculated. A positive vertical force means the plough wants to dig into the clay, with a negative force the plough tends to push itself out of the clay. The total

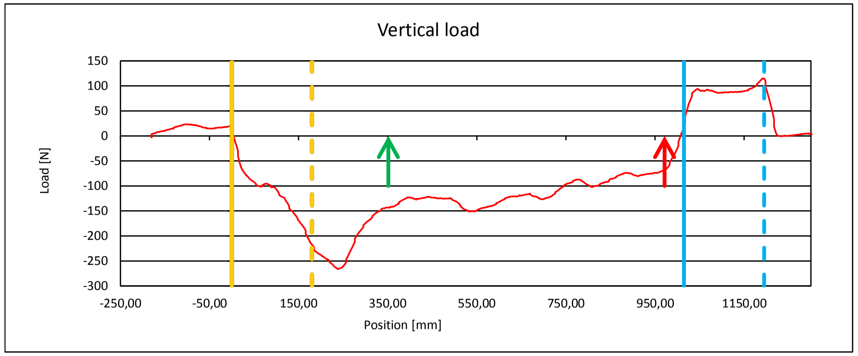
Measured results





Left the position in time is logged by the distance sensor. From this data the velocity can by calculated, seen in the graph on the right side. The high frequency fluctuations are produced by the sensor, the low frequency fluctuations are a result of the electric motor frequency controller. The controller manages a fairly constant speed for increasing loads.





The graph at the top displays the horizontal force measured in Newton, the bottom graph displays the summation of the 2 vertical sensors. Positive values are pulling forces. The plough exercising an pressure force in vertical direction, forcing the plough upward if not constrained. The position on the plough is relative to the distance of the leading edge of the plough and the start of the clay block(s).

The continuous vertical yellow line is the point where the leading edge first makes contact with the clay. The blue line is where the plough leading edge exits the clay. The dashed yellow line is where the trailing edge of the plough enters the clay. The blue dashed line is where the trailing edge exits the clay. When there are multiple clay blocks, multiple continous lines with matching dashed lines indicate the entry and exit points of the plough.

The average values on the first sheet are measured between the green and red vertical arrows. The start and end distance is chosen to have the larged distance with relative constant values.

4.5.2. Ploughing forces experiments

The goal of these experiments are to determine the adhesion factor and the frontal cutting forces for different types of clay. The horizontal pulling force is measured, this force includes the frontal cutting force and the adhesion force at the sides of the plough which are in contact with the clay.

To separate these two forces, multiple test per clay type needs to be run. The test sequence and the test numbers can be found in table 4.5. There are three small scale ploughs made with the same frontal area, but each plough is elongated to increase the adhesion area along the side. These three ploughs are pulled through the clay at the same velocity and depth. Those three test are repeated for each type of clay. For each clay type there will be three data points that can be extrapolated to find a relation between increasing adhesion surface and pulling force.

Because clay has a lot of variables, there could be a large measurement error between the different samples of each type of clay. Therefor one test must be completely duplicated to find out if the measurement error is reasonable.

Table 4.5: Test sequence ploughing forces

Clay type	Plough	Small	Medium	large
Hard		Test 14	Test 13	Test 12 and 18
Medium		Test 28	Test 3	Test 24
Soft		Test 9	Test 8	Test 6

The frontal ploughing force coefficient, N_c, can be calculated with the data of the experiments. The N_c is a dimensionless fraction of the frontal cutting force, divided by the cohesion of the clay type multiplied by the frontal area of the plough (see eq. 4.1). In the theoretical literature of Meyerhof (1951), the N_c value is between 8.28 for smooth and 8.85 for rough foundation piles.

$$N_c = \frac{F_{cutting}}{c * A_{front}} \tag{4.1}$$

4.5.3. Velocity influence experiments

To determine the velocity influence, during this experimental study, the velocity of the plough is adjusted. The experiments are mostly run at motor setting 6, resulting in a average velocity of 31 mm/s. One experiment with a slower velocity and one with a higher velocity are performed. The slower experiment was done with a motor setting of 3, resulting in a velocity of 17.6 mm/s. The higher velocity test was done at motor setting 24, resulting in a velocity of 123.7 mm/s. With the measured pulling forces at different velocities, the constant material properties of the three formulas described in the literature can be calculated. The results can be compared with the result of the 30 kPa undrained shear strength of Van Gurp (2014). Because there was a limited amount of clay and time, only the hard clay type was used in the velocity influence experiments.

4.5.4. Pulling force verification experiments of the SS4 and HD3 models

The goal of these experiments are to test if the model of Van Gurp (2014) is accurate for the Sea Stallion 4 and heavy Duty 3 small scale models in harder clay then the 30 kPa clay Van Gurp used. The experiments are tested with the medium and hard clay of 80.8 and 131.0 kPa undrained shear strength respectively. The same velocity, depth and frontal area are used as Van Gurp used in his experiments. The frontal ploughing force coefficient (N_c) and adhesion factor α_a are taken from earlier experiments from this report. The forces of the cable and skids do not apply for this small scale experiments. The results of the model of Van Gurp (2014) with the newly found parameters is compared with the pulling force of the small scale experiments.

4.5.5. Adhesion force reduction experiments

The goal is to investigate possibilities to reduce the adhesion force during ploughing. This force can be up to 70% of the total pulling force while making a trench in clay. For these experiments there are three ploughs made with differences in adhesion area, but have the same dimensions as the large plough of the adhesion experiments (see fig. 4.7 earlier in this chapter). In table 4.6 an overview of the adhesion reduction test numbers can be found. The full list of test report numbers can be found in appendix V.

The Alpha plough is made to simulate the HD3 plough (see fig. 4.7a). The cutouts of the Alpha plough are filled with clay before the experiment. This will simulate the vertical metal strips of the HD3 plough. Because there was a limited amount of medium clay, the Alpha plough is only used in soft and hard clay (see table 4.5). To see if the gaps of the plough are filled during ploughing and to know what the influence is of the gaps are, an extra test in the hard clay is done. In the hard clay, two scenarios are tested, one where the gaps of the plough are filled with clay and one where the gaps are left empty.

The Bravo plough is made to simulate the non-smooth surface of beetles (see fig. 4.7b). On both side two convexes are mounded. There are three different sets of convex shapes with heights of 3, 5 and 7 mm. The diameter of the convex disk is for all the three height is same. The convex shape with a height of 5 mm is used in all of the three different types of clay. Because there was a limited amount of medium and soft clay, the convex shapes with height of 3 and 7 mm are only used in the hardest clay. After all the planned tests where carried out, there was still hard clay left. Therefor an extra experiment could be carried out. In this experiment the convex shapes are replaced with 2mm thick and 10mm width metal strips running vertically. The hypothesis is that the strips will widen the trench so the sides of the plough do not come in contact with the clay. The test number of this test is 36.

The Charlie plough is made to experiment with lubrication of water from the adhesion area (see fig. 4.7c). Within the plough there are four vertical holes that each lead to a column of holes in the side of the plough. The bottom of the holes is welded shut, so the water that is pumped from the top of the plough can only escape form the holes in the side of the plough. A water pump is used to pressurise the water. The water flow of the pump can be connected to one of the columns or can be split to multiple columns. To measure the influence of water pressure and water flow though one or more columns multiple test in the hard clay are performed. Also one test in the soft clay, to measure the difference in adhesion force with the other adhesion reduction ploughs.

Table 4.6: Test sequence ploughing forces

Clay type Plough	Alpha	Bravo 3mm	Bravo 5mm	Bravo 7mm	Charlie
Hard	Test 16 and 38	Test 17 and 22	Test 15	Test 23	Test 25,30 and 35
Medium			Test 29		
Soft	Test 10		Test 11		Test 33

5
Results

5.1. Results adhesion factor

The results of the pulling force versus adhesion area tests are shown in graph 5.1. In the graph there are four lines. Each line represents a type of clay. The lines are extrapolated from data points collected from the tests with extra small,small, medium, and large adhesion area. The line with yellow points is data from Van Gurp (2014). The frontal cutting force is can be found at the point where the lines cross the Y-axis. The force per adhesion area is determined by the gradient of the line.

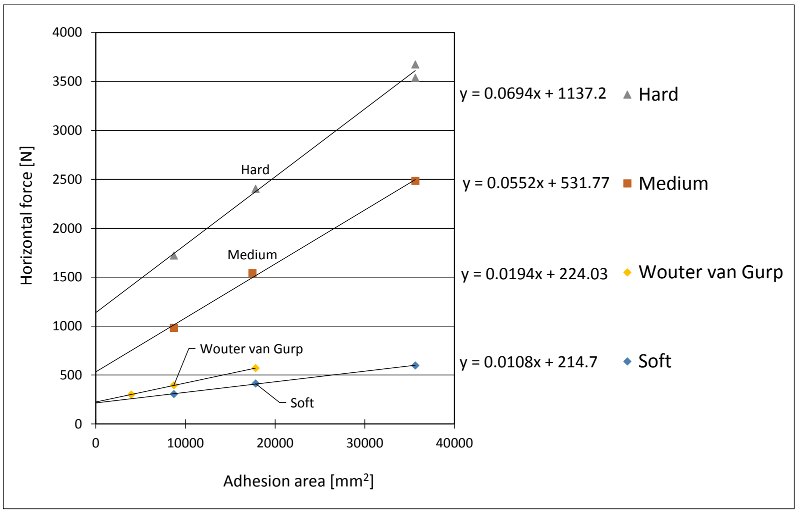


Figure 5.1: Adhesion area influence on horizontal pulling force

In table 5.1 the scaled cutting force and the adhesion factor are calculated. The cutting force is scaled to an undrained shear strength of 30 kPa. Van Gurp stated that when cutting at the same rate, the cutting force is constant when scaled to the same undrained shear strength. The scaled cutting force of the medium and hard clay types are nearly the same as the 224.0 kPa that Van Gurp measured. This confirms that the cutting force can be scaled linear with undrained shear strength up to a undrained shear strength of clay of 131 kPa.

The three adhesion factors gathered in this research and the one of Van Gurp, are placed in graph 5.2. In this graph, also results of previous research [7] are shown, mostly of foundation pile driving research. The adhesion factor for the medium and hard clay follow the path of the research of Peck. The soft clay has a adhesion factor much lower then predicted by previous adhesion research of foundation piles. This research and that of Van Gurp has been done with higher velocities then the pile driving experiments. With higher velocities the adhesion factor is slightly increased.

Clay type (kPa)	Cutting force (N)	Adhesion force (kPa)	Scaled cutting force (30 kPa)	Adhesion/cohesion
Hard (131.0)	1137.2	69.4	219.0	0.53
Medium (80.8)	531.77	55.2	222.1	0.68
Soft (25.0)	214.7	10.8	280.9	0.43

Table 5.1: Adhesion/cohesion

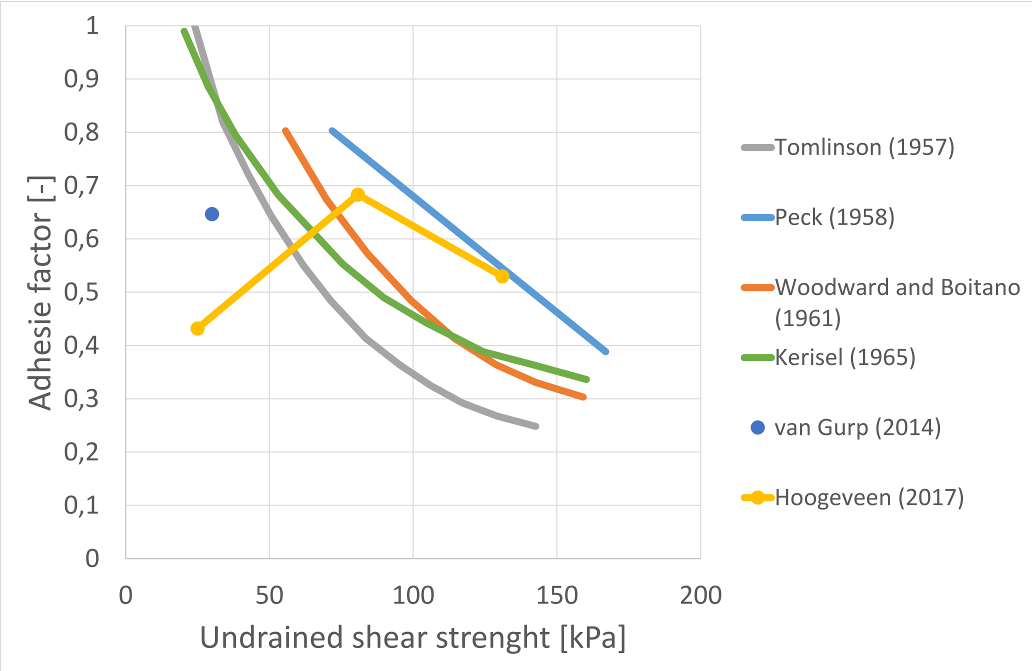


Figure 5.2: Adhesion factors comparred

5.2. Results frontal ploughing force coefficient

In table 5.2 the results of the experiments are shown, including the results of the experiment of Van Gurp (2014). The frontal area of all these experiments was 940 mm^2, 10 mm plough width by 94 mm depth. The N_c value of the soft clay type stands out with a value of 9.961, the other clay types have a value of just below 8. The manufacturer of the soft clay has made the clay smoother then that used by Van Gurp. This could explain the high N_c value.

Table 5.2: Frontal cutting force and N_c value of clay types

Clay Type	USS (kPa)	Cutting force (kPa)	N_c
Van Gurp	30.0	224.0	7.943
Soft	25.0	214.7	9.961
Medium	80.8	531.8	7.876
Hard	131.0	1137.2	7.766

From the N_c value calculation from the experiments a couple conclusions can be made. First, a N_c value assumption of eight, which is used in practice, is a close assumption. Second, the N_c value decreases a bit in value. The value of N_c is decreasing with increasing clay strength, except for the soft clay type. This decrease in N_c value with higher cohesion values could be caused by the fact that upper failure zone has a bigger volume with higher cohesion. The upper failure zone fails under lower pulling force in comparison with the lower failure zone

5.3. Results of velocity influence experiments

The three velocity tests in the hard clay had the following velocity and pulling force; the slowest test had a velocity of 17.6 m/s and had a pulling force of 3289 N, the average velocity test a velocity of 32.7 mm/s and a pulling force of 3537 N, the highest velocity test had a velocity of 123.7 mm/s and a pulling force of 4123 N. With those numbers the constant material properties of the three researches from literature can be calculated. The results are shown in table 5.3. In figure 5.3 the three measured values are shown with black squares. The point of the three formulas, with the calculated constants, are also shown. The prediction of horizontal pulling force by Miedema (1992) is not going to zero when the velocity is zero, while the other two are.

Table 5.3: Strain rate

	Wismer & Luth	Dayal & Allen	Miedema	
	m	λ	Su_y	Su_0
Van Gurp (2014), medium plough	0.12	0.32	368	110
Hard clay, large plough	0.116	0.30	2970	739

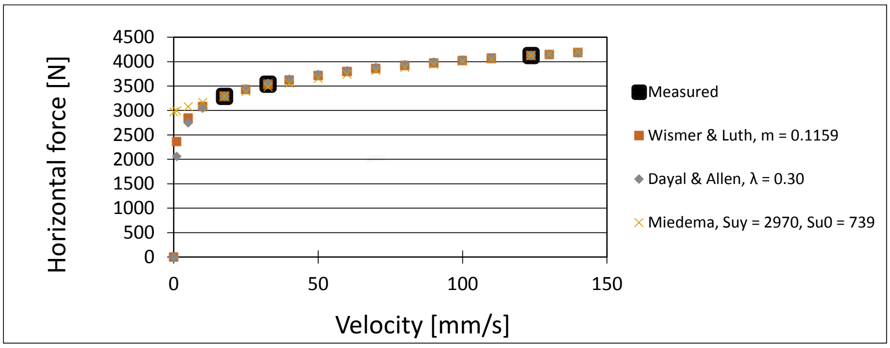


Figure 5.3: Three prediction models for the velocity influence on horizontal pulling force from small scale experiment measurements

The results of this experiment can be used to make velocity and pulling force predictions for future trenching operations. The two results of the 30 kPa clay used by Van Gurp and the hard 131 kPa clay show that the the material properties of Wismer & Luth (1972) and Dayal & Allen (1975) are relative constant. With those two formulas the relation between velocity and pulling force can be fairly accurate predicted for trenching though clay.

5.4. Results of SS4 and HD3 scale model experiments

The results of two experiments of Van Gurp (2014) and four of this experimental study are shown in figure 5.4. The horizontal force needed to pull the plough through the clay soils is shown for the predicted force in blue and the measured forces by the small scale experiments in orange. The results of Van Gurp his prediction and measurement for the SS4 is really close, the prediction of the horizontal force on the HD3 is a bit lower but still within the 10% deviation. The experiments of the SS4 and HD3 ploughs in the medium clay (M) are both over predicted. The measured force of the SS4 in medium clay is 7% lower then predicted and the HD3 3%. In contradiction with the medium clay, in the hard clay (H) the measured forces are higher then predicted. For the SS4 the measured forces are only 2% higher then predicted, but for the HD3 plough the measured forces exceeds the prediction by 11%. This is a significant under estimation of the pulling force.

The narrow plough model of Van Gurp did estimate the horizontal ploughing force of the SS4 and HD3 scale models in three different clay types within a 10% margin, except for the HD3 plough in the hardest clay. The experiments are executed in similar conditions except for the clay. Therefor in the model the N_c and α_a of the clay types are used. The other parameters (velocity, depth, tip shape, frontal and adhesion area) are held constant in these six experiments. These parameters are calculated with the result of experiment in the soft clay used by Van Gurp. The question was if these parameters could be used in harder clay types. Because the predictions by the model fit the measured results within

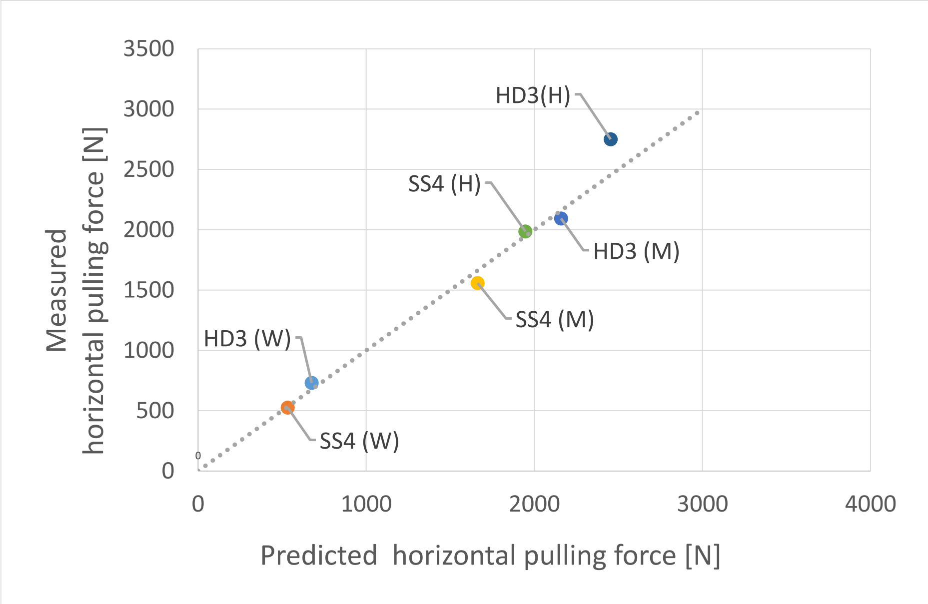


Figure 5.4: Comparison between predicted and measured force of the small scale SS4 and HD3 plough. (W) is clay of 30kPa, (M) is clay of 80.0 kPa, (H) is clay of 131 kPa undrained shear strength

10%, except the HD3 in hard clay, the parameters that stayed constant are likely to be constant for clay strengths up to 130 kPa undrained shear strength. The N_c value found by experiments of the three clay types are all just below eight. So eight is a good estimation of the N_c, to be on the save side the value of nine used by Primo Marine can be used. The α_a found with the Small, Medium, and Large ploughs resulted in a good estimation of the SS4 and HD3 ploughs. The adhesion contributes to a large part of the total pulling force, which can be seen by the greater forces needed by the HD3 then the SS4 that has a significant smaller adhesion area.

5.5. Results adhesion reduction ploughs

The adhesion force in soft clay is shown in graph 5.5. The blue bar, with an adhesion force of 384.9 N, is the pulling force minus the frontal cutting force of the Large plough (see fig. 5.1). The three adhesion reduction ploughs have the same adhesion area and frontal cutting force as the Large plough. In this graph the frontal cutting force is also deducted from the pulling force of the three adhesion reduction ploughs. With a reduction of almost 70% (117.8 N) adhesion force, the Charlie plough has the best results. The water pressure used in the Charlie plough experiment was 4 bar and only the first 2 vertical columns where opened. Also the Alpha and Bravo plough had a significant reduction of 52% and 39% respectively.

The adhesion force in hard clay is shown in graph 5.6. The adhesion force of the Large plough in hard clay is 2473.4 N. The Alpha plough, with vertical gaps, has a reduction of 52% when the gaps are filled with clay and 58% when the gaps where left empty. The Bravo plough was used with three different convex heights, the 3 mm had the best result with an adhesion reduction of 66%. The yellow bars are the result of the Charlie plough with water nozzles at the adhesion area. Three tests where performed, with a four or five bar water pressure at the pump and one or two vertical tubes connected to the pump. The test where only one vertical tube was connected to the water pump, the adhesion reduction was the lowest. An increase in water pressure with two tubes open had an small reduction of adhesion. The highest reduction of adhesion with the Charlie plough was 63%. A final test with the Bravo plough was performed with a 2 mm thick vertical metal strip was placed at each side of the plough, instead of 2 convex shapes at each side. This resulted in the lowest adhesion force of 532.8 N, an adhesion reduction of 78%.

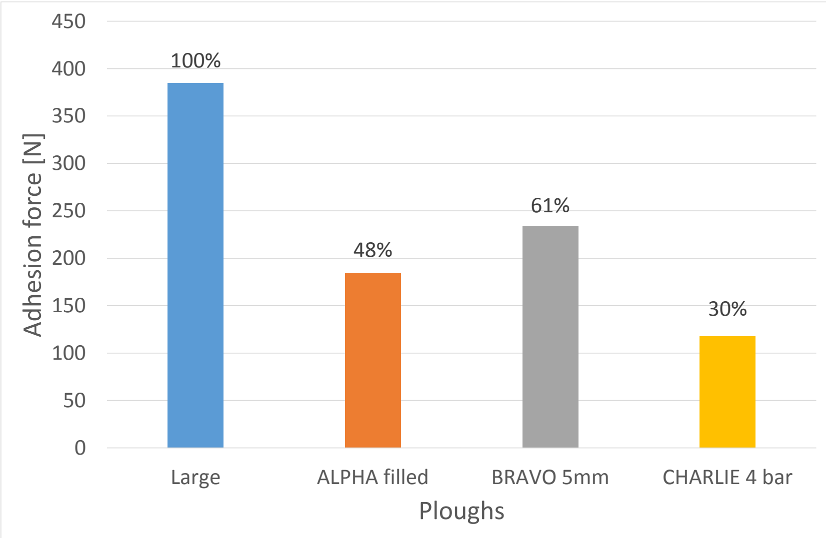


Figure 5.5: Reduction of the adhesion force of the reduction ploughs in soft clays

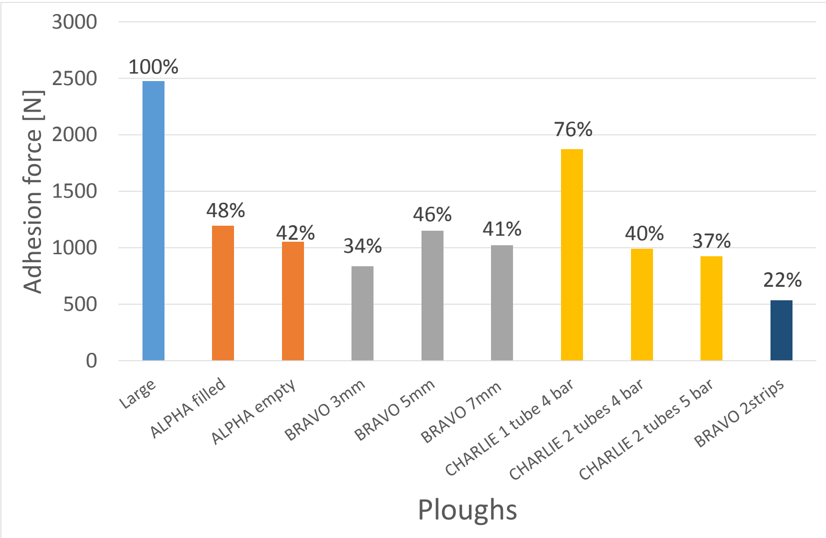


Figure 5.6: Reduction of the adhesion force of the reduction ploughs in soft clays

5.5.1. Results ALPHA plough

The Alpha plough (see fig. 5.7) had a reduction of 52% in both the soft and hard clay. With the vertical gaps empty in the hard clay the pulling force was reduced a bit more. This reduction is probably because there was no clay to clay friction. Therefore, the pulling force probably is a combination of adhesion at the metal surface an residual cohesive friction. At all the tests it could be observed that the gaps of the plough scraped the sides of the trench, this will cause an extra force when trenching.

5.5.2. Results BRAVO plough

The Bravo plough with 5 mm convex shape height (see fig. 5.8) had been tested in all three different clay types. In the soft clay the adhesion reduction in comparison with the Large plough is 39%, in the medium clay 72% and in the hard clay 54%. In each clay type the convexes created a gap between the clay and the plough surface behind the convex. These gaps did not collapse during or after ploughing. The extra force that is needed for the convexes to push the clay aside is in all cases smaller then the reduction of adhesion. As a final experiment two vertical metal strips of 2 mm were placed where the convexes normally are placed (see fig. 5.9). This experiment resulted in the lowest adhesion force of all experiments. During trenching, one side of the plough did not touch the clay at all and the other side just slightly. Because the plough barely touched the clay this resulted in a great reduction of the pulling force.

5.5.3. Results CHARLIE plough

The Charlie plough (see fig. 5.10) has the largest reduction in pulling force in the soft clay. In the hardest clay type the reduction is also significant but was not the largest of the used plough types. The large reduction of adhesion could be explained by the type of clay that is used. The clay that is used is sold as pottery clay and one of the characteristics is that the clay must not adhere to skin when the clay is wet. It could be that clay with higher undrained shear strength will have a smaller reduction of adhesion when using water to lubricate the surface.

summarising adhesion reduction methods

All three methods reduced the pulling force with a significant amount, both in the soft clay as well as the hard clay. In the soft clay the water lubricated Charlie plough had the best result, followed by the ridged surface of the Alpha plough and the convexes of the Bravo plough had the least reduction of the three. There was more clay available of the hard type, therefor more experiment where done in comparison with the soft clay. Again all three methods had a significant adhesion reduction. In the hard clay the Bravo plough and the Charlie plough had the best result of the three ploughs. The absolute best result was made with the 2mm strips on both sides of the Bravo plough. Widening the trench so the sides of the plough barely make contact with the clay is a plausible method to reduce the adhesion force. When using the convex shapes on the Bravo plough, the height of the convex shapes make a difference in pulling forces. The smallest convexes (3 mm) had the best result, but with the result of the medium (5 mm) and the highest (7 mm) there is no trend found. There could be a trend found with the Charlie plough: the more water is pressured through the nozzles the less adhesion there is. When the amount of nozzles was increased and when the pressure was increased the adhesion was reduced.

Figure 5.7: Side of the Alpha Plough after test

Figure 5.8: Side of the Bravo Plough after test

Figure 5.9: Side of the Bravo Plough with 2mm strips after test

Figure 5.10: Side of the Charlie Plough after test

6
Conclusions

The goals of this research can be split into two parts. The first part is to increase the knowledge and therefore the accuracy of estimating the pulling force of a narrow subsea plough in clay soils. The second part is to investigate ways to reduce the adhesion of the plough, because the adhesion force is a large part of the total pulling force. Therefore, this conclusion is divided into two sections.

6.1. Estimating pulling forces

For subsea ploughing with narrow ploughs in clay, the most extensive model to estimate the pulling force is made by Van Gurp (2014). The equation to calculate the horizontal pulling force consist out of multiple parameters (see eq. 6.1). Van Gurp used experiments in 30 kPa undrained shear strength clay to gather the input of the parameters. In this study, the objective is to research if the pulling force can be estimated by the undrained shear strength of the clay soil. The forces of the cable and skids during ploughing operations are not part of this research.

$$F_h = S_u(v) \cdot \alpha_{depth}(d) \cdot (\alpha_{tip} \cdot b \cdot d \cdot N_c + \alpha_a \cdot A_{adh}) + F_{cable} + F_{skids} \tag{6.1}$$

The clay strength influences the parameters of the model. The three most relevant parameters have been measured with isolated experiments with three different clay types. The three parameters are: the adhesion factor α_a, the frontal ploughing coefficient N_c, and the shear strength dependent of velocity ($S_u(v)$).

The adhesion factor is variable with undrained shear strength. Multiple researches of pile driving have made predictions of adhesion versus undrained shear strength (see fig. 5.2). The results of this experimental study show that with the softest clay of around 30 kPa the adhesion factor is lower then other researches predict. With higher strength clays, of 80 and 131 kPa, the adhesion factor is higher then most researches predict. The lower adhesion factor for softer clay could be explained by the fact that the clay is disturbed during the cutting at the front of the plough. When the clay is disturbed the residual shear strength and thus the adhesion is lower than when the clay is undisturbed. During ploughing operations in softer clay the adhesion factor will be lower than the undrained shear strength of the clay.

The frontal ploughing force coefficient N_c should be relatively constant for all clay types, between eighth and nine. For the softest type of clay, the N_c value was higher then expected, with a value of ten. The medium and hard clay had a N_c value of just lower then eight.

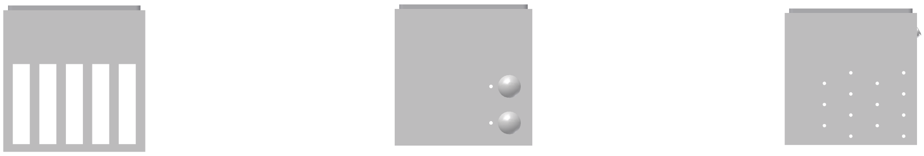
The velocity influence ($S_u(v)$) in the model of Van Gurp (2014) is predicted by the logarithmic model of Dayal & Allan (see eq. 3.18). The material property constant found by Van Gurp is 0.32. The experiments in this study with 131 kPa clay resulted in a value of 0.30.

With the new (α_a) and confirmed (N_c and $S_u(v)$) parameters the plough pulling model is verified with small scale test of the SS4 and HD3 ploughs in the medium and hard clay. In the medium clay, the predicted value of the SS4 is 7% higher then measured and for the HD3 3% higher then measured. In the hard clay, the SS4 prediction is 2% lower then measured and for the HD3 12% lower then measured. Three out of the four test are within a 10% range, one test did underestimate the measured forces with a significant amount of 12%.

Overall, with the new data a step has been made to improve the understanding of the process of ploughing a narrow trench in subsea clay.

6.2. Reducing adhesion forces

In clay, the adhesion force contributes for a large part to the pulling force needed to trench. Three different methods are researched to reduce the clay to metal adhesion (see fig. 6.1).



(a) ALPHA plough (b) BRAVO plough (c) CHARLIE plough

Figure 6.1: Adhesion force reduction ploughs, ploughing direction is to the right

The Alpha plough uses the method of vertical gaps where clay builds up, in order to create a sheared clay to clay surface. In the soft clay, a reduction of 52% is achieved, the same amount of reduction as in the hard clay.

The Bravo plough uses the methods of a non-smooth surface, which consist of convex shapes that pushes the clay off the metal adhesion surface. In the soft clay, a reduction of 39% was achieved, in the medium clay a reduction of 72%, and in the hard clay 54%. These results are obtained with a convex shape with a height of 5mm from the surface. In the hard clay experiments with 3mm and 7mm convex height have been executed, resulting in reduction of adhesion force of 66 and 59% respectively. The absolute best result in hard clay was made with the 2mm strips on both sides of the Bravo plough. Widening the trench so the sides of the plough barely make contact with the clay is a plausible method to reduce the adhesion force.

The Charlie plough uses the method of lubrication with water to reduce the adhesion force. In the soft clay, a reduction of adhesion force of 69% is achieved. This is the highest percentage of the three methods in soft clay. In the hard clay, a reduction of 63% is achieved. The water pressure and amount of nozzles has influence on the reduction of adhesion force. Higher pressure and more nozzles result in less adhesion.

These experiments show that with practical solutions, the adhesion forces can be reduced by a large amount in comparison to a flat metal surface.

7 Recommendations

This final chapter of the report is split into three parts. The first part are recommendations for the materials and methods used during the experiments. The second part covers thoughts about how to improve the accuracy of predicting the ploughing forces. The last part gives recommendations on how to make steps in decreasing the adhesion forces.

7.1. Experimental set-up

- The clay and water container have a limited size. The small scale models that are used are the maximum depth and width, without enduring boundary effects. Larger scale experiments will give more accurate results but cannot be executed in this experimental setup. A larger set-up is recommended, if more accurate results are desired or larger scale ploughs need to be tested.
- The clay that consisted out of one piece gave the most consistent pulling force. For better results and easier handling, use clay out of one piece.
- The clay that is used during this experimental study was made in factories. This was done too get constant results. The clay on the seabed in a product of nature and will not be constant. A step to increase the prediction of cutting and adhesion forces is to gain knowledge over type of clay and the inconsistencies of the clay on the seabed.
- On two occasions, the plough would deflect from the straight line path and run into the end-plate next to the exit-gap where it should run though. Optimising the directional stability can be beneficial to reduce the chance of breaking parts of the set-up.

7.2. Estimating pulling force

- Gather pulling force data of the full scale ploughs and the soil during trenching operation at sea. Compare the results with predictions made by the plough pulling force model including the parameters found by experiments.
- A next step is to find the relation of pulling force and clay soils mixed with layers of sand. The experimental set-up of this study, would be too small to simulate the effects of sand and clay layers during ploughing.
- Better predictions can be made with more clay data. The adhesion factor cannot be predicted by the undrained shear strength with a one-on-one relationship. The adhesion, and thus shear strength, is dependent on clay condition and composition; plough geometric and velocity; adhesion surface material; and probably more unknown factors. A database with clay composition, undrained shear strength and adhesion factor will increase the knowledge and accuracy of the plough pulling force model, and possible other disciplines where clay has to be moved.
- The velocity influence on the horizontal pulling force is tested with the adhesion and frontal forces combined. A possibility is that one of the two is influenced more by increasing or decreasing

velocity then the other. To know the velocity influence of each of the two force, separate tests have to be performed.

7.3. Reducing adhesion force

- These experiments show a lot of potential to reduce the adhesion force between metal and clay. The concepts of adhesion reducing methods have to be developed further, before it can be used for full scale trenching. Especially, the behaviour in sand and start ploughing from zero velocity must be determined. The concepts can have negative properties in these circumstances.
- To know how much reduction can be achieved at full scale ploughing, the percentage of adhesion force from full scale ploughing operation is needed. When the reduction is known a cost and benefit analysis can be made.
- When choosing a water nozzle solution to reduce the adhesion force, additional power consumption and deck space for the pump installation should be taken into account.

Nomenclature

α	Ploughing angle	$^\circ$
α_a	Adhesion	$-$
$\alpha_{angle}(\alpha)$	Plough angle influence factor	$-$
$\alpha_{depth}(d)$	Depth factor	$-$
α_{tip}	Tip shape influence factor	$-$
δ	External friction angle	$^\circ$
γ	Unit weight	N/m^3
λ	Logarithmic strain rate dependency coefficient	$-$
ρ_S	Density of solids	kg/m^3
ρ_t	Density of the soil	kg/m^3
ρ_w	Density of water	kg/m^3
$\rho_{in-situ}$	In-situ density	kg/m^3
ρ_{sub}	Density of submerged soil	kg/m^3
σ_1	First principle stress	Pa
σ_2	Second principle stress	Pa
σ_N	Normal principle stress	Pa
φ	Internal friction angle	$^\circ$
A	Area	m^2
b	Plough width	m
c	Cohesion	Pa
d	Ploughing depth	m
d_c	Critical depth	m
e	Void ratio	$-$
F_c	Cutting force	N
F_h	Horizontal force	N
F_v	Vertical force	N
g	Gravitational constant	m/s^2
I_L	Liquidity index	%
I_P	Plasticity index	%
m	Exponential strain rate dependency coefficient	$-$

M_s	Mass of solids	kg
M_t	Mass of soil	kg
M_w	Mass of water	kg
n	Porosity	$-$
N_γ	Dimensionless coefficient for unit weight	$-$
N_c	Dimensionless coefficient for cohesion	$-$
N_q	Dimensionless coefficient for surcharge	$-$
S	Degree of saturation	$-$
S_u	Undrained shear strength	Pa
v	Velocity of the plough	m/s
V_p	Volume of pores	m^3
V_s	Volume of solids	m^3
V_t	Volume of the soil	m^3
V_w	Volume of water	m^3
v_{ref}	Reference velocity	m/s
w	Moisture content	%
w_L	Liquid limit	%
w_P	Plastic limit	%
W_t	Weight of the soil	N

List of Figures

List of Tables

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I

Data of the linear relation of the sensors

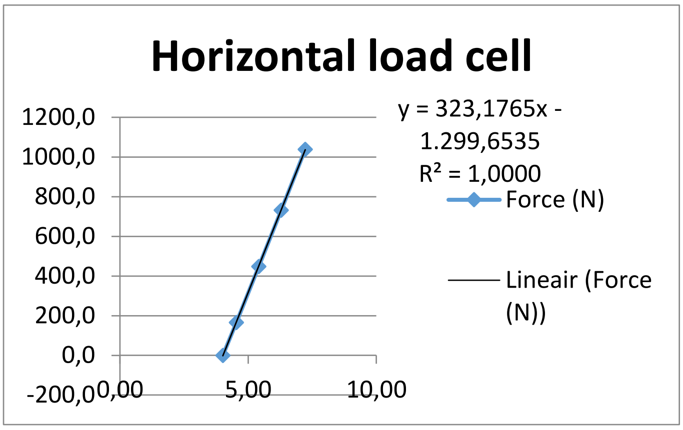
Figures are on the next page.

Calibration load cells

Date: 16-6-2016

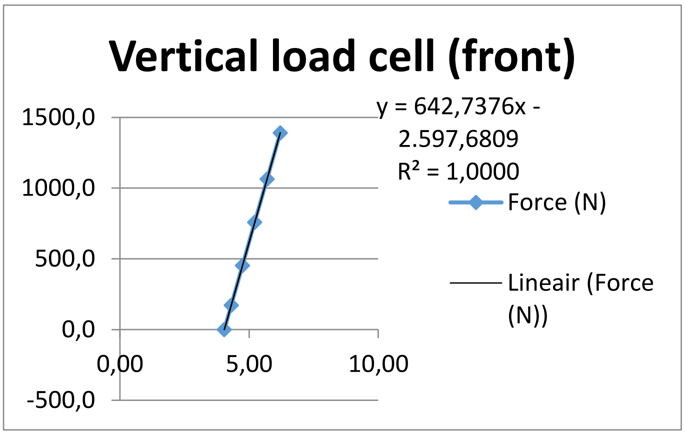
Amplifier# SY409131540
load cell # 258078
Position Horizontal load cell

mA	Weight (Kg)	Force (N)
4,01	0	0,0
4,5384	16,9	165,8
5,41	45,7	448,3
6,29	74,5	730,8
7,23	105,8	1037,9



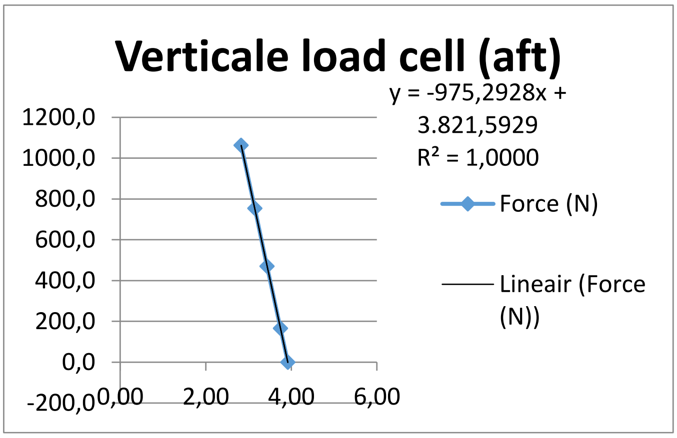
Amplifier# 1000197822
load cell # P2C037132
Position Vertical load cell (front)

mA	Weight (Kg)	Force (N)
4,04	0	0,0
4,31	17,4	170,7
4,75	46,1	452,2
5,22	77,2	757,3
5,70	108,5	1064,4
6,21	141,8	1391,1



Amplifier# SY409131538
load cell # P2C036952
Position Vertical load cell (aft)

mA	Weight (Kg)	Force (N)
3,92	0	0,0
3,75	16,9	165,8
3,44	48	470,9
3,15	76,8	753,4
2,83	108,3	1062,4
2,51	141,3	1386,2



Distance meter

mA	Distance [mm]
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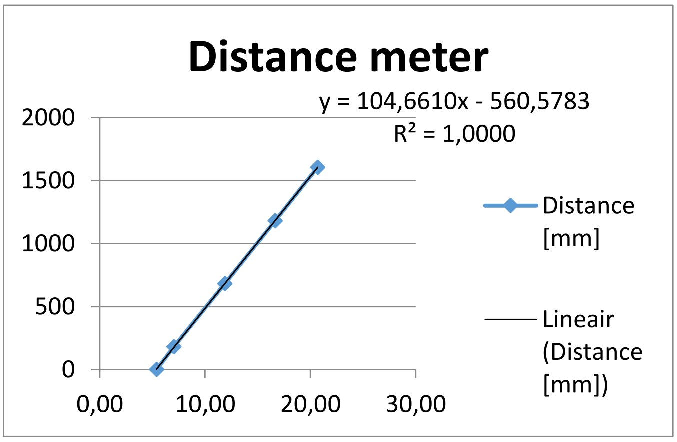
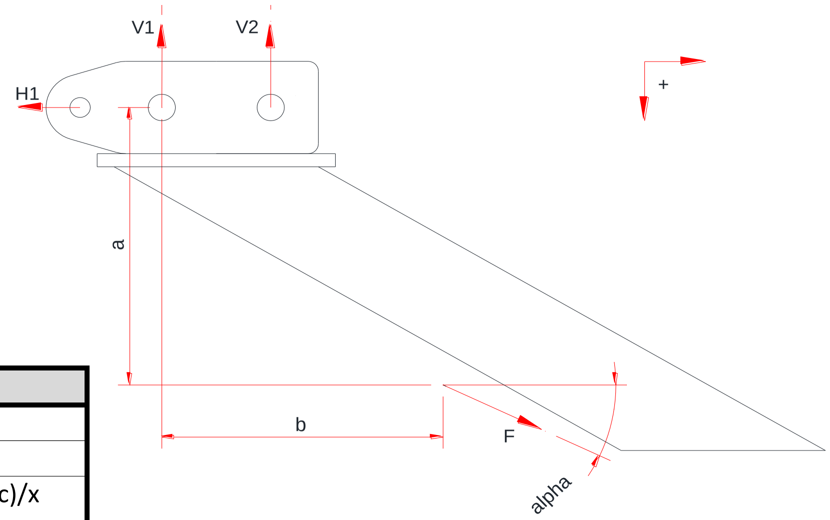
7,04	181
11,88	681
16,65	1181
20,69	1606



General data			
Force	F	Variable	N
Weight plough	Wp	20	N
Angle alpha	α	Variable	°
Length a	a	170	mm
Length b	b	105	mm
Length c (Cog plough to V1)	c	25	mm
Distance between V1 and V2	x	90	mm

Calculate load		Formula
Total horizontal load H1	Hor	COS(alpha*∏/180)*F
Total vertical load	V	SIN(alpha*∏/180)*F+Wp
Load in loadcell V2	Ver. Aft	(-Hor*a+SIN(α*∏/180)*F*b+Wp*c)/x
Load in loadcell V1	Ver. front	V-ver. Aft



Loading situation										
Angle [deg]	Weight [kg]	Calculated loads [N]			Measured loads [N]			Deviation [%]		
		Hor	Ver. front	Ver. Aft	Hor	Ver. front	Ver. Aft	Hor	Ver. front	Ver. Aft
10	32,5	302,9	577,7	-504,3	283,55	590,3	-484,18	6%	-2%	-4%
10	67,5	639	1202,7	-1070,1	614,75	1202,3	-1040,18	4%	0%	-3%
10	130,5	1244,1	2327,8	-2088,5	1212,25	2270,1	-2047,88	3%	2%	-2%
10	157	1498,6	2801,1	-2516,8	1464,95	2716,9	-2466,78	2%	3%	-2%
15	95	858,8	1648,1	-1380,8	901,75	1687,3	-1431,18	-5%	-2%	4%
15	75	697,4	1300,7	-1093,8	672,75	1256,3	-1061,18	4%	3%	-3%
20	78	706	1305,1	-1028,2	704,25	1297,3	-1036,18	0%	1%	1%
20	124,5	1132,1	2084,2	-1652,1	1105,75	2049,3	-1656,68	2%	2%	0%

II

Drawings experimental setup

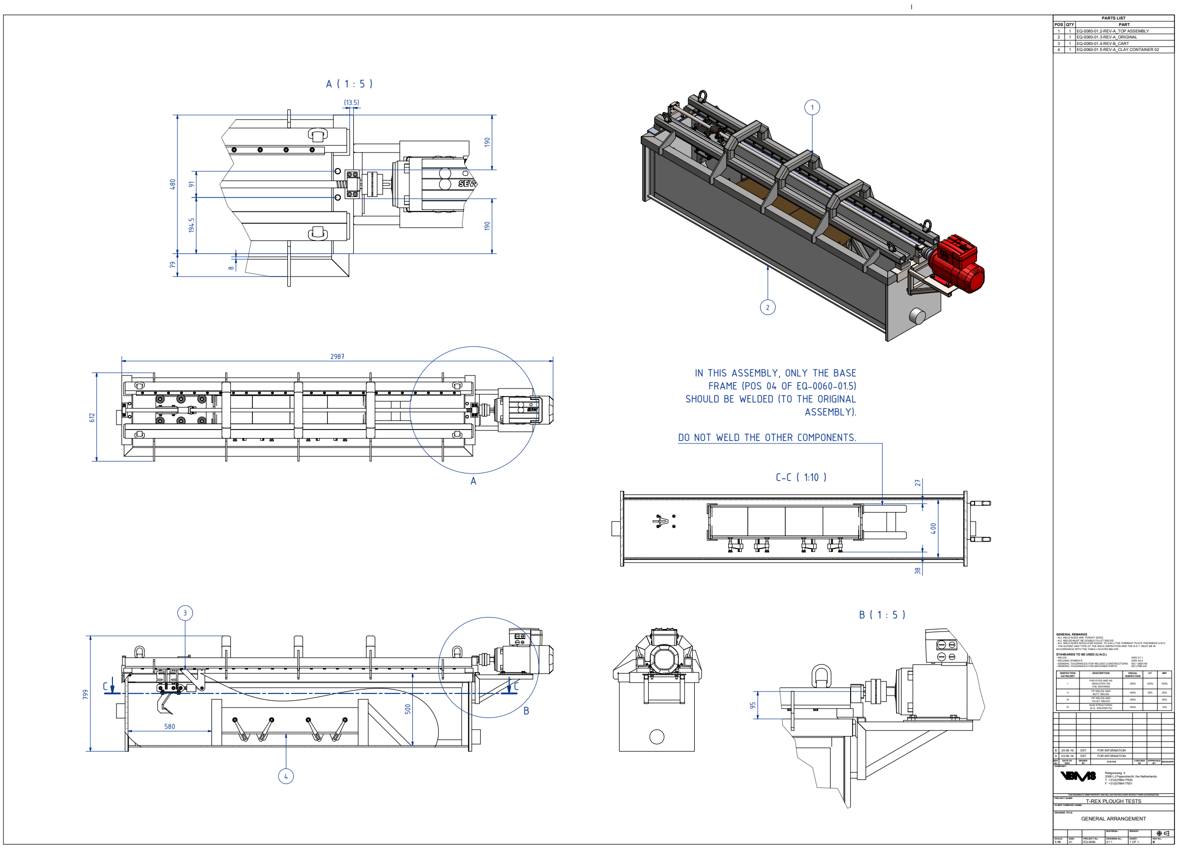


Figure II.1: Main Assembly

III

Clay properties

In the clay report on the next pages the names of the clay correspond to the names provided in this thesis report as follows:

Name in clay reports	Equivalent name
K11.000	Soft
Heteren	Medium
Wienerberger	Hard

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PO Box 76
3350 AB Papendrecht
The Netherlands

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F +31 78 6969901

laboratorium@boskalis .com
www.boskalisenviron mental.com

VBMS BV
attn. Mr. E. Hoogeveen
Rietgorsweg 4
3356 LJ PAPENDRECHT

Subject

VBMS Klei monsters

Your reference

A00 (Algemeen R&D VBMS)

Our reference

201973

Page

1 of 3

Attachments

2

Dear Sir,

We are sending you the report regarding "VBMS Klei monsters, Adhesion Research" project.

Please do not hesitate to contact us if you have any questions concerning this report (+31 78 6969 836).

We trust to have informed you adequately.

Kind regards,

Jasper Visser

Boskalis Environmental

Summary of results

Test	Unit	205580	205581
Moisture content	%	27.2	19.5
Dry matter content	%	78.6	83.7
Density (Situ)	Mg/m³	1.888	2.100
Specific gravity	Mg/m³	2.66	2.65
Plastic limit	%	16	15
Liquid limit	%	41	44
Plasticity index	%	25	29
Density (Dry)	Mg/m³	1.475	1.761

Nr.	Monsternaam
205580	K11000
205581	Wienerberger

Sampling:

The samples were delivered to us on 22 December 2016.

Sample storage:

Method/SOP information

TestType	Method	SOP-code
Density volume ring method (Dry)	NEN	W004
Density volume ring method (Situ)	NEN	W004
Liquid limit	RAW	W021
Moisture content	NEN-ISO	W002
Plastic limit	RAW	W021
Plasticity index	RAW	W021
Particle size distribution	BS	W010

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laboratorium@boskalis .com
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VBMS bv
t.a.v. Dhr. E. Hoogeveen
Postbus 282
3350 AG PAPENDRECHT

Onderwerp

Klei Heteren

Uw referentie

Onze referentie

171492

Pagina

1 van 3

Bijlage(n)

1

Geachte heer,

Hierbij ontvangt u het rapport betreffende "Klei Heteren, Ploegen in klei".

Indien u vragen of opmerkingen heeft, kunt u contact met ons opnemen via telefoonnummer 078-6969836, of per e-mail laboratorium@boskalis.com.

Wij gaan er van uit u hiermee naar behoren te hebben geïnformeerd.

Met vriendelijke groet,

C. E. v. Bergeijk.

Chantal van Bergeijk

Resultaten samenvatting

Analyse	Eenheid	173578
Vochtgehalte	%	17.2
Droge stof	%	85.3
Rolgrens	%	16
Vloeigrens	%	36
Plasticiteitsindex	%	20

Nr.	Monsternaam
173578	01

Monstername:

De monsters zijn door u aangeleverd op 21 april 2016.

Bewaartermijn:

Op 21 oktober 2016 wordt het monstermateriaal uit onze opslag verwijderd. Wanneer een langere bewaartijd gewenst is, verzoeken wij u dit tijdig aan te geven.

Methode/SOP informatie

Analyse	Methode	SOP-code
Hydrometer	BS	W011
Vloeigrens	RAW	W021
Vocht gehalte / Droge stof	NEN-ISO	W002
Rolgrens	RAW	W021
Plasticiteits index	RAW	W021
Zeving	BS	W010

Boskalis Environmental

Project: VBMS Clay Samples **Projectnumber:** A00 (Alg. R&D VBMS) **Method:** Based on BS
Labnumber: 201973

205580 - K11000		205581 - Wienerberger					
Sieve (µm)	Percentage through sieve	Sieve (µm)	Percentage through sieve	Sieve (µm)	Percentage through sieve	Sieve (µm)	Percentage through sieve
2000	100%	2000	100%				
1400	100%	1400	100%				
1000	100%	1000	100%				
710	100%	710	99%				
500	100%	500	99%				
355	100%	355	98%				
250	100%	250	98%				
180	100%	180	96%				
125	100%	125	93%				
90	99%	90	89%				
63	98%	63	87%				
47	97%	48	81%				
33	95%	34	78%				
24	89%	24	74%				
17	86%	17	68%				
9	77%	9	61%				
5	70%	5	52%				
3	64%	3	46%				
1	57%	1	39%				

D90	25	D90	97	D90		D90	
D80	11	D80	43	D80		D80	
D70	5	D70	19	D70		D70	
D60	2	D60	8	D60		D60	
D50		D50	4	D50		D50	
D40		D40	2	D40		D40	
D30		D30		D30		D30	
D20		D20		D20		D20	
D10		D10		D10		D10	

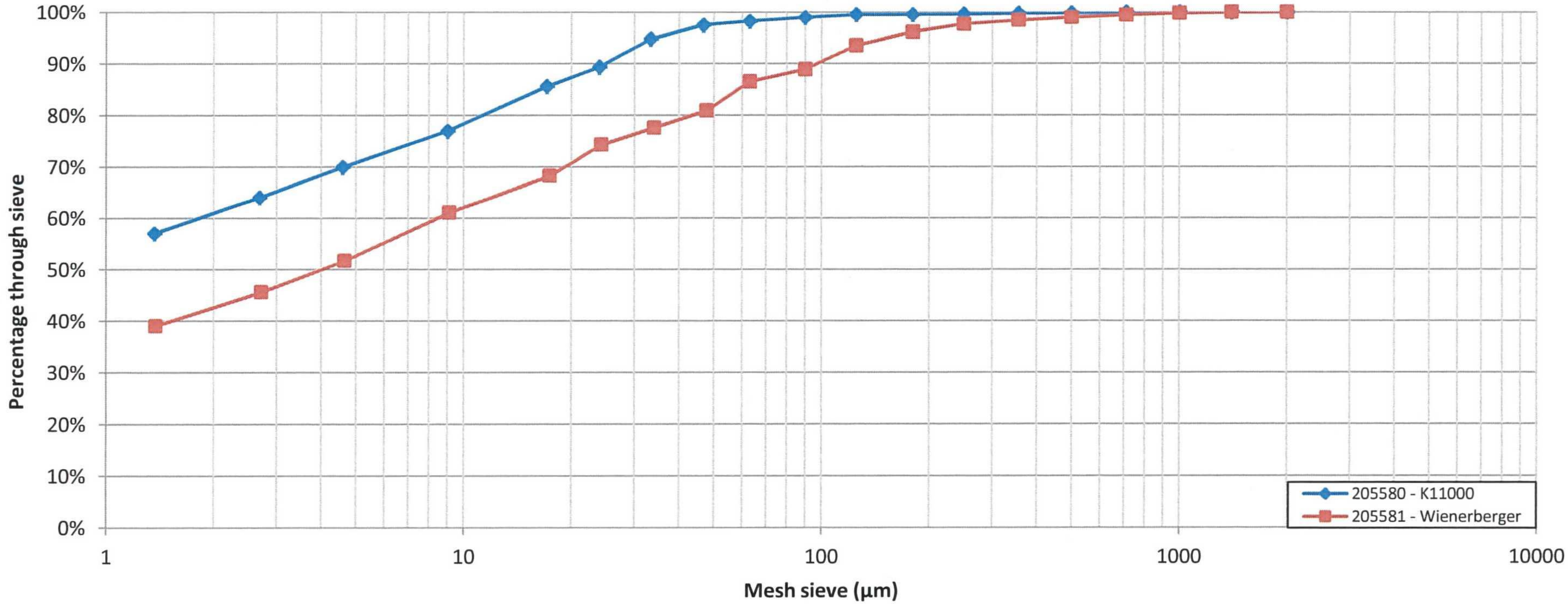
% > 2 mm	0%	% > 2 mm	0%	% > 2 mm		% > 2 mm	
DMF totaal		DMF totaal		DMF totaal		DMF totaal	
D60/D10		D60/D10		D60/D10		D60/D10	

Remarks:
Pretreatment was performed on the samples to remove the organic components from the samples.

Boskalis Environmental

Labnumber: 201973
Projectnumber: A00 (Alg. R&D VBMS)

VBMS Clay Samples



Sample:		D10	D20	D30	D40	D50	D60	D70	D80	D90	% > 2mm	DMF	D60/D10
Sieve	Name	µm	µm	µm	µm	µm	µm	µm	µm	µm		(total)	
1	205580 - K11000						2	5	11	25	0.0%		
2	205581 - Wienerberger				2	4	8	19	43	97	0.0%		
3													
4													

Boskalis Environmental

Project: Heteren **Projectnummer:** - **Methode:** gebaseerd op BS 1377

Labnummer: 171492

173578	
Maaswijdte zeef (µm)	Percentage door zeef
2000	100%
1400	100%
1000	99%
710	96%
500	92%
355	87%
250	83%
180	79%
125	77%
90	74%
63	72%
48	70%
34	68%
24	65%
17	63%
9	58%
5	53%
2	43%
1	32%

D90	443
D80	194
D70	46
D60	11
D50	4
D40	2
D30	
D20	
D10	

% > 2 mm	0%
DMF totaal	
D60/D10	

Maaswijdte zeef (µm)	Percentage door zeef

Maaswijdte zeef (µm)	Percentage door zeef

Maaswijdte zeef (µm)	Percentage door zeef

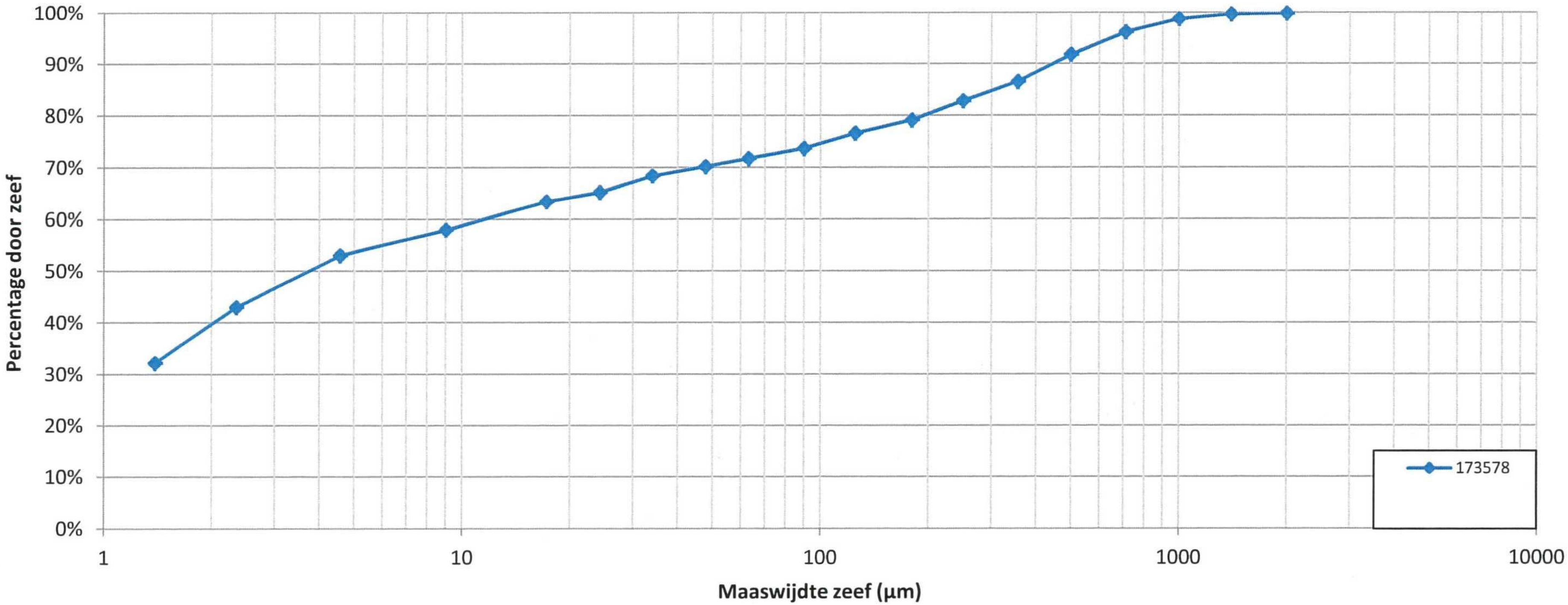
Opmerking:
De hierboven beschreven monsters zijn voorbehandeld waarbij de organische bestandsdelen verwijderd zijn.

Boskalis Environmental

Labnummer: 171492

Projectnummer: -

Heteren



Monster: Nummer	Naam	D10 µm	D20 µm	D30 µm	D40 µm	D50 µm	D60 µm	D70 µm	D80 µm	D90 µm	% > 2mm	DMF (totaal)	D60/D10
1	173578				2	4	11	46	194	443	0.1%		
2													
3													
4													

Boskalis Environmental

Project Adhesion research
Projectnumber A00 (Algemeen R&D VBMS)
Order ID 201973
Lab technician Jvss

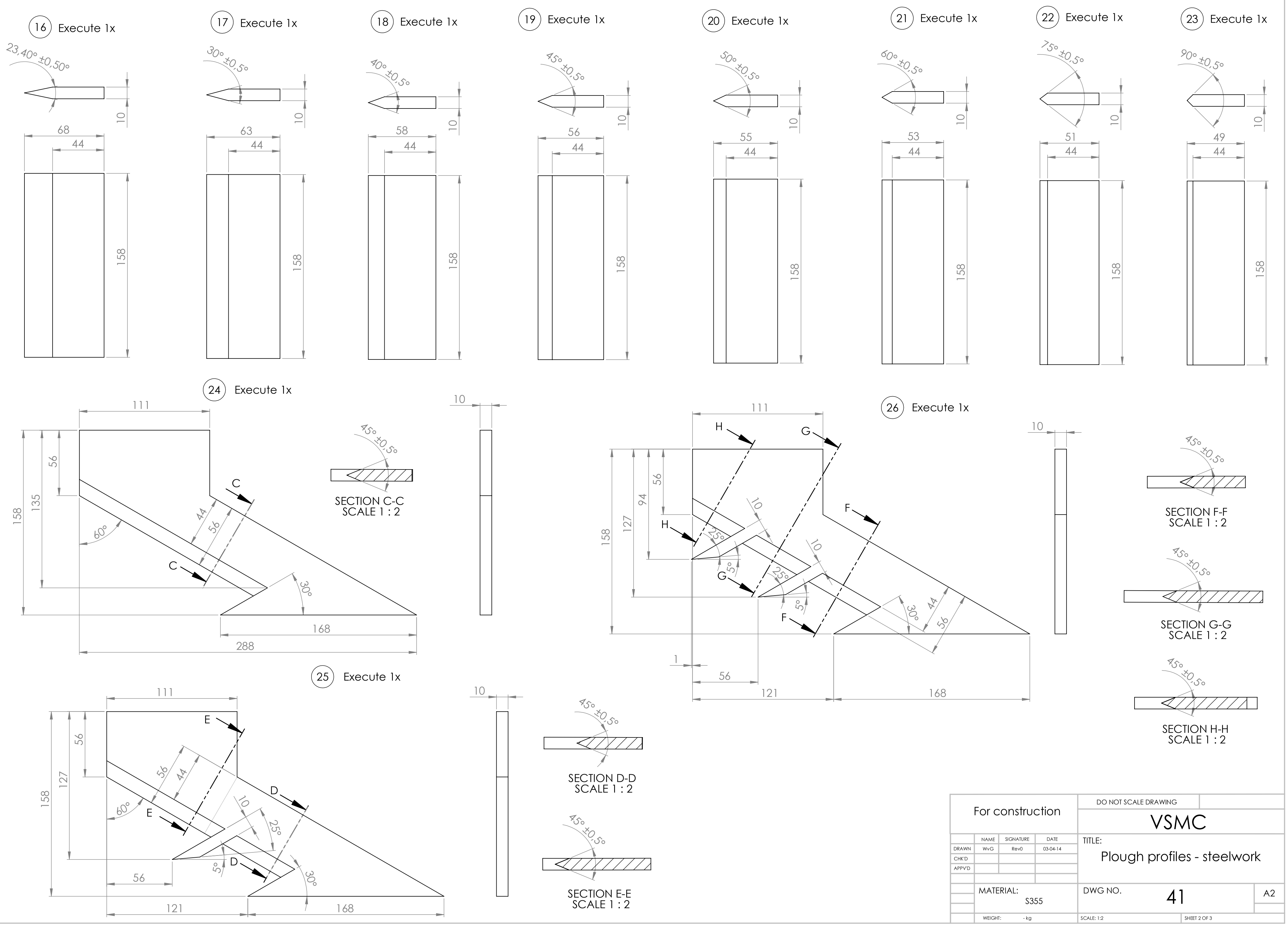
Sample name:	K11000	Wienerberger
V_{water}	41.3%	33.9%
V_{air}	3.3%	0.0%
V_{solids}	55.4%	66.1%
Total volume in percentage	100%	100.0%

Remarks:
The above reported percentages are based on the raw data of the sample and tests. It can be assumed that almost no air is present in sample Wienerberger.

IV

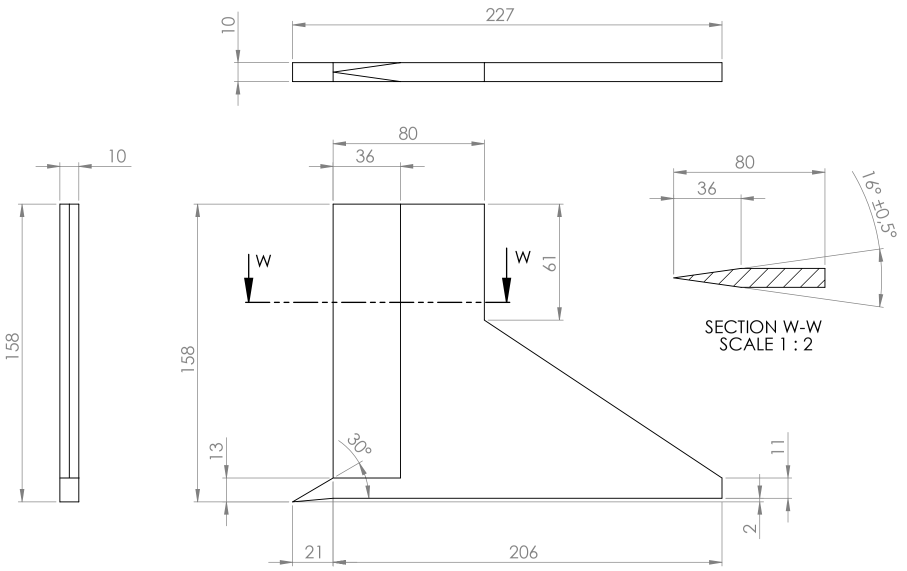
Drawings experimental ploughs

Figures are on the next page.



For construction				DO NOT SCALE DRAWING
	NAME	SIGNATURE	DATE	VSMC
DRAWN	WvG	Rev0	03-04-14	TITLE: Plough profiles - steelwork
CHK'D				
APPV'D				
MATERIAL: S355				DWG NO. 41 A2
WEIGHT: - kg				SCALE: 1:2 SHEET 2 OF 3

27 Execute 1x



For construction				DO NOT SCALE DRAWING
				VSMC
	NAME	SIGNATURE	DATE	TITLE:
DRAWN	WvG	Rev0	03-04-14	Plough profiles - steelwork
CHK'D				
APPV'D				
MATERIAL: S355				DWG NO. 41 — A2
WEIGHT: - kg				SCALE: 1:2 — SHEET 3 OF 3

V

Test reports

Table V.1: List of test reports

Test number	Plough	Clay	Additional info	Page number
1	SS4	M		89
2	HD3	M		92
3	M	M		95
4	M	W	4 strips	98
5	M	M	4 strips	102
6	L	S		106
7	L	S		109
8	M	S		112
9	S	S		115
10	ALPHA	S		118
11	BRAVO	S	h=5 mm convex	121
12	L	H		124
13	M	H		127
14	S	H		130
15	BRAVO	H	h=5 mm convex	133
16	ALPHA	H		136
17	BRAVO	H	h=3 mm convex	139
18	L	H		142
19	SS4	H		145
20	L	H	dry	148
21	HD3	H		151
22	BRAVO	H	h=3 mm convex	154
23	BRAVO	H	h=7 mm convex	157
24	L	M		160
25	CHARLIE	H	1 tube, 4 bar	163
26	M	H	dry	166
27	S	H	dry	169
28	S	M		172
29	BRAVO	M	h=5 mm convex	175
30	CHARLIE	H	2 tubes, 4 bar	178
31	L	H	clay in 4 pieces	181
32	L	S	dry	184
33	CHARLIE	S	2 tubes, 4 bar	187
34	L	H	max. torque	190
35	CHARLIE	H	2 tubes, 5 bar	193
36	BRAVO	H	2 strips	196
37	L	H	V=63 m/h	199
38	ALPHA	H		202
39	M	S	dry	205
40	S	S	dry	208
41	L	H	V=445 m/h	211

TEST REPORT 01

General information

Test number:	1	Length of clay box:	1040 mm
Date of test:	14-9-2016	Water on top of clay:	69 mm
Time of test:	13:00	Depth of the plough:	94 mm
Test profile:	SS4	Set motor velocity:	-20 [-]
		Clay type:	Medium

Particular during test

Particulars of the clay block:

0

Particular events during the test:

Put permanent and whiteboard marker on the side of the plough. This to check if the permanent marker stays on the plough and the whiteboard marking fades away. Could be usefull when testing with convexes and water nozzles. The permanent marking is faded away a bit. The whiteboard marker is faded away completely on the bottom 6/7 cm and is still visible on the top 2/3 cm.

Material properties of the clay

Average shear strength*: 80 kPa **Average of front+aft fieldvane tests block 2+3*

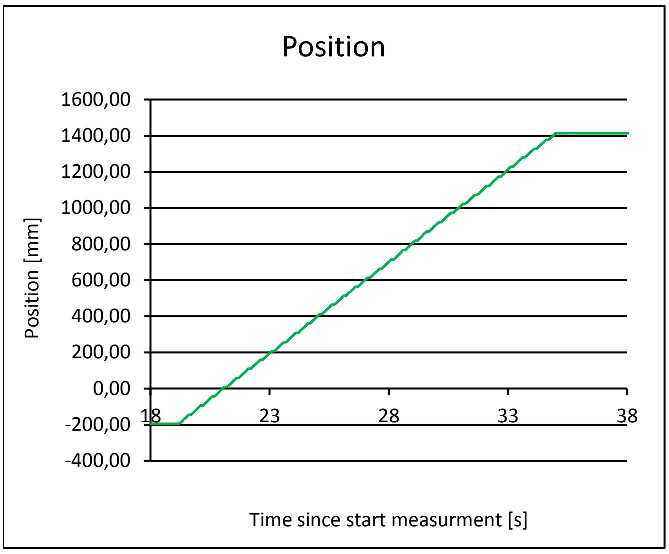
	Block 1	Block 2	Block 3	Block 4	
Handvane test before trenching:	80	77	65	70	kPa
	-	84	60	-	kPa

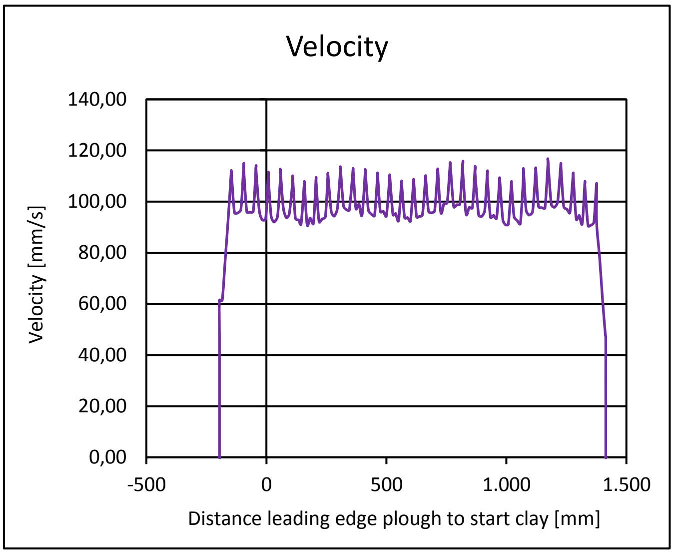
		Block 2	Block 3	
Handvane test after trenching:		55	43	kPa
Fieldvane test after trenching:	Top	79	69	kPa
	Front	90	70	kPa
	Aft	91	69	kPa

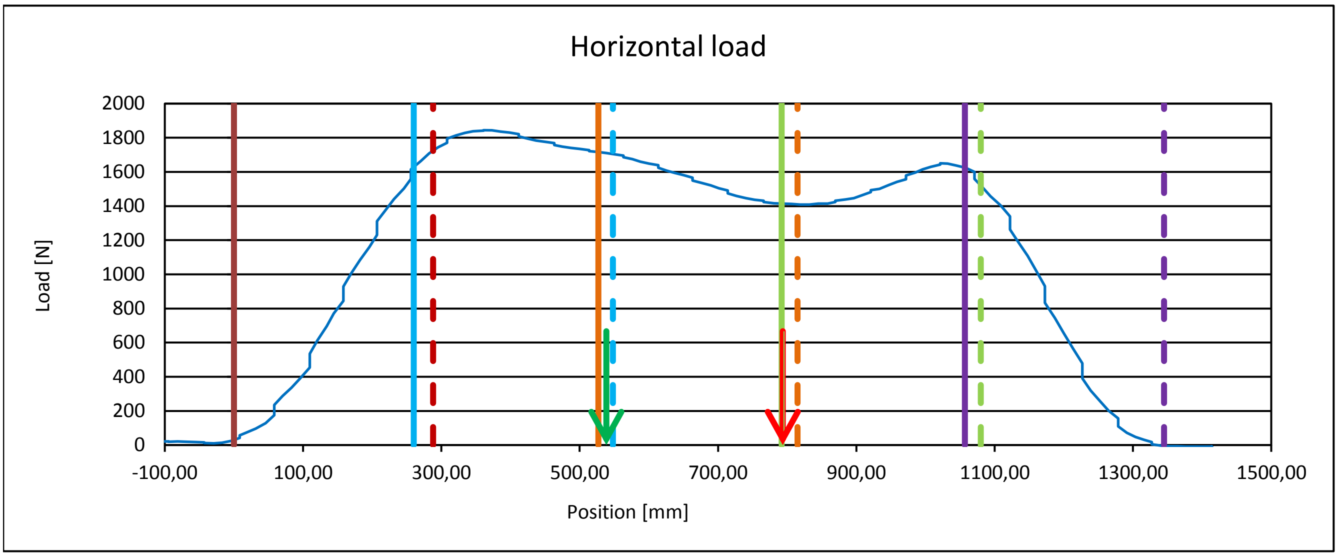
Averages in measuring length

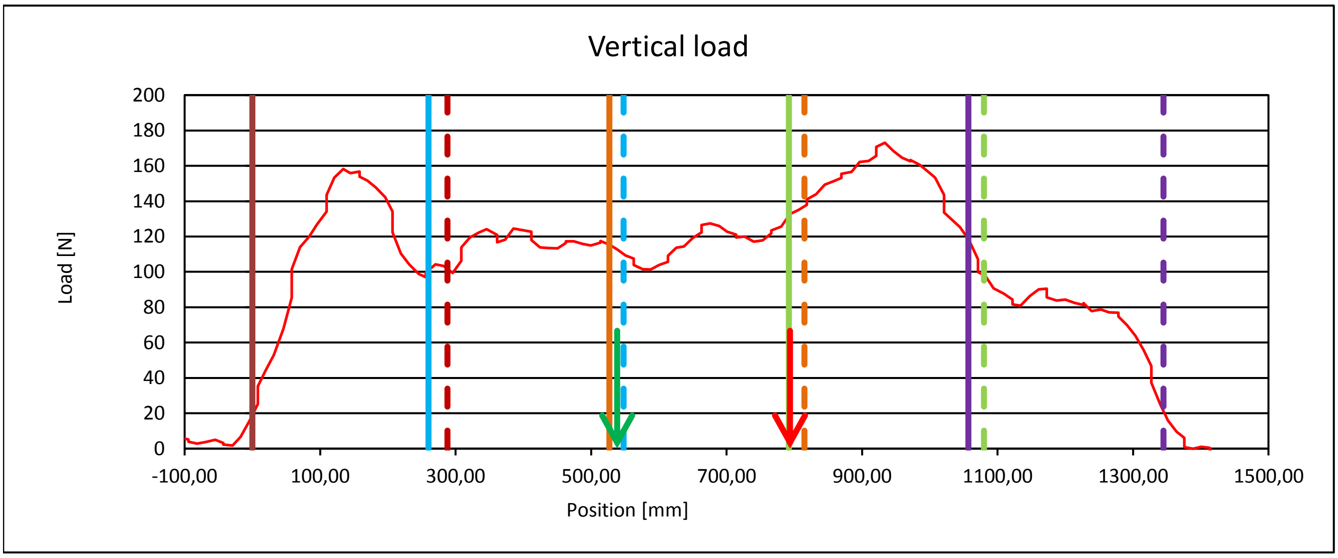
Start measuring length	538,5	mm
End measurement length	793,6	mm
Totaal length	255,1	mm
Average speed	101,5	mm/s
Average speed	365,4	m/h
Horizontal load cell	1557,5	N
Total Vertical load	116,4	N
Total force	1561,8	N
Angle of total force	4,3	Degree

Measured results









Not available

Frontview during trenching

Sideview during trenching

Top of first block

Top of second block

Top of third block

Top of fourth block

Right side of the trench from the third block

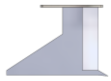
Middle of the second block
(cut perpendicular to the plough path)

Left side of the trench from the third block

TEST REPORT 02

General information

Test number:	2	Length of clay box:	1036 mm
Date of test:	14-9-2016	Water on top of clay:	69 mm
Time of test:	16:00	Depth of the plough:	94 mm
Test profile:	HD3	Set motor velocity:	-20 [-]
		Clay type:	Medium



Particular during test

Particulars of the clay block:

Last block was not cut right and has a curvature on the surface.

Particular events during the test:

The plough ran into the end plate of the clay container. The plough did drift off to the right during the last block and stopped immediately when hit the clay container. Tip of the plough has a dent on the right side.

Material properties of the clay

<u>Average shear strength*:</u> <u>82</u> kPa *Average of front+aft fieldvane tests block 2+3

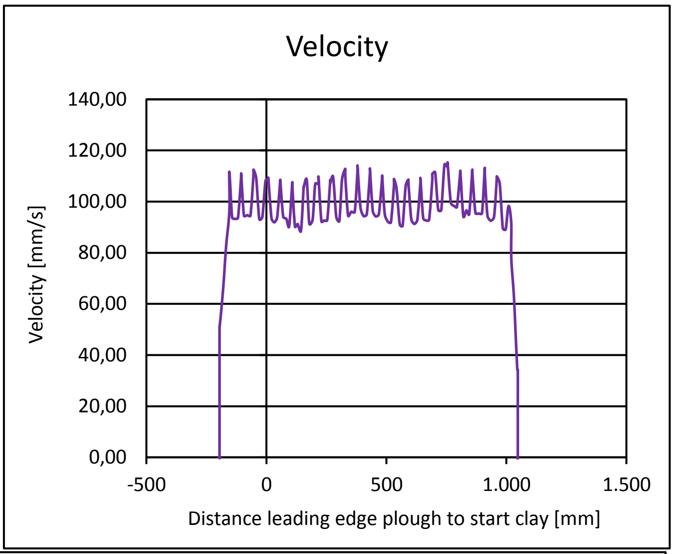
	Block 1	Block 2	Block 3	Block 4	
Handvane test before trenching:	50	56	88	130	kPa
	-	59	95	-	kPa

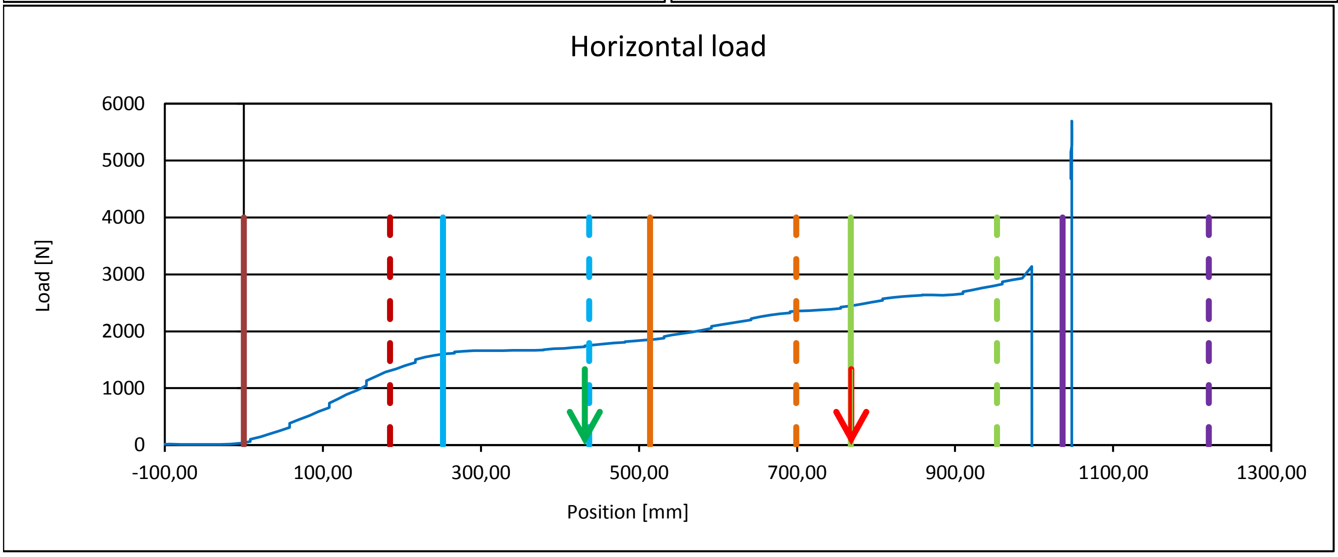
		Block 2	Block 3	
Handvane test after trenching:		45	55	kPa
Fieldvane test after trenching:	Top	59	84	kPa
	Front	65	96	kPa
	Aft	73	92	kPa

Averages in measuring length

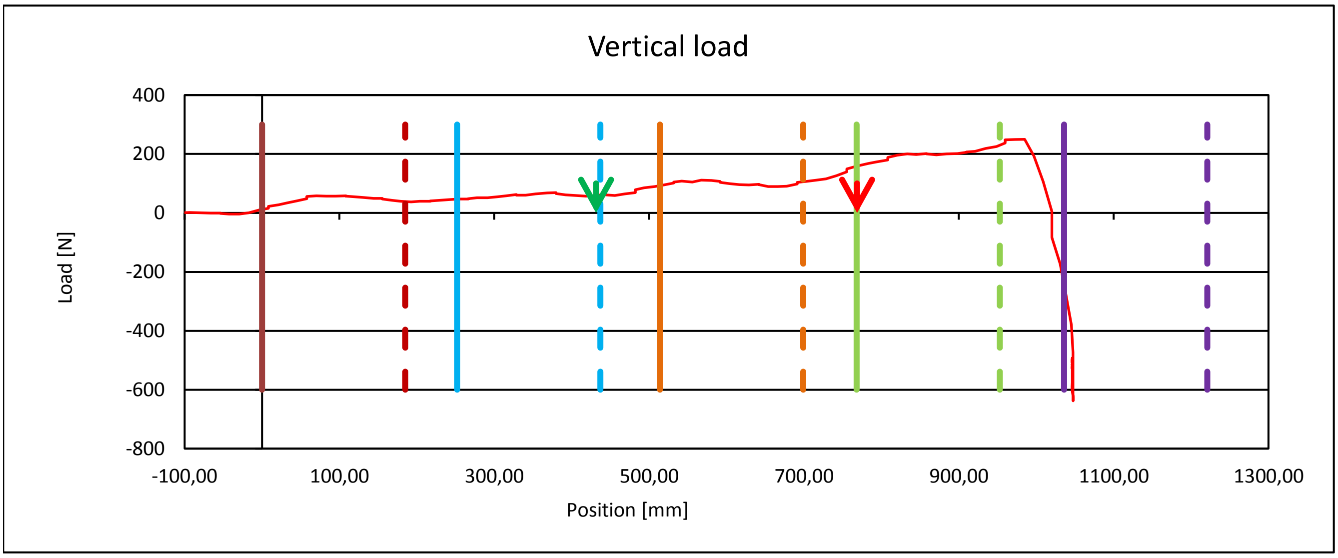
Start measuring length	431,4	mm
End measurement length	768,6	mm
Totaal length	337,2	mm
Average speed	101,8	mm/s
Average speed	366,4	m/h
Horizontal load cell	2093,7	N
Total Vertical load	99,4	N
Total force	2096,0	N
Angle of total force	2,7	Degree

Measured results





Between 1000 and 1050mm the force went to -1172137 N because the plough ran into the end of the metal clay container.



Frontview during trenching

Sideview during trenching

Top of first block

Top of second block

Top of third block

Top of fourth block

Middle of the second block
(cut perpendicular to the plough path)

Right side of the trench from the third block

Left side of the trench from the third block

TEST REPORT 03

General information

Test number:	3	Length of clay box:	1036 mm
Date of test:	22-9-2016	Water on top of clay:	69 mm
Time of test:	13:30	Depth of the plough:	94 mm
Test profile:	M	Set motor velocity:	-6 [-]
		Clay type:	Medium

Particular during test

Particulars of the clay block:

0

Particular events during the test:

The ballscrew of the spindle broke during the test. Therefor the test was stopped after 48 sec at 850 mm from start clay blocks.

Material properties of the clay

<u>Average shear strength*:</u> <u>91</u> kPa **Average of front+aft fieldvane tests block 2+3*

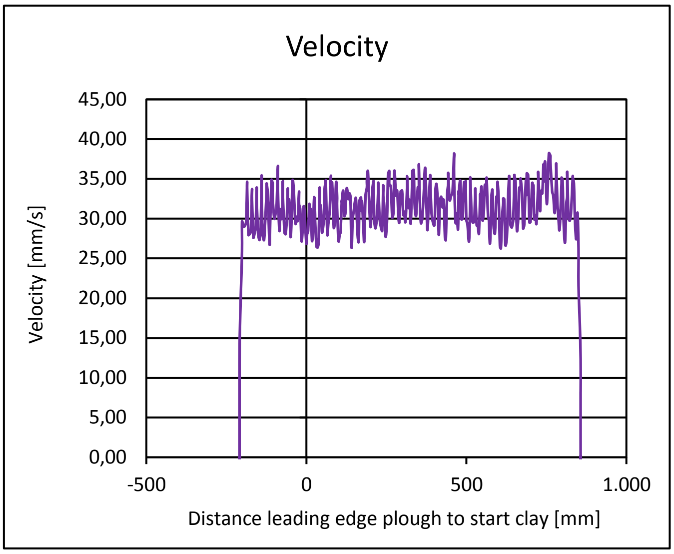
	Block 1	Block 2	Block 3	Block 4	
Handvane test before trenching:	77	86	92	130	kPa
	-	82	88	-	kPa

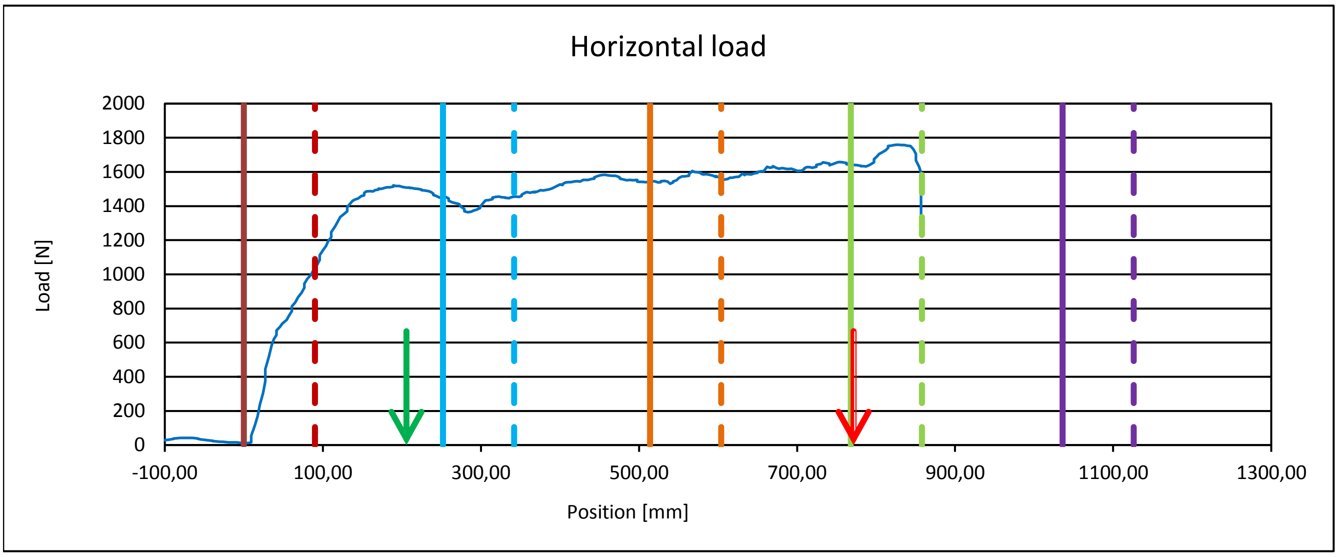
		Block 2	Block 3	
Handvane test after trenching:		52	53	kPa
Fieldvane test after trenching:	Top	84	94	kPa
	Front	80	95	kPa
	Aft	88	100	kPa

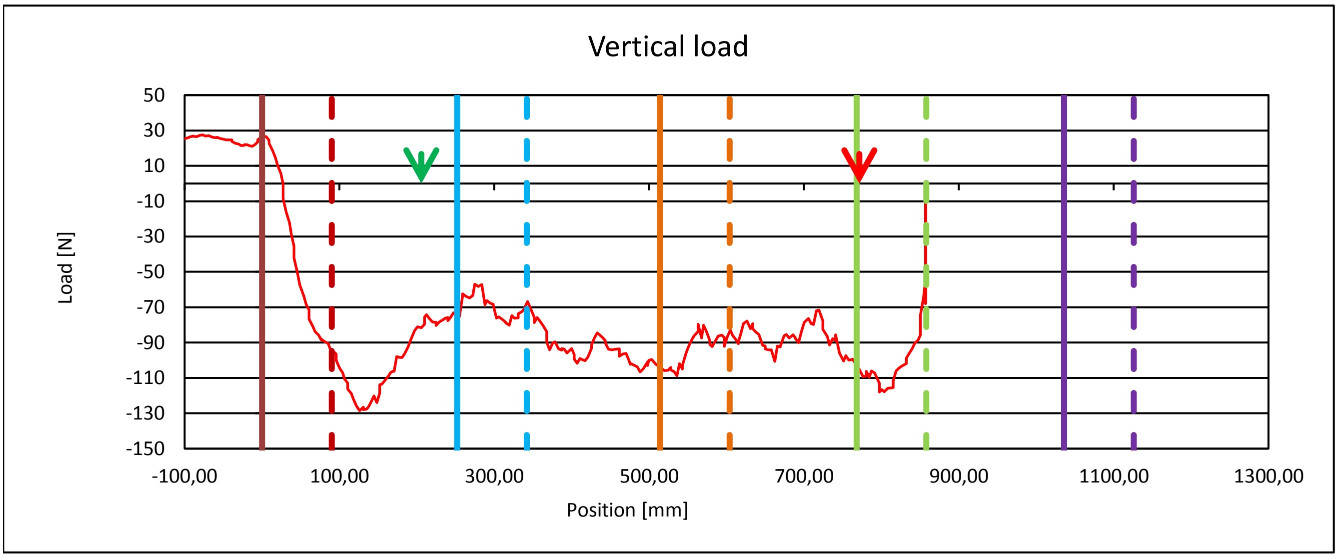
Averages in measuring length

Start measuring length	205,8	mm
End measurement length	771,5	mm
Totaal length	565,8	mm
Average speed	32,3	mm/s
Average speed	116,2	m/h
Horizontal load cell	1540,1	N
Total Vertical load	-86,7	N
Total force	1542,5	N
Angle of total force	-3,2	Degree

Measured results

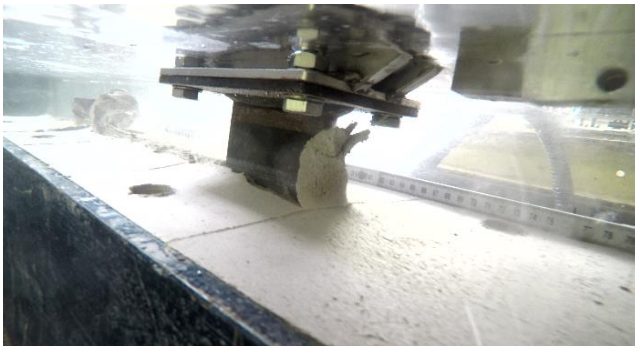






Not available

Frontview during trenching



Sideview during trenching

Top of first block

Top of second block

Top of third block

Top of fourth block

Middle of the second block
(cut perpendicular to the plough path)

Right side of the trench from the third block

Left side of the trench from the third block

TEST REPORT 04

General information

Test number:	4	Length of clay box:	1100 mm
Date of test:	10-10-2016	Water on top of clay:	55 mm
Time of test:	15:00	Depth of the plough:	126 mm
Test profile:	M	Set motor velocity:	-6 [-]
		Clay type:	Wouter (W)

Particular during test

Particulars of the clay block:

After the test the red markings could be seen on the clay. The area behind the gap of the 2 strips at each side showed an increasing contact area along the ploughing direction.

Particular events during the test:

Plough of 90 mm in length installed with 4 strips of different width glued to the leading edge. Each strip in 43 mm in depth and 1 cm in length. The strips has a width of 1, 2, 4 and 6 mm. The side of the plough is painted by whiteboardmarker to indicate the friction surface of the clay.

Material properties of the clay

<u>Average shear strength*:</u> <u>32</u> kPa **average of handvane test after trenching block 2 to 6*

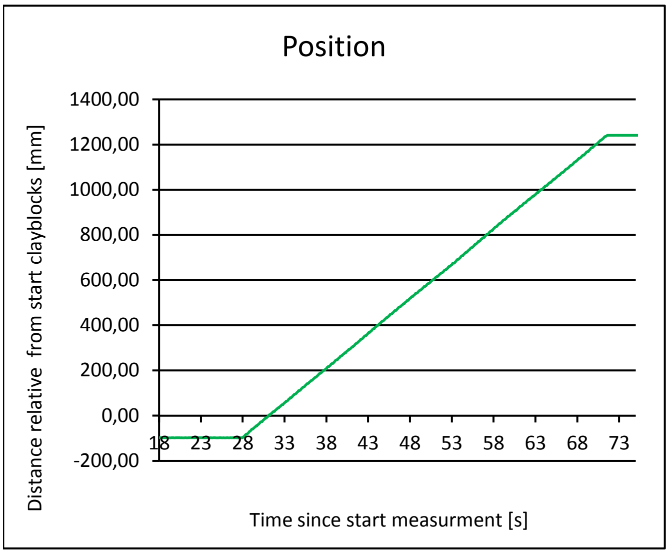
	Block 1	Block 2	Block 3	Block 4	
Handvane test before trenching:	31	37	33	34	kPa
	Block 5	**Block 6**	**Block 7**		
Handvane test before trenching:	33	34	40		kPa

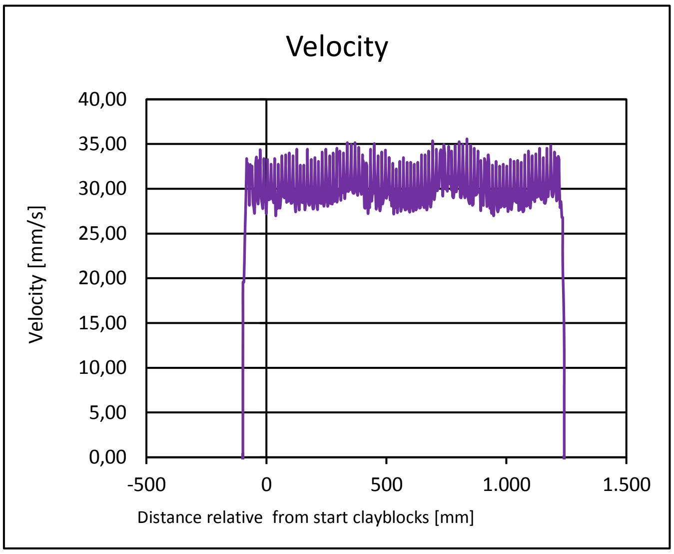
	Block 2	Block 3	Block 4	Block 5	Block 6
Handvane test after trenching: (kPa)	35	35	30	29	32

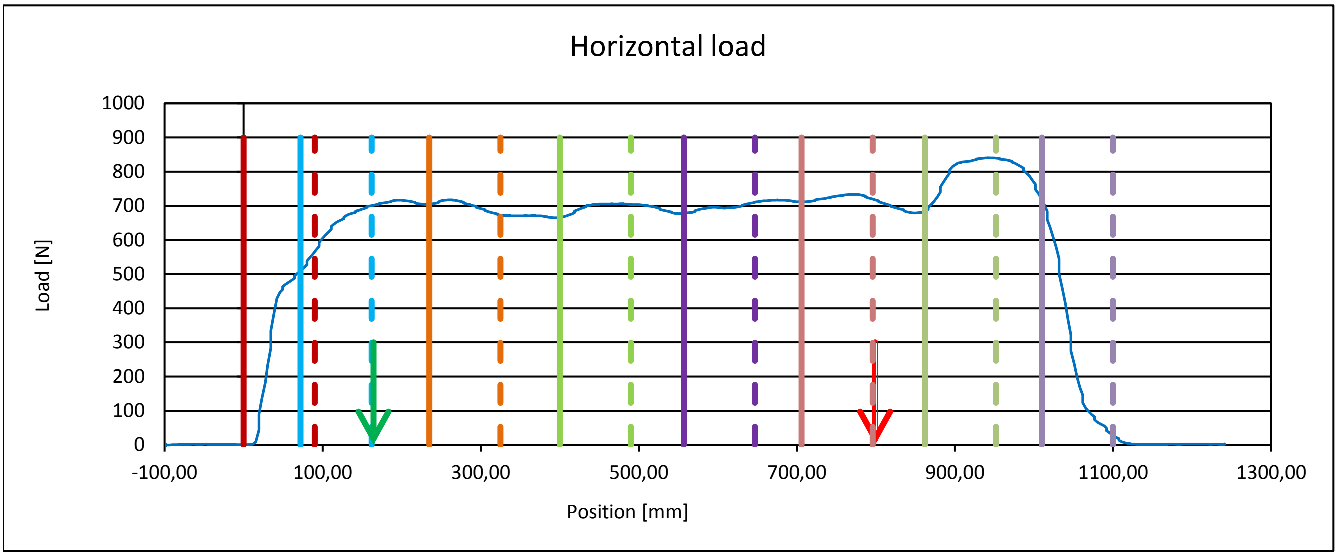
Averages in measuring length

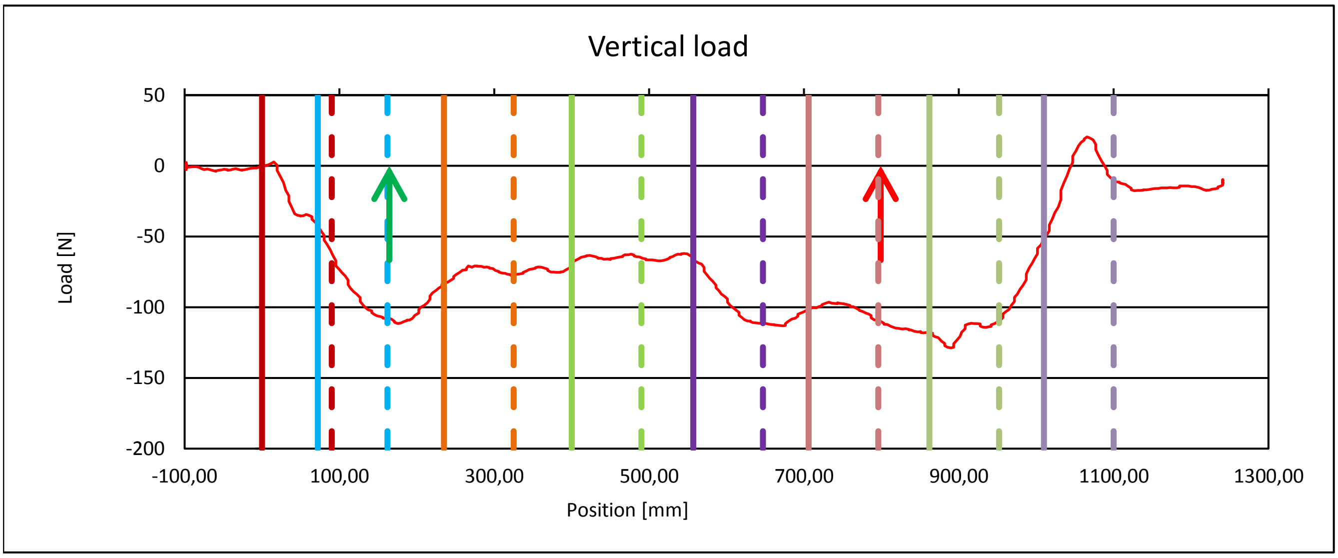
Start measuring length	164,4	mm
End measurement length	799,1	mm
Totaal length	634,7	mm
Average speed	30,8	mm/s
Average speed	110,8	m/h
Horizontal load cell	700,2	N
Total Vertical load	-84,9	N
Total force	705,3	N
Angle of total force	-6,9	Degree

Measured results





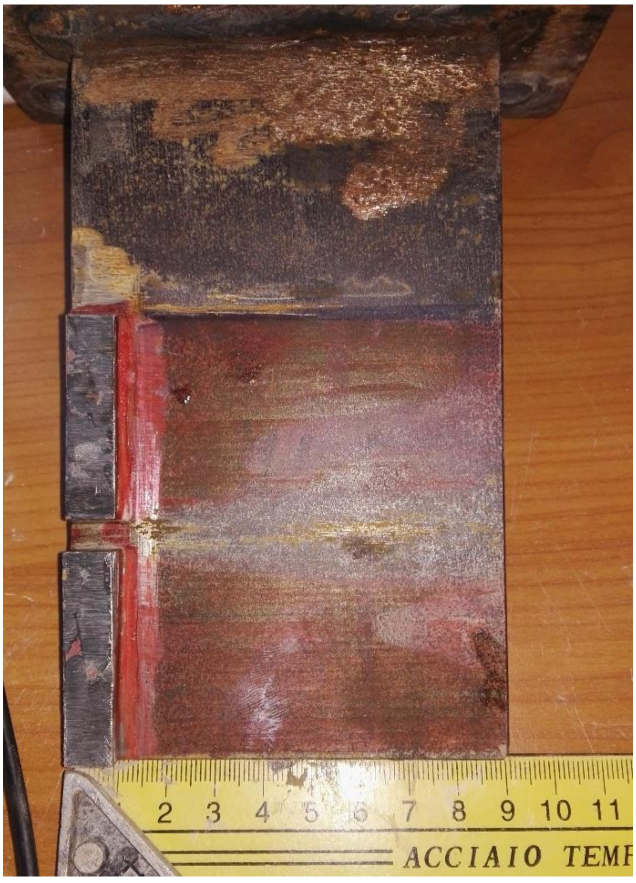




Right side of plough before trenching

Right side of plough after trenching

Left side of plough before trenching



Left side of plough after trenching

Frontview during trenching

Sideview during trenching

Top of first block

Top of second block

Top of third block

Top of fourth block

Middle of the third block
(cut perpendicular to the plough path)

Right side of the trench from the 4th/5th block

Left side of the trench from the 4th/5th block

TEST REPORT 05

General information

Test number:	5	Length of clay box:	1013 mm
Date of test:	11-10-2016	Water on top of clay:	55 mm
Time of test:	14:00	Depth of the plough:	126 mm
Test profile:	M	Set motor velocity:	-6 [-]
		Clay type:	Medium

Particular during test

Particulars of the clay block:

After the test the red markings could be seen on the clay. The area behind the gap of the 2 strips at each side showed an increasing contact area along the ploughing direction.

Particular events during the test:

Medium plough of 90 mm in length installed with 4 strips of different width glued to the leading edge. Each strip in 43 mm in depth and 1 cm in length. The strips has a width of 1, 2, 4 and 6 mm. The side of the plough is painted by whiteboardmarker to indicate the friction surface of the clay.

Material properties of the clay

Average shear strength*: 130 kPa **Average of front+aft fieldvane tests block 2+3*

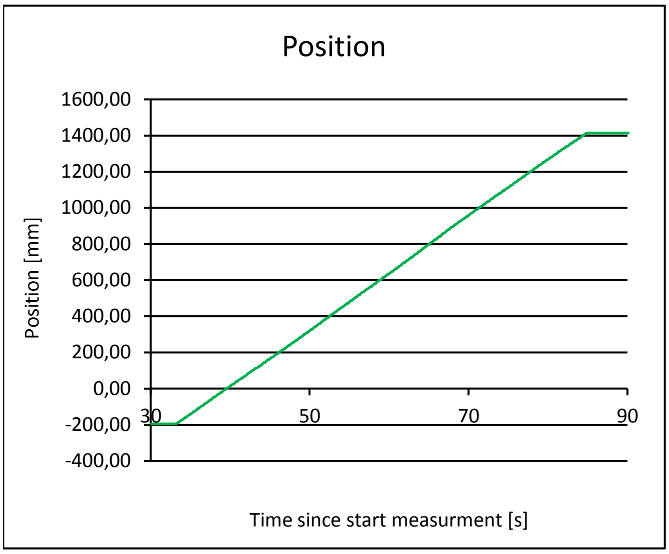
	Block 1	Block 2	Block 3	Block 4	
Handvane test before trenching:	83	120	121	142	kPa
	-	138	135	-	kPa

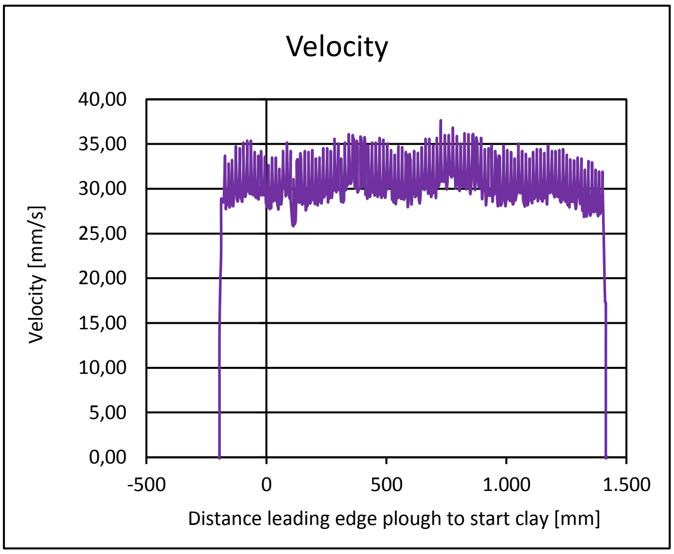
		Block 2	Block 3	
Handvane test after trenching:		74	75	kPa
Fieldvane test after trenching:	Top	130	130	kPa
	Front	130	130	kPa
	Aft	130	130	kPa

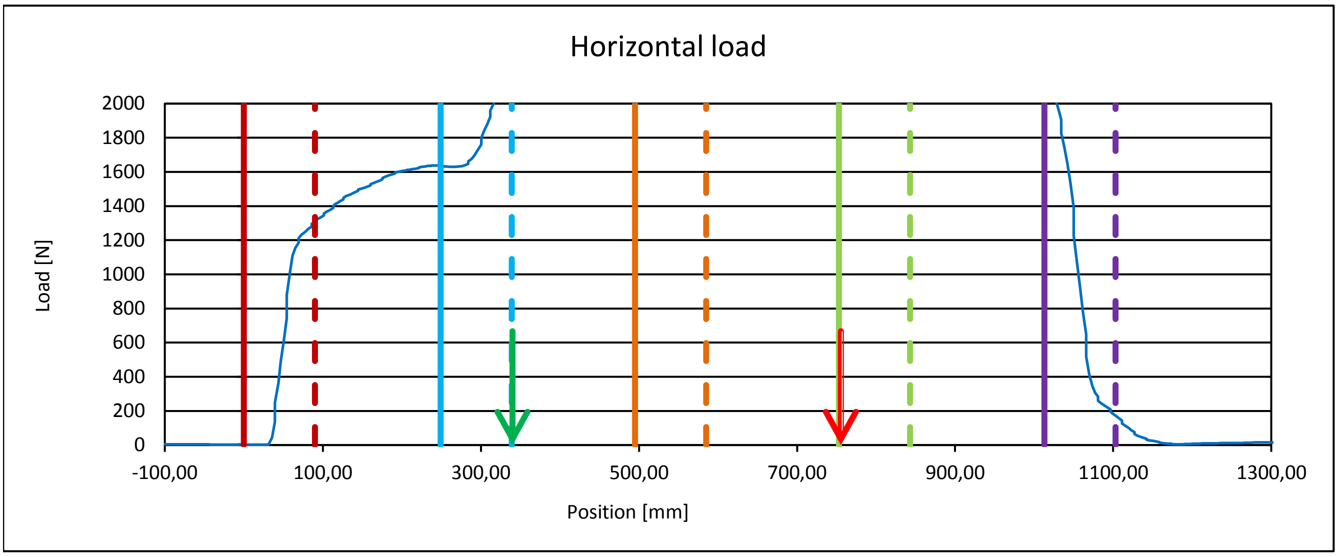
Averages in measuring length

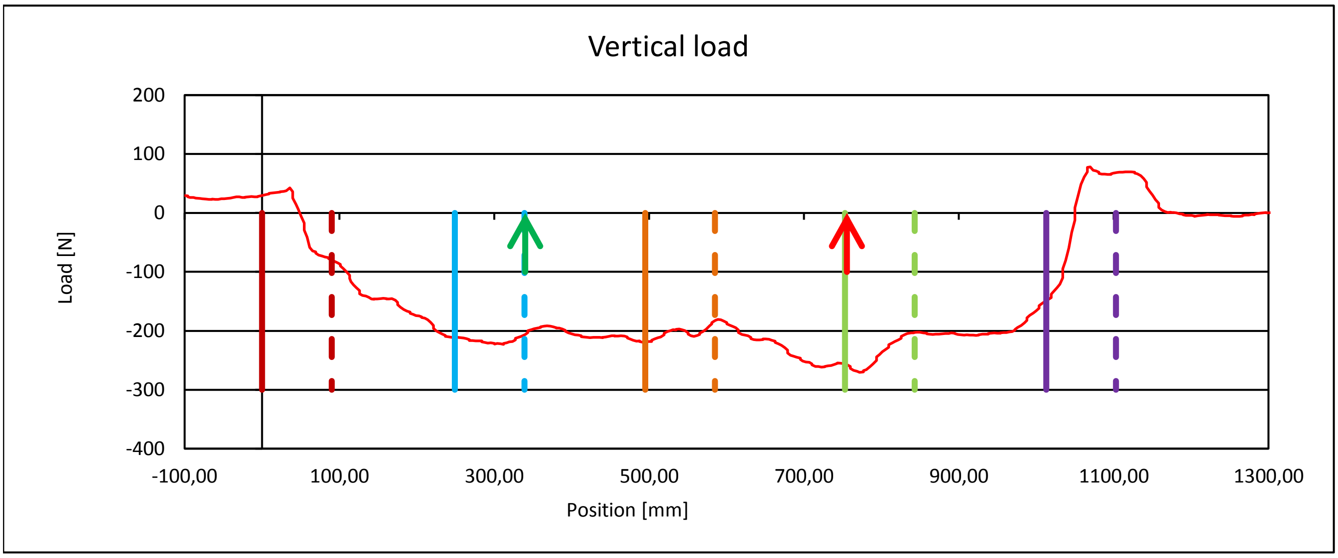
Start measuring length	339,9	mm
End measurement length	755,5	mm
Totaal length	415,5	mm
Average speed	31,7	mm/s
Average speed	114,0	m/h
Horizontal load cell	2427,9	N
Total Vertical load	-214,2	N
Total force	2437,4	N
Angle of total force	-5,0	Degree

Measured results







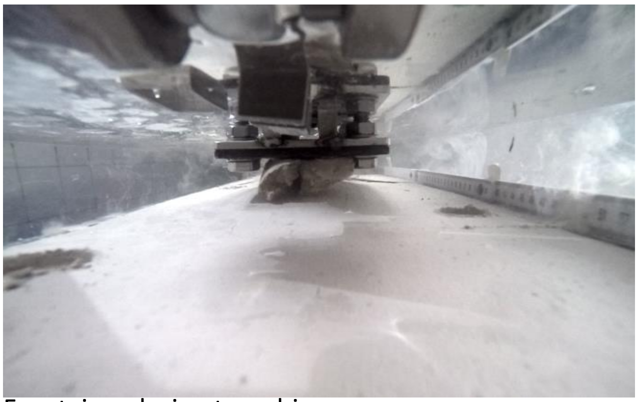


Right side of plough before trenching

Right side of plough after trenching

Left side of plough before trenching

Left side of plough after trenching


Frontview during trenching


Sideview during trenching


Top of first block


Top of second block


Top of third block


Top of fourth block

Middle of the second block
(cut perpendicular to the plough path)


Right side of the trench from the third block


Left side of the trench from the third block

TEST REPORT 06

General information

Test number:	6
Date of test:	31-10-2016
Time of test:	14:00
Test profile:	L

Length of clay box:	1025 mm
Water on top of clay:	69 mm
Depth of the plough:	94 mm
Set motor velocity:	-6 [-]
Clay type:	Soft

Particular during test

Particulars of the clay block:

0

Particular events during the test:

The plough did not have an angle of exectly 90 to the plough path. Therfore the right side of the plough had a smaller contact area with the clay then the left side. The screws on the stabilizer pins where very tight. This holds the plough in a fixed angle and could not "weathervane". Due to the 'drift' the plough forced itself to the right side.

Material properties of the clay

<u>Average shear strength*:</u> <u>24,2</u> kPa

<u>Average residual shear strength*:</u> <u>14,0</u> kPa

**average of field vane test before trenching block 3 to 7*

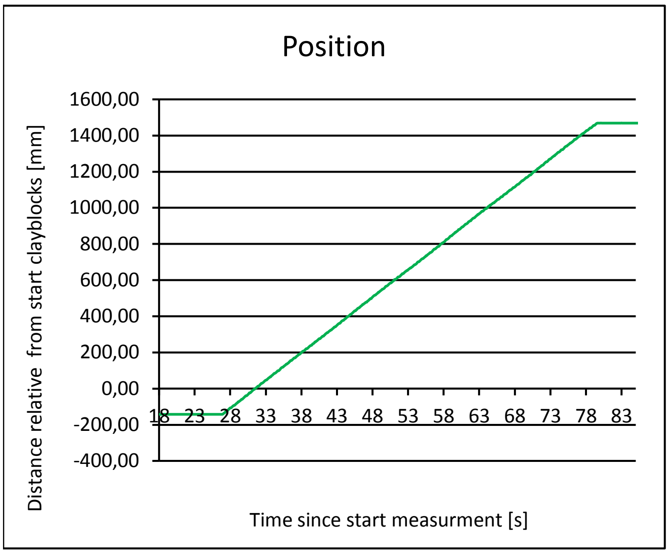
Field vane clay strength tests	**Block 1**	**Block 2**	**Block 3**	**Block 4**	
Shear strength test before trenching:	23	24	24	24	kPa
Residual strength test before trenching:	12	14	13	14	kPa
Shear strength test after trenching:	21	22	20	21	kPa

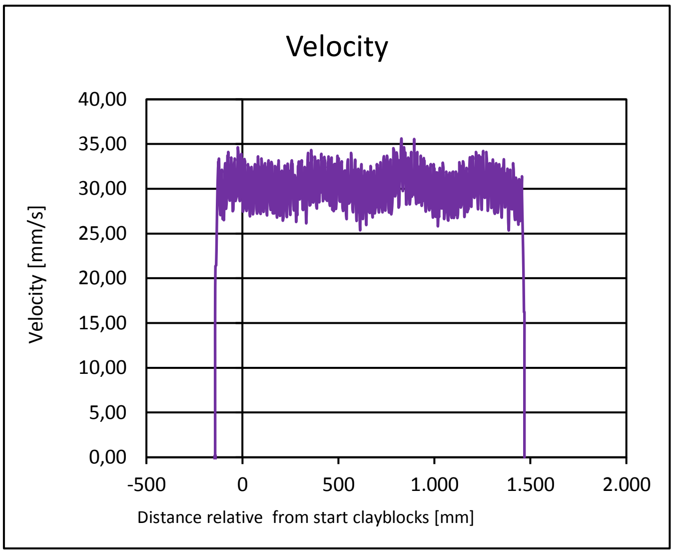
	Block 5	**Block 6**	**Block 7**	**Block 8**	
Shear strength test before trenching:	24	24	25	25	kPa
Residual strength test before trenching:	13	14	16	16	kPa
Shear strength test after trenching:	22	20	22	22	kPa

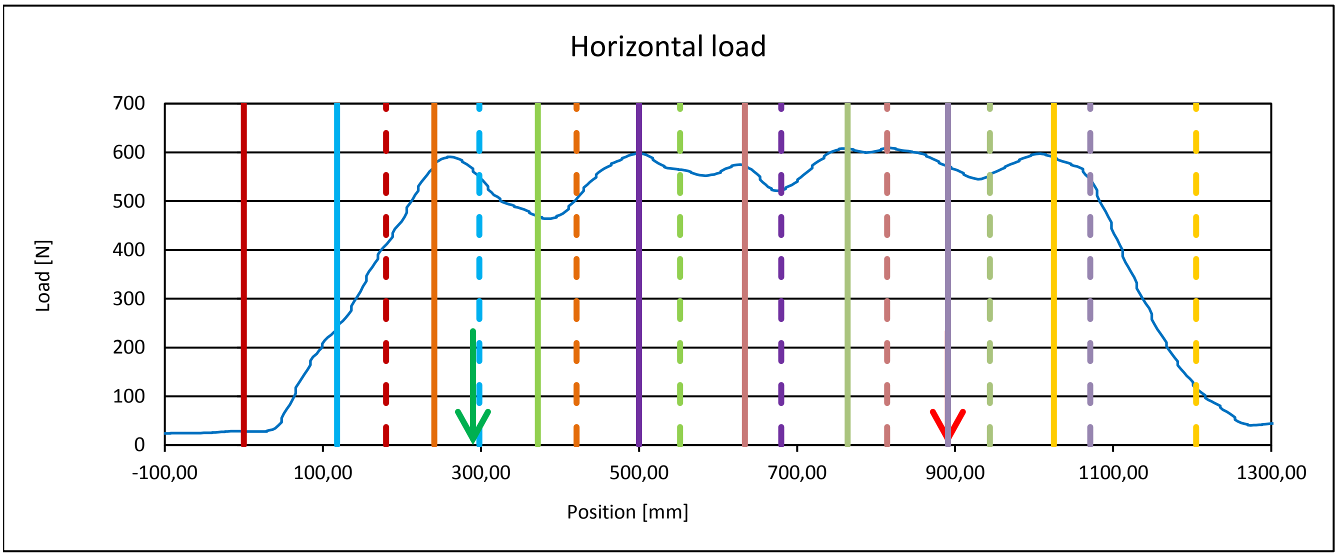
Averages in measuring length

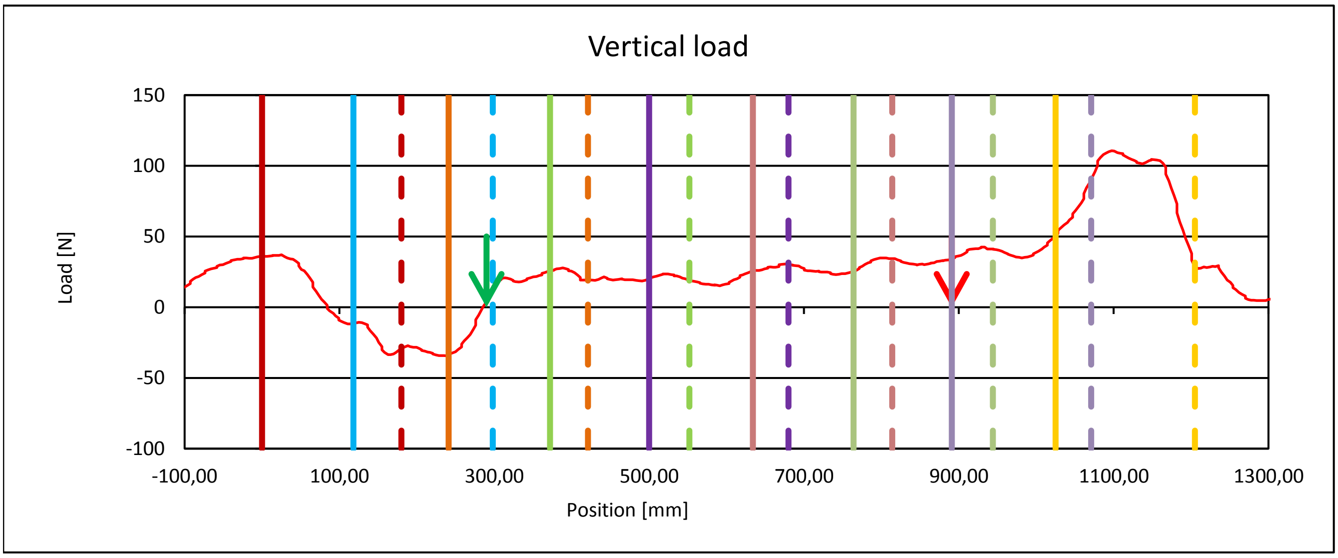
Start measuring length	289,9	mm
End measurement length	890,8	mm
Totaal length	600,9	mm
Average speed	30,8	mm/s
Average speed	111,0	m/h
Horizontal load cell	556,3	N
Total Vertical load	24,0	N
Total force	556,8	N
Angle of total force	2,5	Degree

Measured results

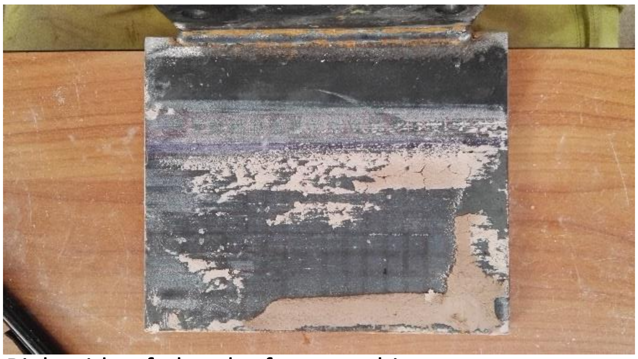








Left side of plough after trenching



Right side of plough after trenching

Frontview during trenching

Sideview during trenching

Top of first section

Top of middle section

Top of last section

Cross section

Sides of the trench

TEST REPORT 07

General information

Test number:	7	Length of clay box:	1008 mm
Date of test:	1-11-2016	Water on top of clay:	69 mm
Time of test:	10:00	Depth of the plough:	94 mm
Test profile:	L	Set motor velocity:	-6 [-]
		Clay type:	Soft

Particular during test

Particulars of the clay block:

0

Particular events during the test:

Left out the two spacers at the back of the cart. To enable the plough to 'weathervane' a bit more.

Material properties of the clay

Average shear strength*: 25,7 kPa

Average residual shear strength*: 16,3 kPa

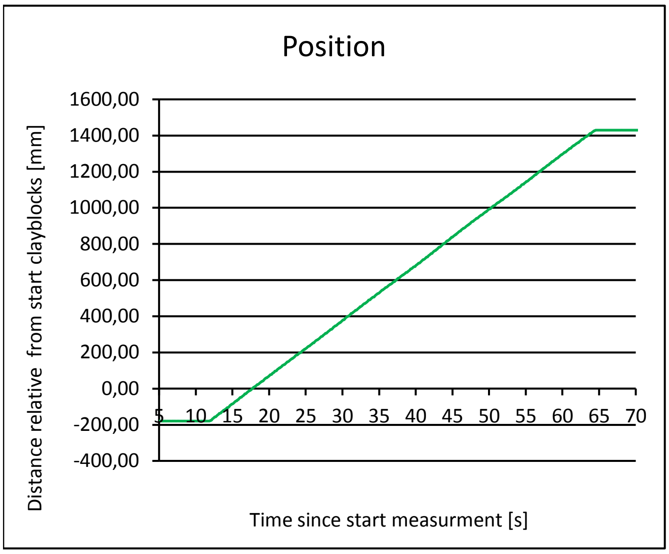
**average of field vane test before trenching block 5 to 7*

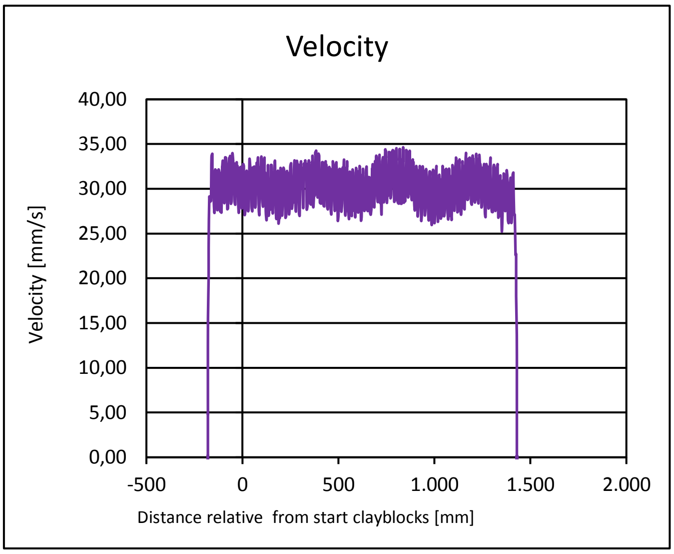
Field vane clay strength tests	**Block 1**	**Block 2**	**Block 3**	**Block 4**	
Shear strength test before trenching:	23	24	25	26	kPa
Residual strength test before trenching:	14	13	16	16	kPa
Shear strength test after trenching:	20	22	22	21	kPa
	Block 5	**Block 6**	**Block 7**	**Block 8**	
Shear strength test before trenching:	25	26	26	26	kPa
Residual strength test before trenching:	17	16	16	17	kPa
Shear strength test after trenching:	21	23	22	24	kPa

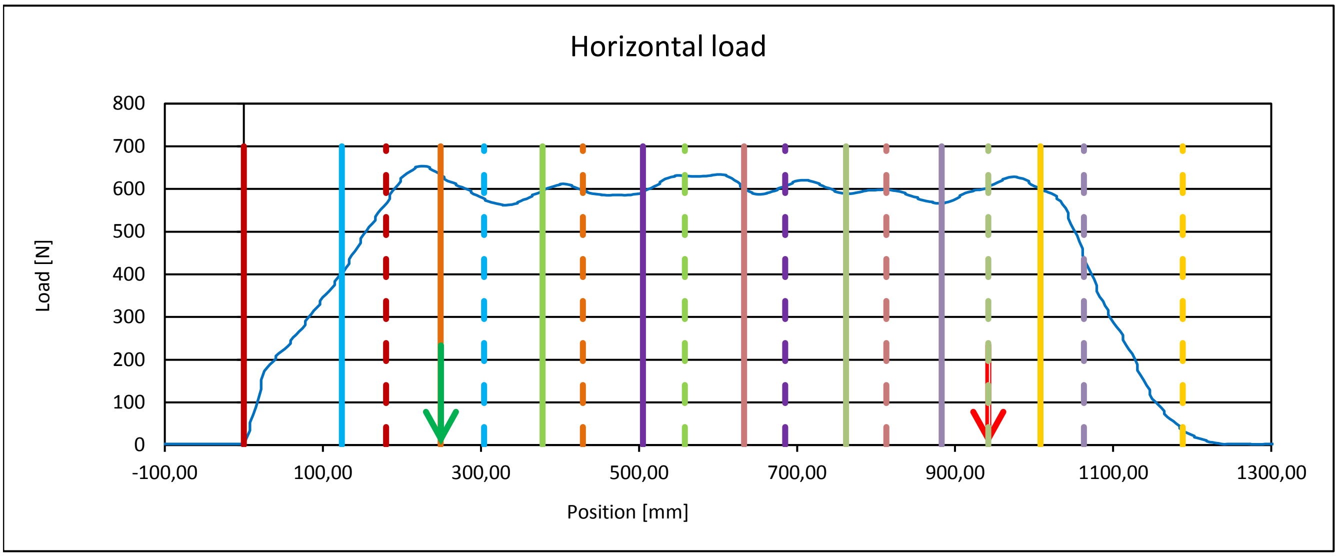
Averages in measuring length

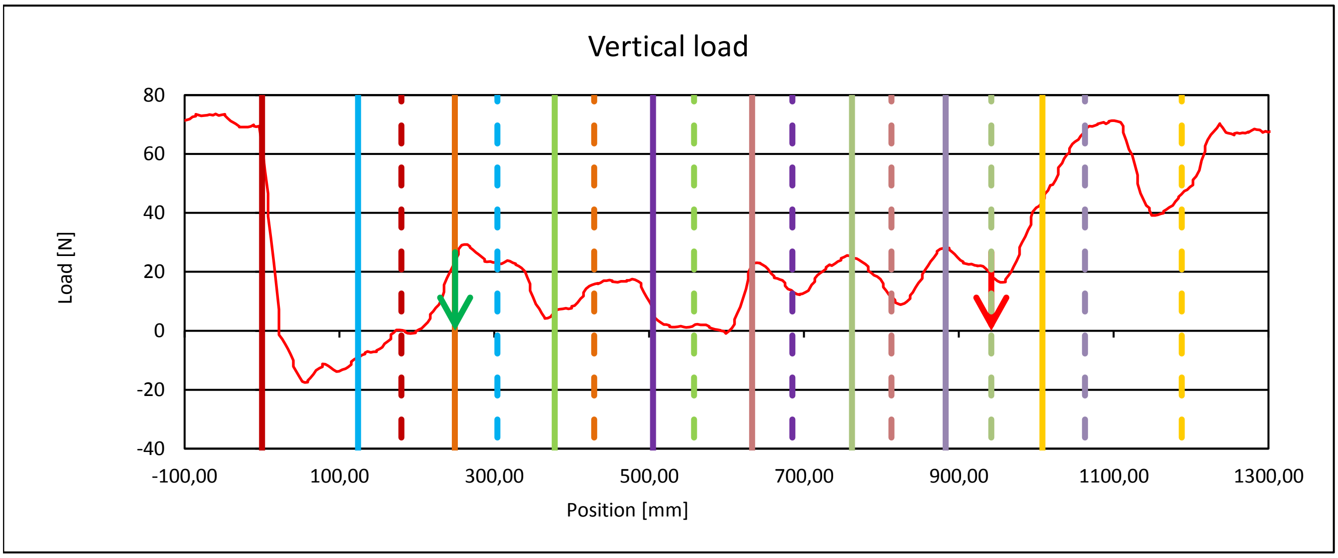
Start measuring length	249,4	mm
End measurement length	942,0	mm
Totaal length	692,6	mm
Average speed	30,9	mm/s
Average speed	111,2	m/h
Horizontal load cell	598,0	N
Total Vertical load	15,5	N
Total force	598,3	N
Angle of total force	1,5	Degree

Measured results

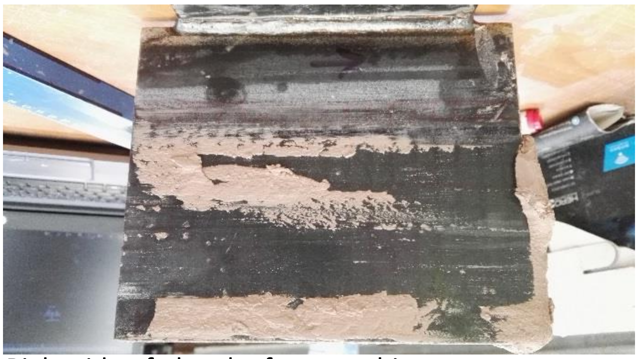




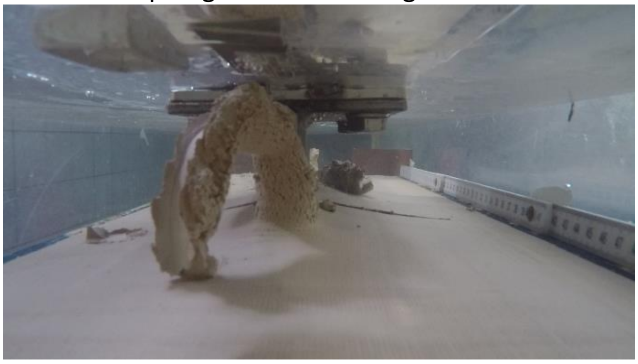




Left side of plough after trenching



Right side of plough after trenching



Frontview during trenching

Sideview during trenching

Top of first section

Top of middle section

Top of last section

Cross section

Sides of the trench

TEST REPORT 08

General information

Test number:	8	Length of clay box:	1005	mm
Date of test:	1-11-2016	Water on top of clay:	69	mm
Time of test:	15:00	Depth of the plough:	94	mm
Test profile:	M	Set motor velocity:	-6	[-]
		Clay type:	Soft	

Particular during test

Particulars of the clay block:

0

Particular events during the test:

Left out the two spacers at the back of the cart. To enable the plough to 'weathervane' a bit more.

Material properties of the clay

Average shear strength*: 25,7 kPa

Average residual shear strength*: 15,7 kPa

**average of field vane test before trenching block 5 to 7*

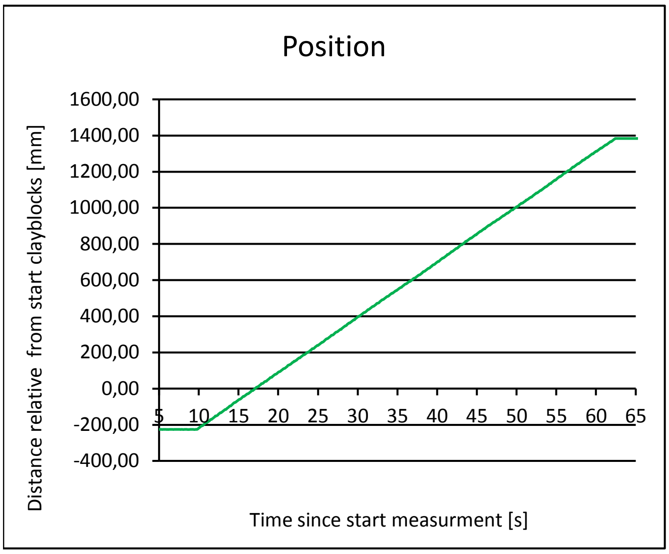
Field vane clay strength tests	**Block 1**	**Block 2**	**Block 3**	**Block 4**	
Shear strength test before trenching:	23	24	24	26	kPa
Residual strength test before trenching:	14	15	16	16	kPa
Shear strength test after trenching:	20	22	22	21	kPa

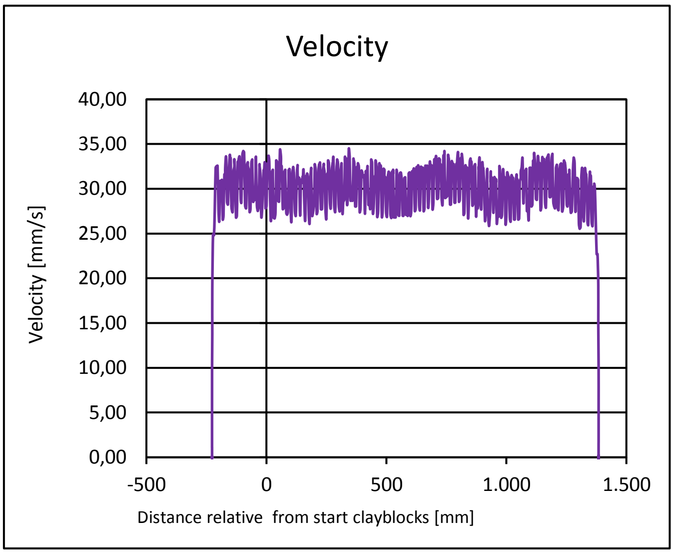
	Block 5	**Block 6**	**Block 7**	**Block 8**	
Shear strength test before trenching:	25	26	26	27	kPa
Residual strength test before trenching:	16	15	16	17	kPa
Shear strength test after trenching:	22	22	22	24	kPa

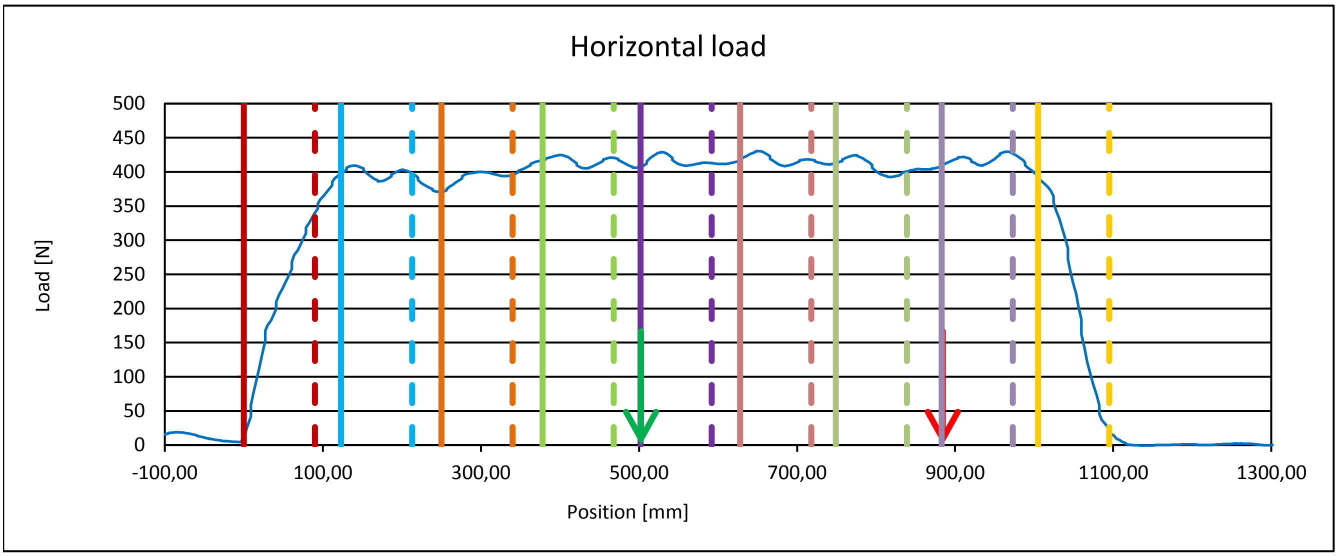
Averages in measuring length

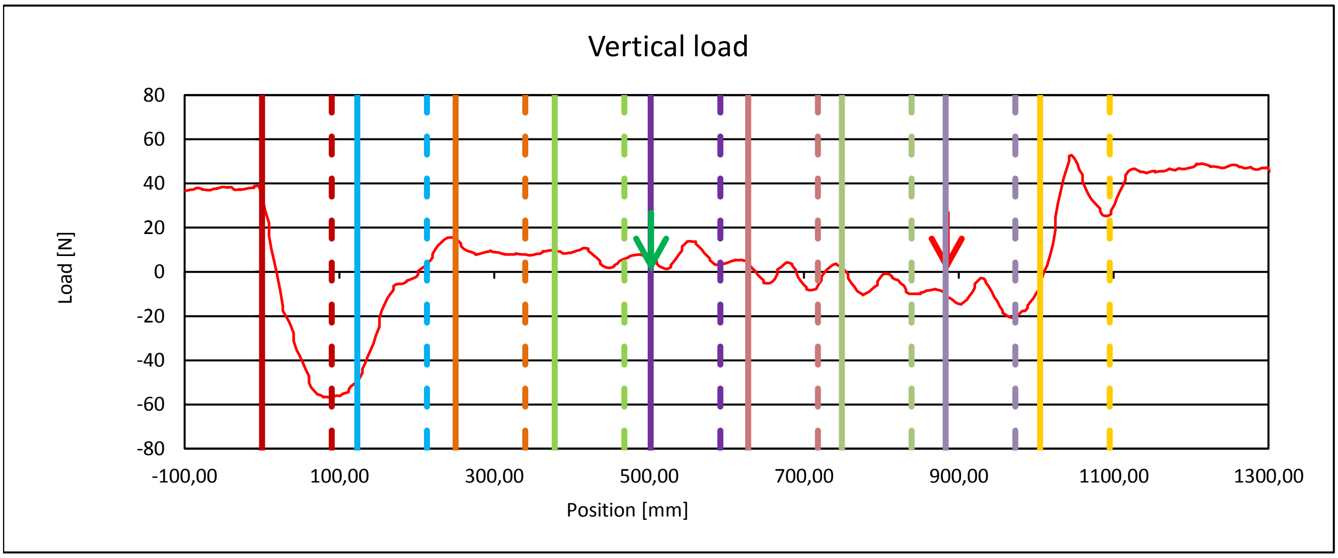
Start measuring length	502,6	mm
End measurement length	884,4	mm
Totaal length	381,8	mm
Average speed	30,7	mm/s
Average speed	110,5	m/h
Horizontal load cell	413,0	N
Total Vertical load	-0,5	N
Total force	413,0	N
Angle of total force	-0,1	Degree

Measured results









Left side of plough after trenching

Right side of plough after trenching

Frontview during trenching

Sideview during trenching

Top of first section

Top of middle section

Top of last section

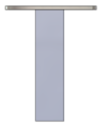
Cross section

Sides of the trench

TEST REPORT 09

General information

Test number:	9	Length of clay box:	1015 mm
Date of test:	2-11-2016	Water on top of clay:	69 mm
Time of test:	13:00	Depth of the plough:	94 mm
Test profile:	S	Set motor velocity:	-6 [-]
		Clay type:	Soft



Particular during test

Particulars of the clay block:

0

Particular events during the test:

Left out the two spacers at the back of the cart. To enable the plough to 'weathervane' freely.

Material properties of the clay

Average shear strength*: 24,5 kPa
Average residual shear strength*: 15,4 kPa

**average of field vane test before trenching block 2 to 7*

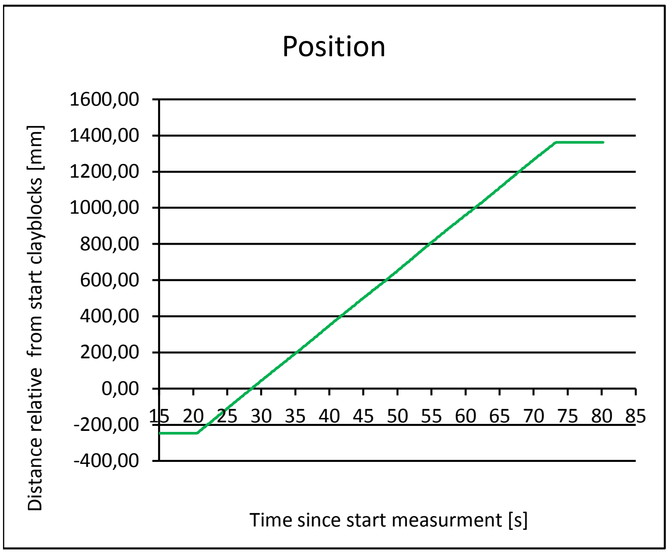
Field vane clay strength tests	**Block 1**	**Block 2**	**Block 3**	**Block 4**	
Shear strength test before trenching:	24	24	24	25	kPa
Residual strength test before trenching:	14	14	15	16	kPa
Shear strength test after trenching:	22	22	22	23	kPa

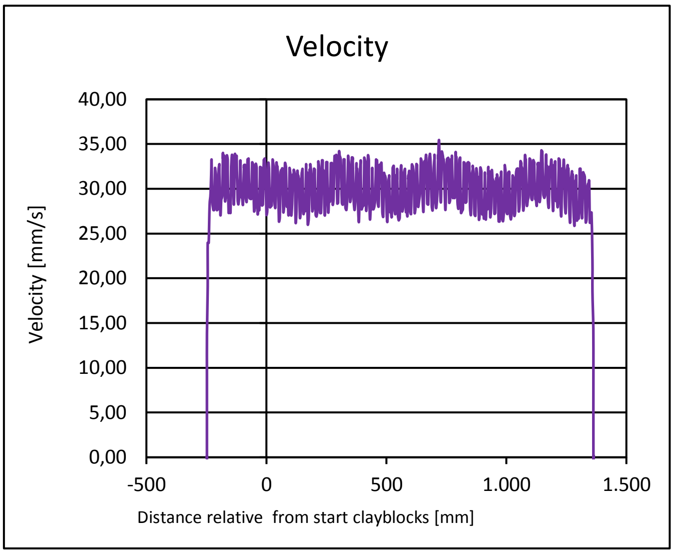
	Block 5	**Block 6**	**Block 7**	**Block 8**	
Shear strength test before trenching:	25	25	25	25	kPa
Residual strength test before trenching:	15	15	16	16	kPa
Shear strength test after trenching:	22	23	22	22	kPa

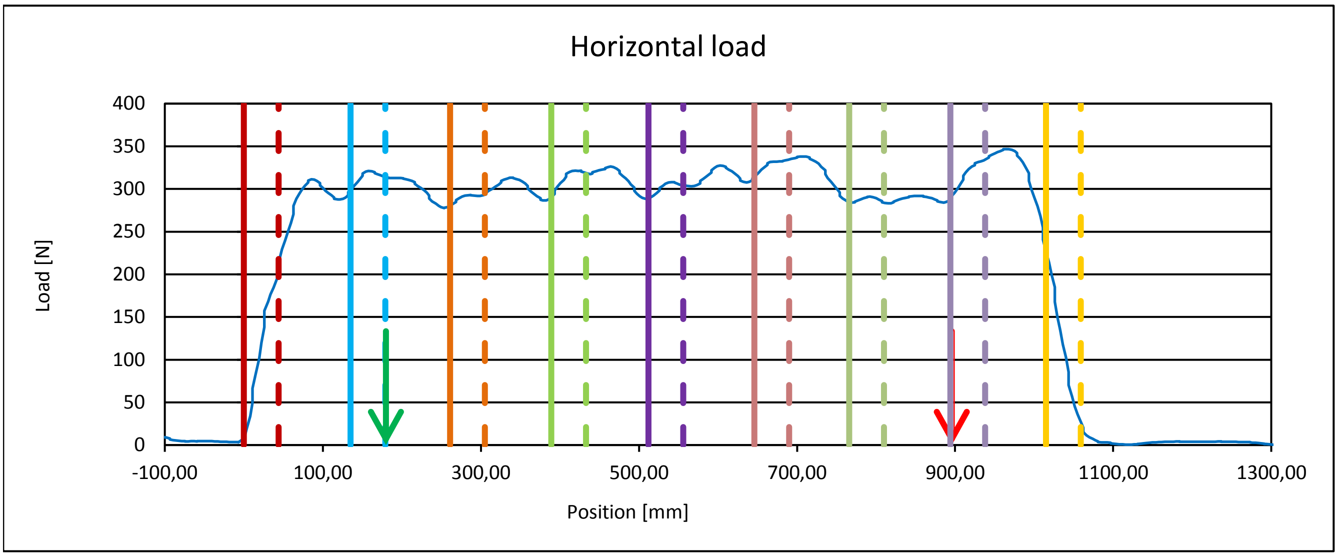
Averages in measuring length

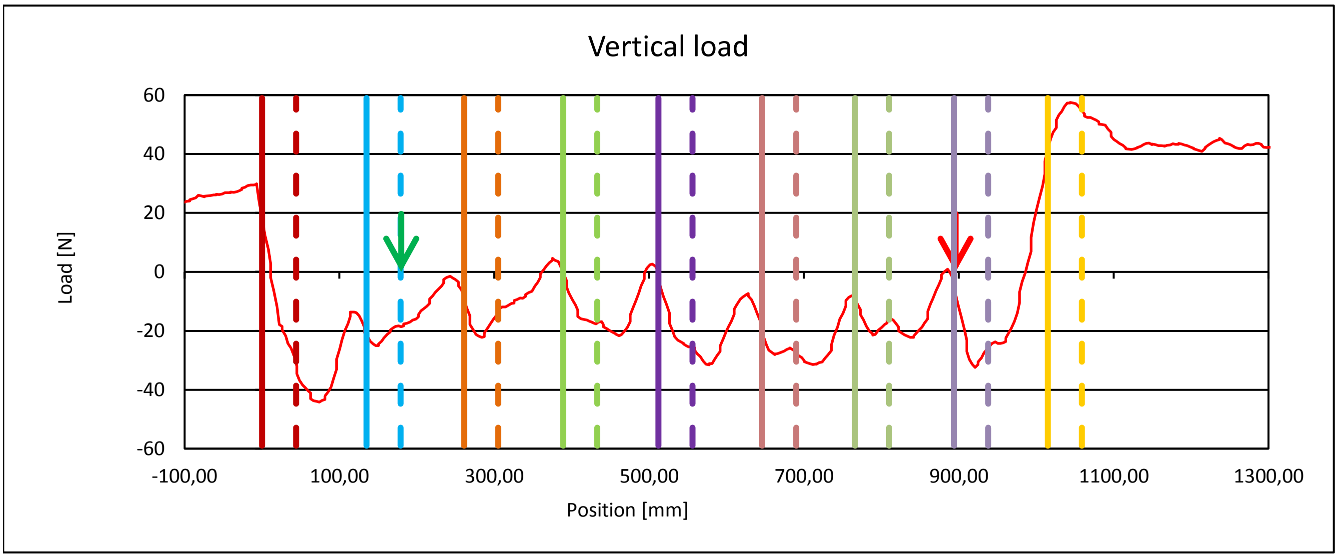
Start measuring length	179,8	mm
End measurement length	895,8	mm
Totaal length	716,0	mm
Average speed	30,7	mm/s
Average speed	110,6	m/h
Horizontal load cell	305,1	N
Total Vertical load	-15,2	N
Total force	305,5	N
Angle of total force	-2,9	Degree

Measured results

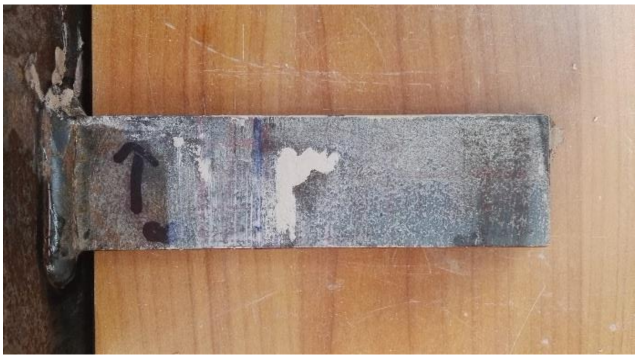








Left side of plough after trenching



Right side of plough after trenching

Frontview during trenching

Sideview during trenching

Top of first section

Top of middle section

Top of last section

Cross section at start of clay container

Sides of the trench

TEST REPORT 10

General information

Test number:	10
Date of test:	4-11-2016
Time of test:	14:00
Test profile:	ALPHA

Length of clay box:	997	mm
Water on top of clay:	69	mm
Depth of the plough:	94	mm
Set motor velocity:	-6	[-]
Clay type:	Soft	

Particular during test

Particulars of the clay block:

0

Particular events during the test:

Gaps of the plough are filled before the test. Left out the two spacers at the back of the cart. To enable the plough to 'weathervane' freely. Plough did drift off and hit the end of the clay container. Plough had to be pulled out vertically out of the clay.

Material properties of the clay

Average shear strength*: 24,0 kPa
Average residual shear strength*: 15,6 kPa

**average of field vane test before trenching block 3 to 7*

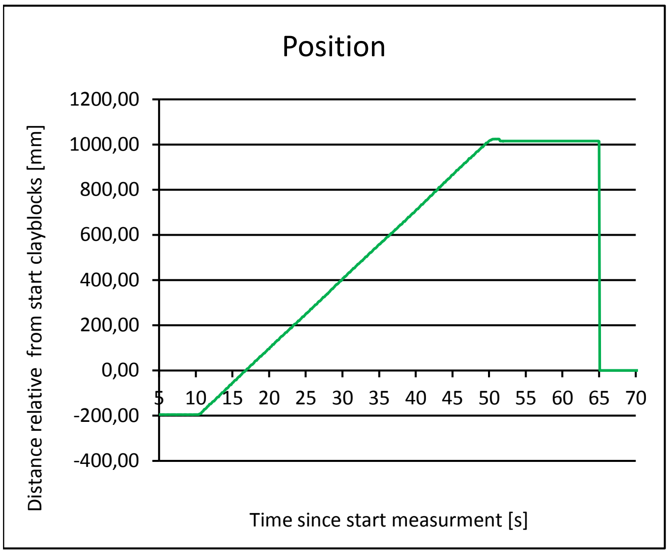
Field vane clay strength tests	**Block 1**	**Block 2**	**Block 3**	**Block 4**	
Shear strength test before trenching:	23	23	24	24	kPa
Residual strength test before trenching:	14	16	15	15	kPa
Shear strength test after trenching:	22	22	20	21	kPa

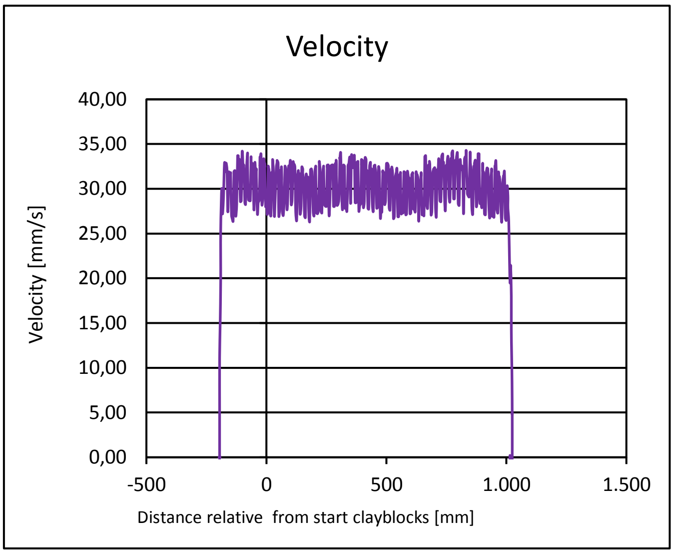
	Block 5	**Block 6**	**Block 7**	**Block 8**	
Shear strength test before trenching:	24	24	24	26	kPa
Residual strength test before trenching:	16	16	16	15	kPa
Shear strength test after trenching:	21	21	22	22	kPa

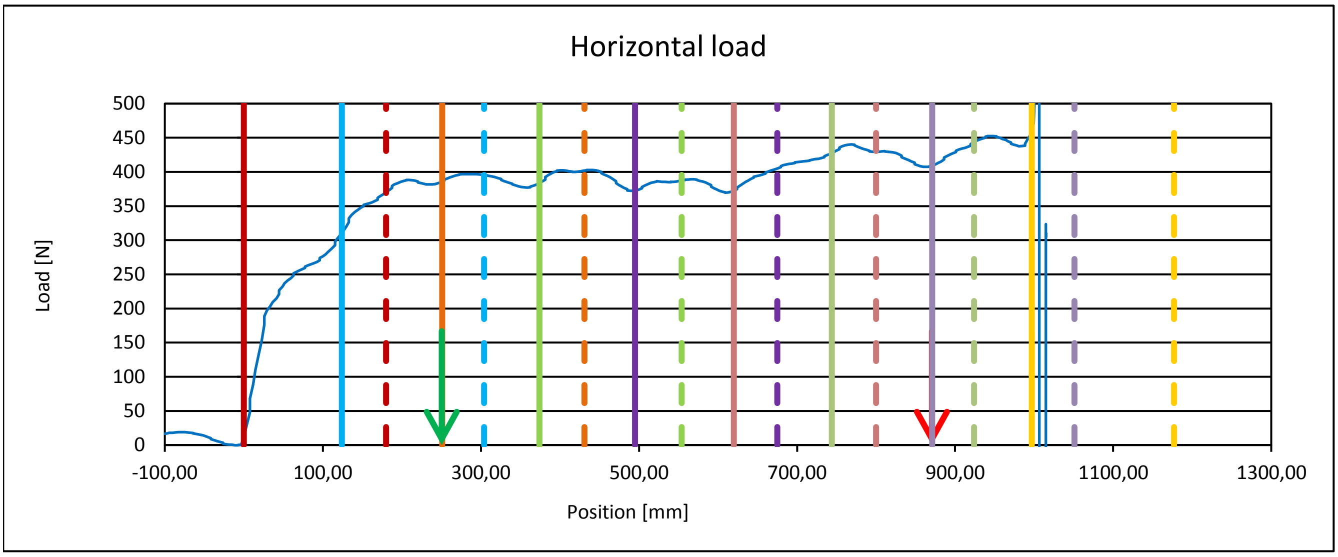
Averages in measuring length

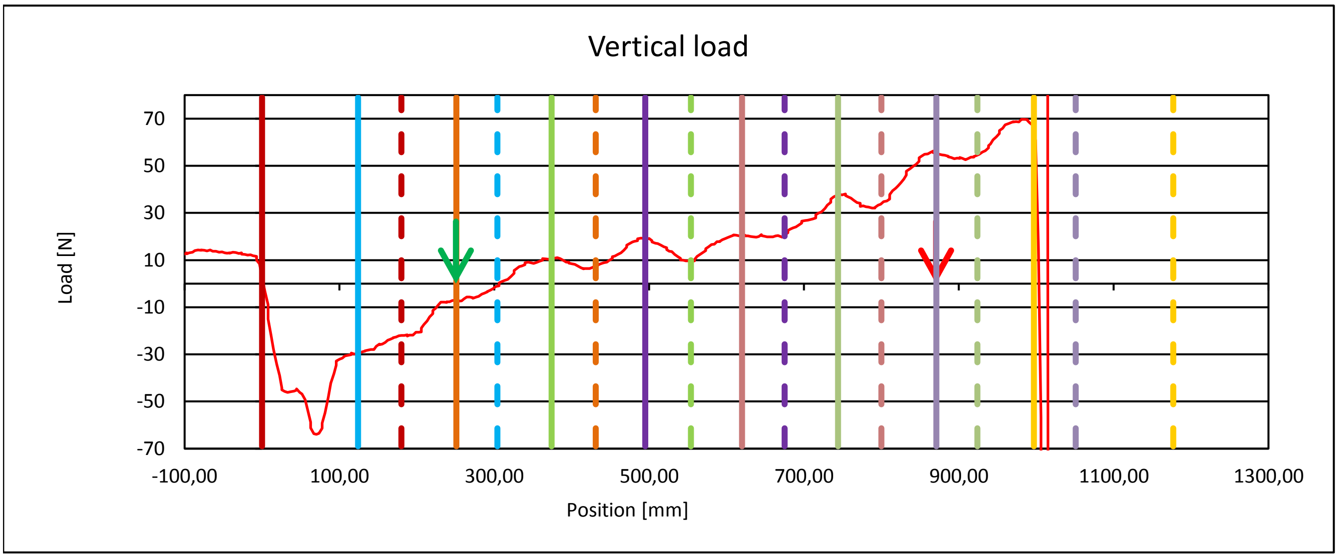
Start measuring length	250,4	mm
End measurement length	870,7	mm
Totaal length	620,3	mm
Average speed	30,8	mm/s
Average speed	111,0	m/h
Horizontal load cell	399,0	N
Total Vertical load	19,0	N
Total force	399,4	N
Angle of total force	2,7	Degree

Measured results










Right side of plough before trenching


Right side of plough after trenching


Frontview during trenching


Sideview during trenching


Top of first section


Top of middle section


Top of last section


Cross section at the start of the clay container


Sides of the trench

TEST REPORT 11

General information

Test number:	11	Length of clay box:	1005 mm
Date of test:	7-11-2016	Water on top of clay:	69 mm
Time of test:	11:00	Depth of the plough:	94 mm
Test profile:	BRAVO	Set motor velocity:	-6 [-]
		Clay type:	Soft

Particular during test

Particulars of the clay block:

0

Particular events during the test:

BRAVO plough with convex height of 5mm. Put back the two spacers at the back of the cart, bend the stabilizer on the right aft side to the outside. It looked like it was a bit bend in and could steer the plough to the right.

Material properties of the clay

Average shear strength*: 24,4 kPa

Average residual shear strength*: 15,6 kPa

**average of field vane test before trenching block 3 to 7*

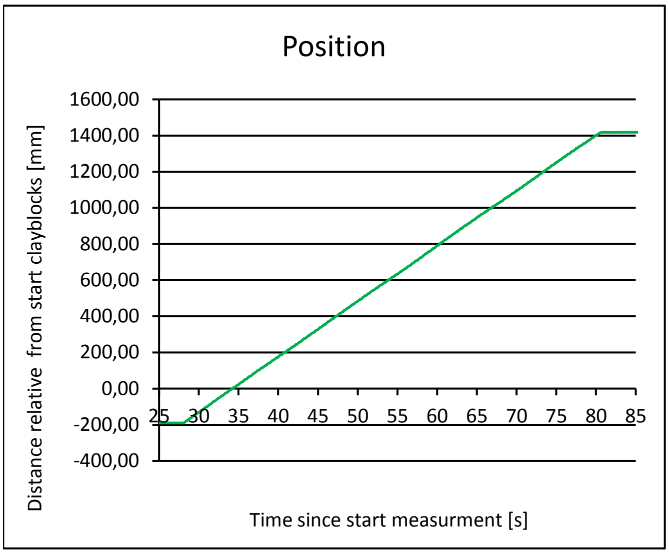
Field vane clay strength tests	**Block 1**	**Block 2**	**Block 3**	**Block 4**	
Shear strength test before trenching:	23	24	24	25	kPa
Residual strength test before trenching:	16	15	16	16	kPa
Shear strength test after trenching:	22	22	21	22	kPa

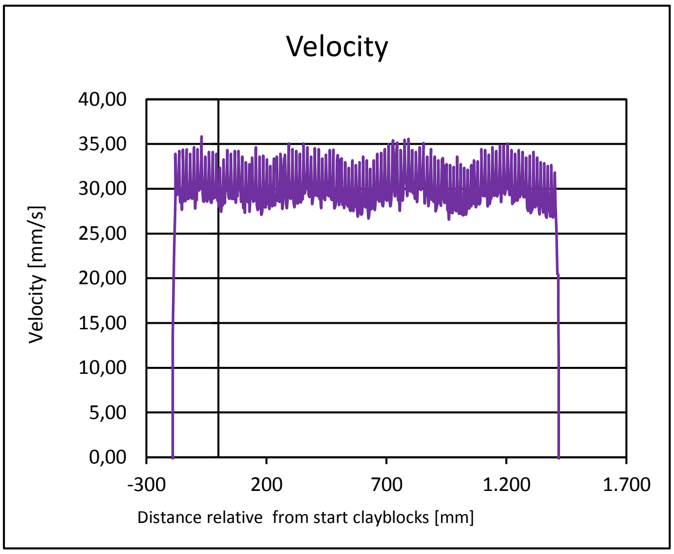
	Block 5	**Block 6**	**Block 7**	**Block 8**	
Shear strength test before trenching:	24	25	25	25	kPa
Residual strength test before trenching:	16	14	16	16	kPa
Shear strength test after trenching:	20	20	22	23	kPa

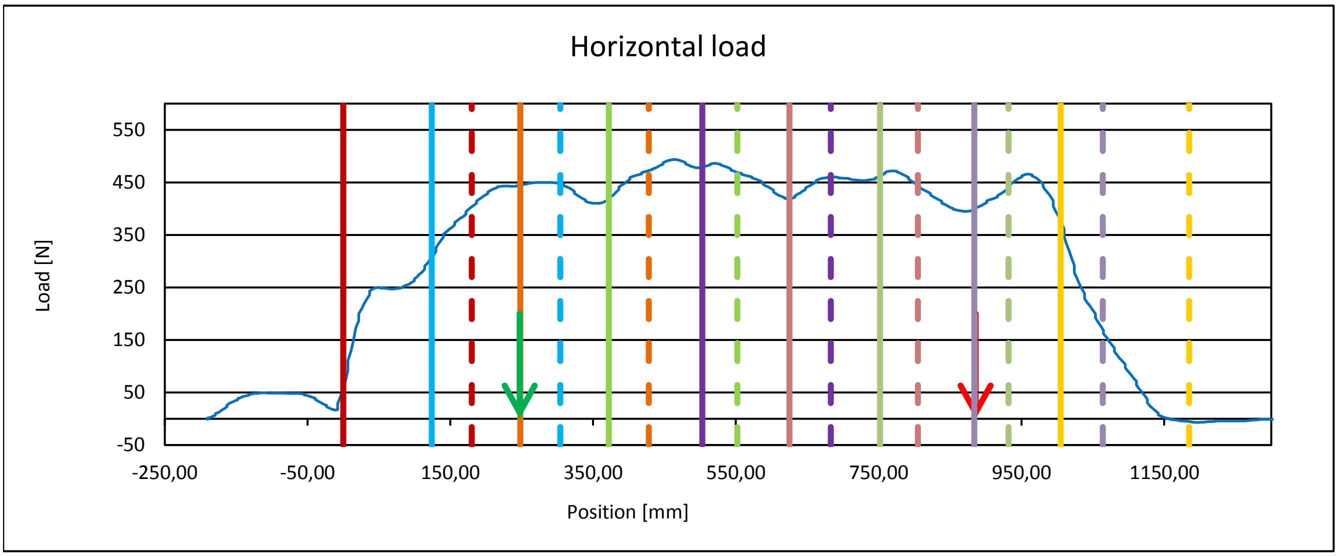
Averages in measuring length

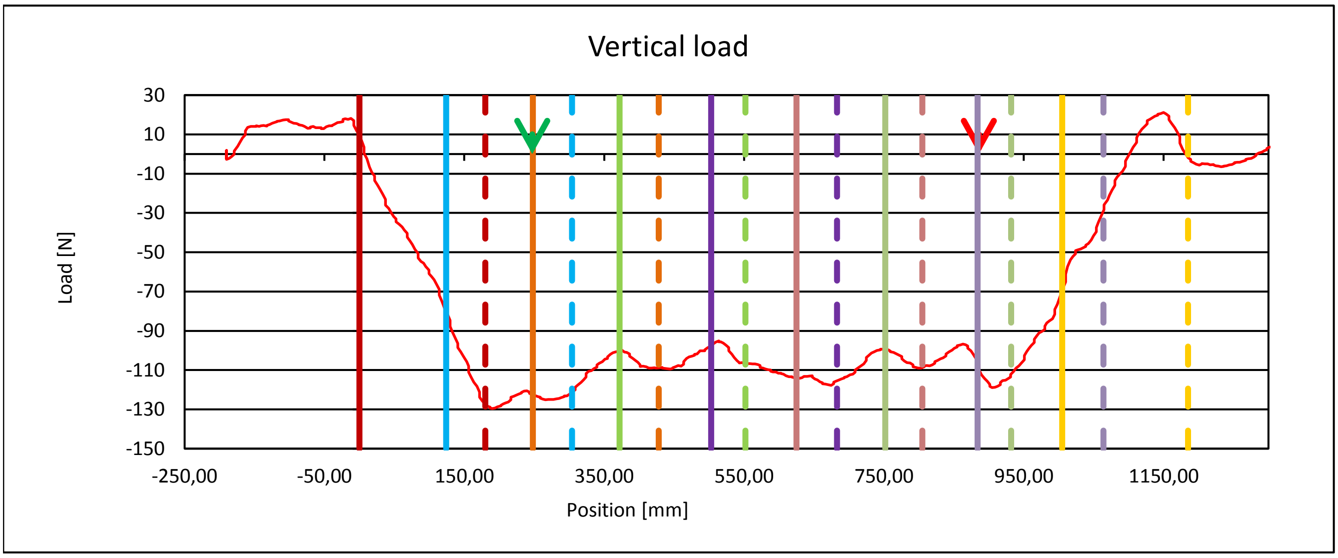
Start measuring length	247,1	mm
End measurement length	885,8	mm
Totaal length	638,7	mm
Average speed	30,9	mm/s
Average speed	111,2	m/h
Horizontal load cell	449,0	N
Total Vertical load	-108,2	N
Total force	461,9	N
Angle of total force	-13,6	Degree

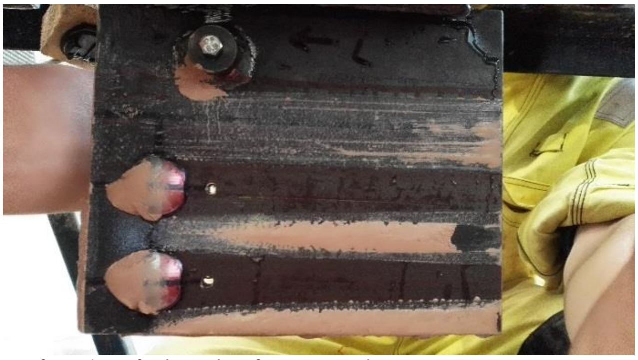
Measured results





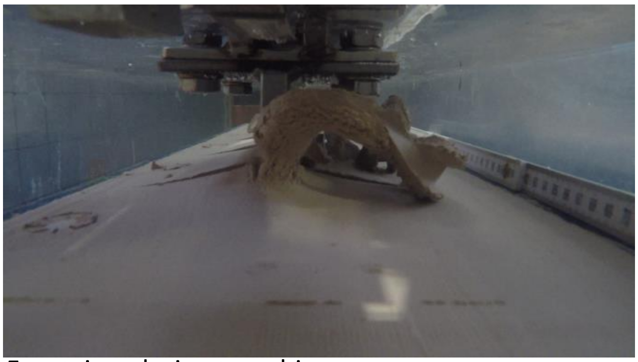






Left side of plough after trenching

Right side of plough after trenching



Frontview during trenching

Sideview during trenching

Top of first section

Top of middle section

Top of last section

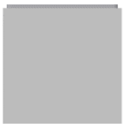
Cross section at the start of the clay container

Sides of the trench

TEST REPORT 12

General information

Test number:	12	Length of clay box:	1015 mm
Date of test:	11-11-2016	Water on top of clay:	69 mm
Time of test:	15:00	Depth of the plough:	94 mm
Test profile:	L	Set motor velocity:	-6 [-]
		Clay type:	Hard



Particular during test

Particulars of the clay block:

0

Particular events during the test:

0

Material properties of the clay

	Before	After	
Average shear strength:	114,5	116,3	kPa
Average residual shear strength:	63,0	55,7	kPa

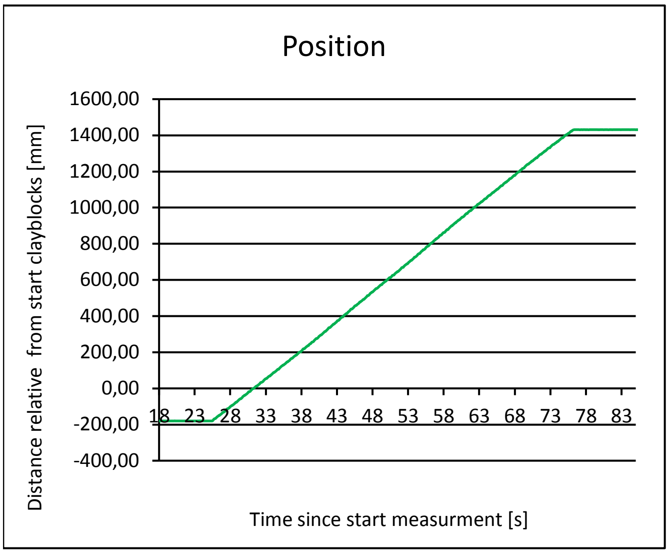
Field vane clay strength tests

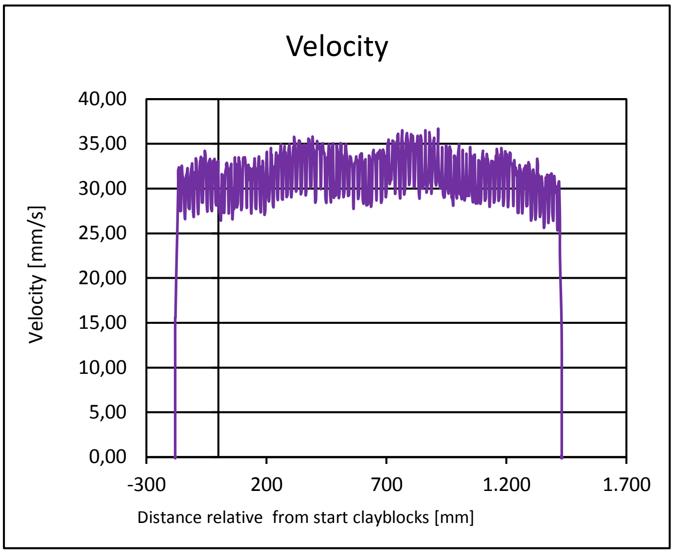
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	102	48	106	62
Left 2	108	84	109	62
Left 3	No test	No test	107	56
Right 1	122	50	128	50
Right 2	126	70	123	50
Right 3	No test	No test	125	54

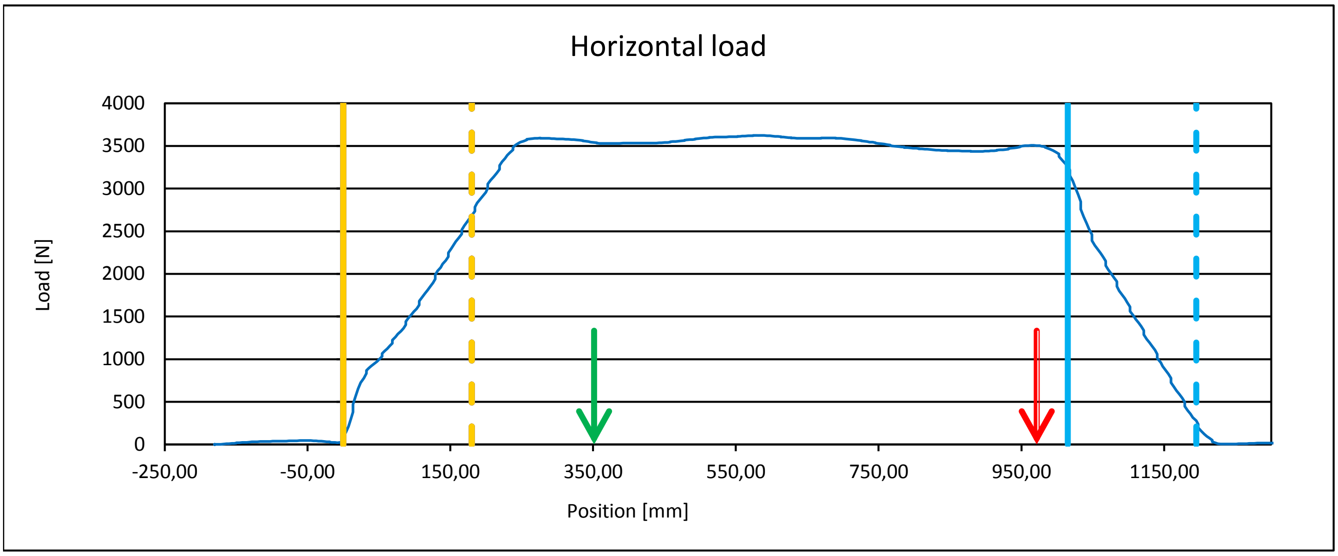
Averages in measuring length

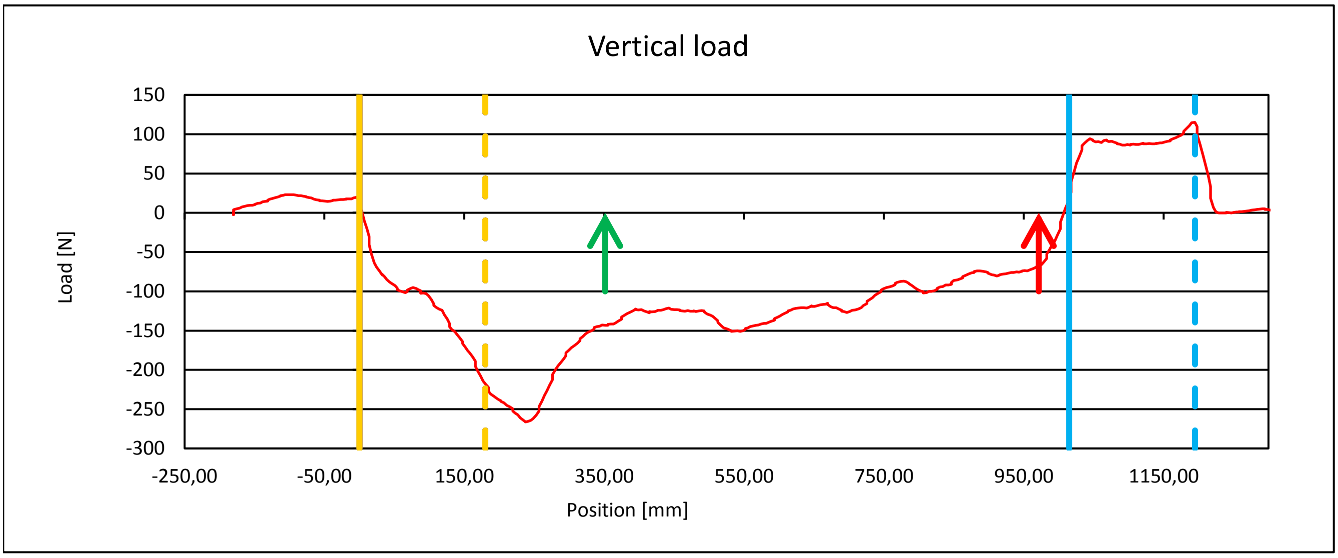
Start measuring length	351,4	mm
End measurement length	971,5	mm
Totaal length	620,1	mm
Average speed	32,7	mm/s
Average speed	117,9	m/h
Horizontal load cell	3537,2	N
Total Vertical load	-112,7	N
Total force	3539,0	N
Angle of total force	-1,8	Degree

Measured results









Left side of plough after trenching

Right side of plough after trenching

Frontview during trenching

Sideview during trenching

Top of first section

Top of middle section

Top of last section

Cross section at the end of the clay container

Sides of the trench

TEST REPORT 13

General information

Test number:	13
Date of test:	14-11-2016
Time of test:	11:00
Test profile:	M

Length of clay box:	1015	mm
Water on top of clay:	69	mm
Depth of the plough:	94	mm
Set motor velocity:	-6	[-]
Clay type:	Hard	

Particular during test

Particulars of the clay block:

0

Particular events during the test:

0

Material properties of the clay

	Before	After	
Average shear strength:	136,8	130,0	kPa
Average residual shear strength:	73,3	67,5	kPa

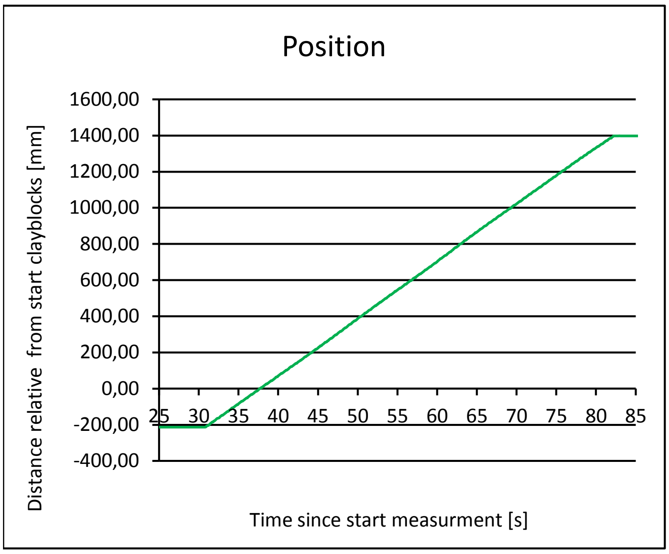
Field vane clay strength tests

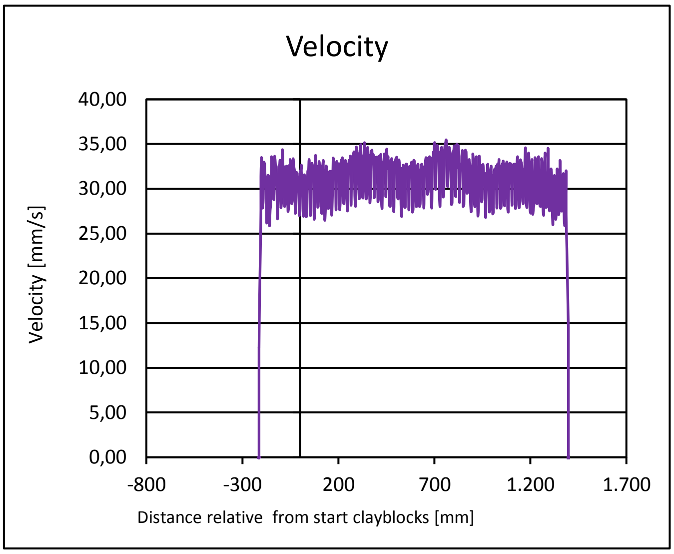
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	146	52	148	74
Left 2	154	70	132	65
Left 3	No test	No test	145	62
Right 1	122	79	125	64
Right 2	125	92	126	68
Right 3	No test	No test	104	72

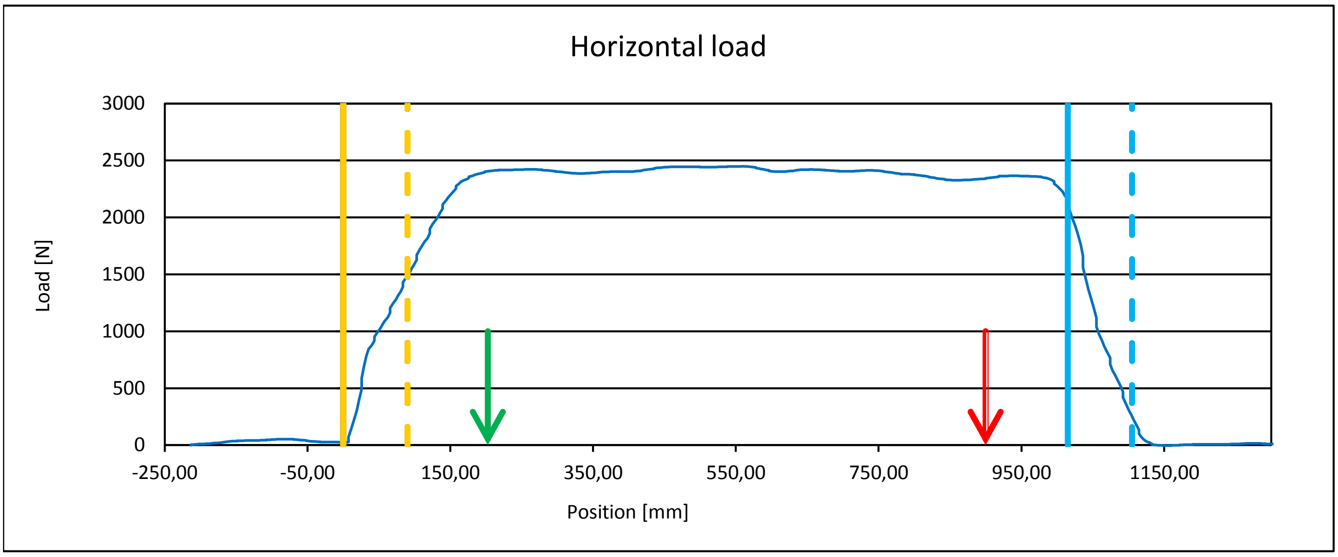
Averages in measuring length

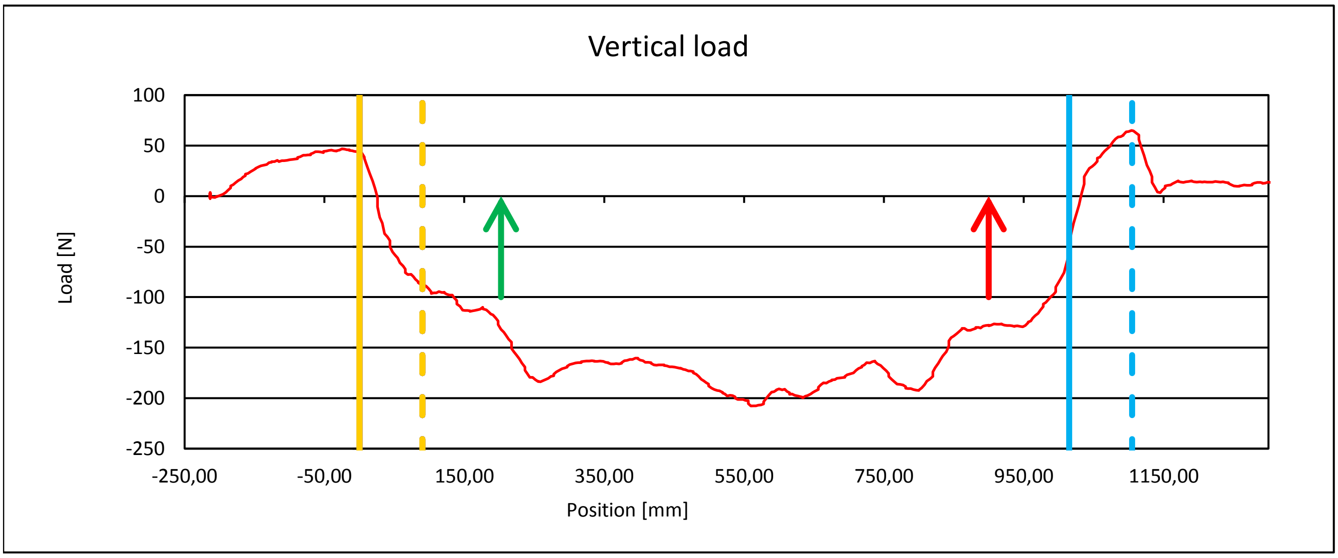
Start measuring length	202,5	mm
End measurement length	899,9	mm
Totaal length	697,4	mm
Average speed	32,0	mm/s
Average speed	115,3	m/h
Horizontal load cell	2405,2	N
Total Vertical load	-173,9	N
Total force	2411,4	N
Angle of total force	-4,1	Degree

Measured results









Left side of plough after trenching

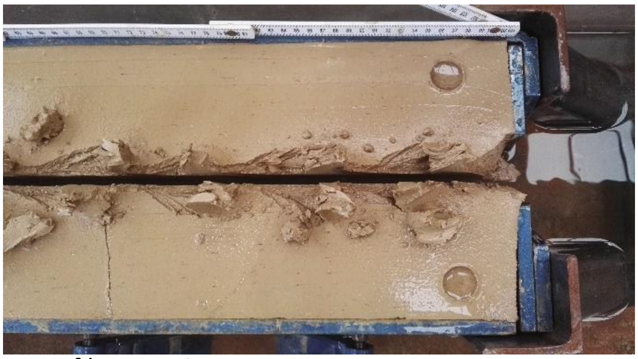
Right side of plough after trenching

Frontview during trenching

Sideview during trenching

Top of first section

Top of middle section



Top of last section

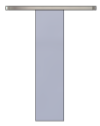
Cross section

Sides of the trench

TEST REPORT 14

General information

Test number:	14	Length of clay box:	1015 mm
Date of test:	14-11-2016	Water on top of clay:	69 mm
Time of test:	16:00	Depth of the plough:	94 mm
Test profile:	S	Set motor velocity:	-6 [-]
		Clay type:	Hard



Particular during test

Particulars of the clay block:

0

Particular events during the test:

0

Material properties of the clay

	Before	After	
Average shear strength:	127,3	129,8	kPa
Average residual shear strength:	92,3	64,3	kPa

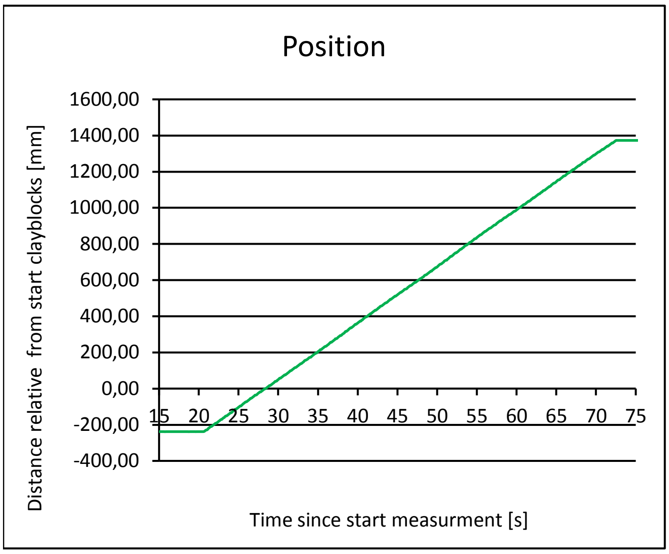
Field vane clay strength tests

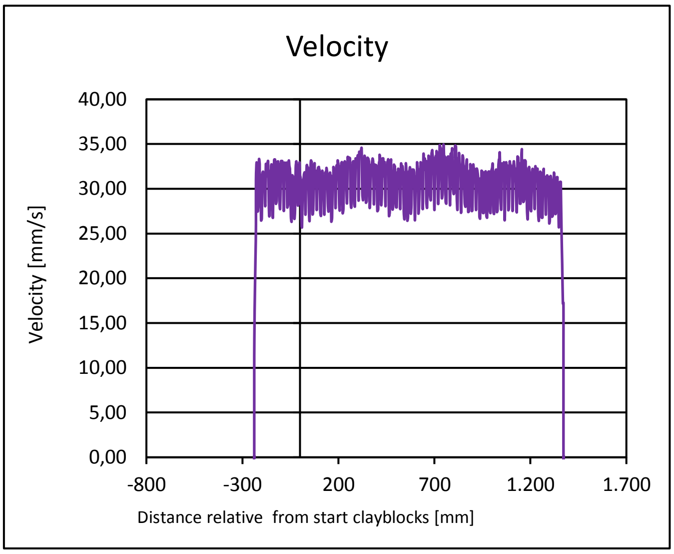
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	129	86	136	72
Left 2	128	86	135	70
Left 3	No test	No test	134	56
Right 1	125	98	124	63
Right 2	127	99	124	62
Right 3	No test	No test	126	63

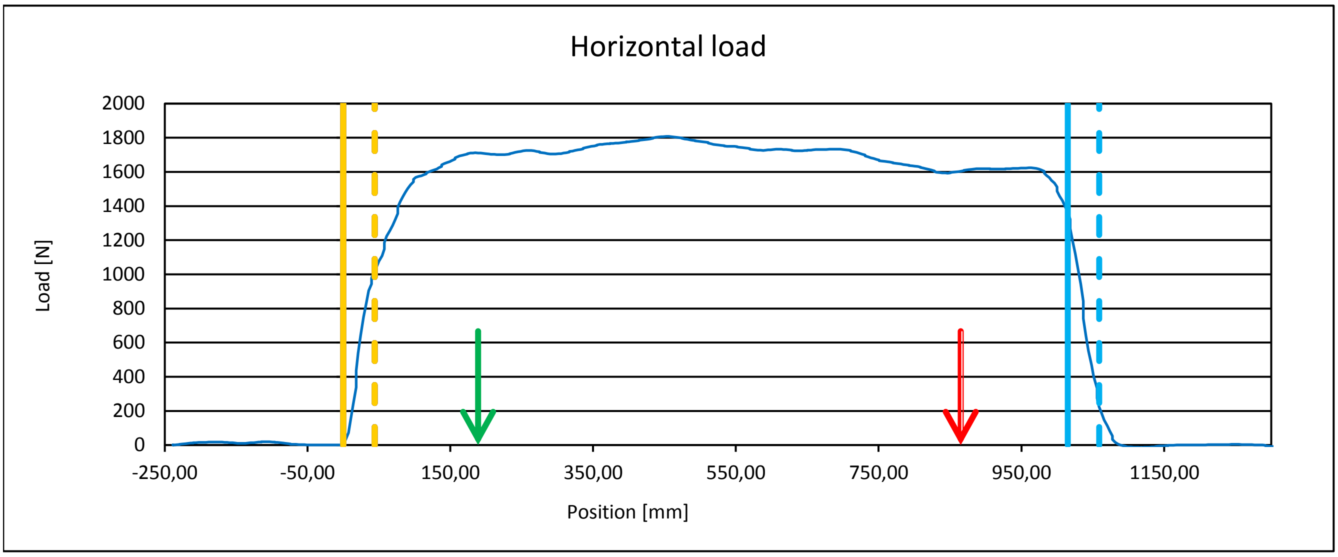
Averages in measuring length

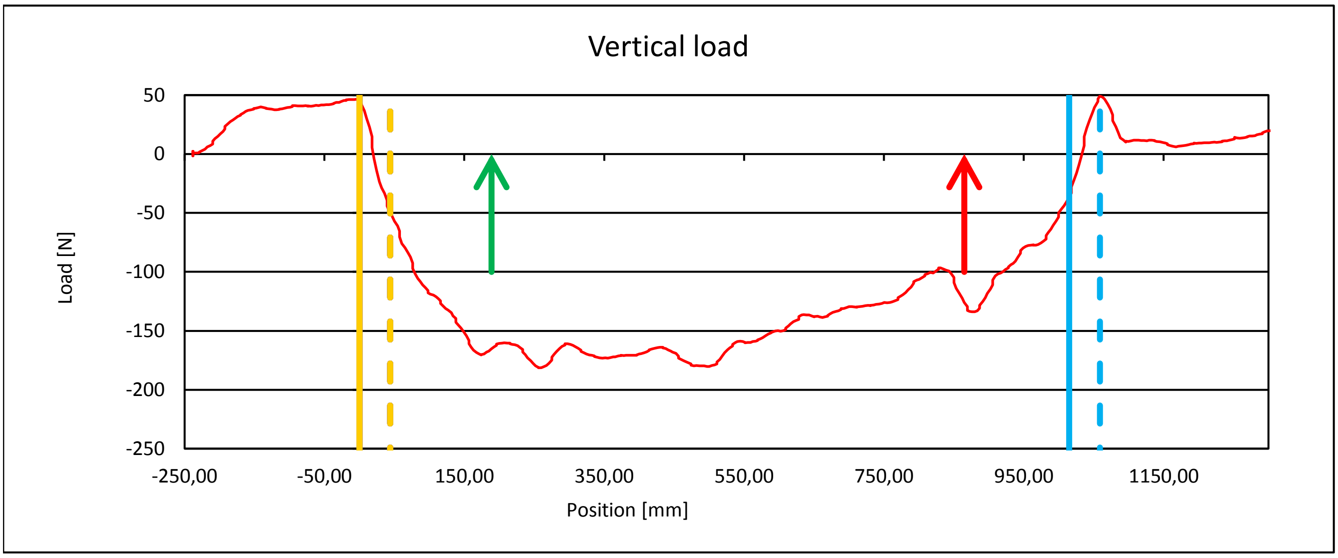
Start measuring length	188,9	mm
End measurement length	865,0	mm
Totaal length	676,1	mm
Average speed	31,6	mm/s
Average speed	113,7	m/h
Horizontal load cell	1721,7	N
Total Vertical load	-151,2	N
Total force	1728,3	N
Angle of total force	-5,0	Degree

Measured results





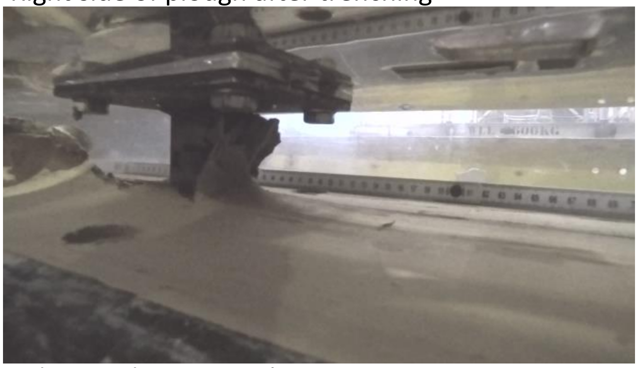


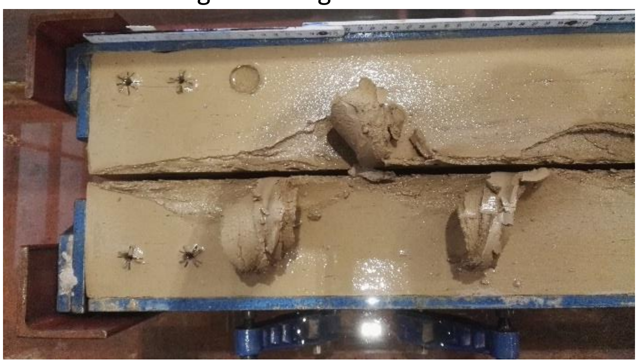



Left side of plough after trenching


Right side of plough after trenching


Frontview during trenching


Sideview during trenching


Top of first section


Top of middle section


Top of last section

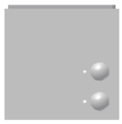

Cross section


Sides of the trench

TEST REPORT 15

General information

Test number:	15
Date of test:	15-11-2016
Time of test:	13:00
Test profile:	BRAVO



Length of clay box:	1015	mm
Water on top of clay:	69	mm
Depth of the plough:	94	mm
Set motor velocity:	-6	[-]
Clay type:	Hard	

Particular during test

Particulars of the clay block:

0

Particular events during the test:

BRAVO plough with convex height of 5mm

Material properties of the clay

	Before	After	
Average shear strength:	120,5	119,0	kPa
Average residual shear strength:	77,3	60,3	kPa

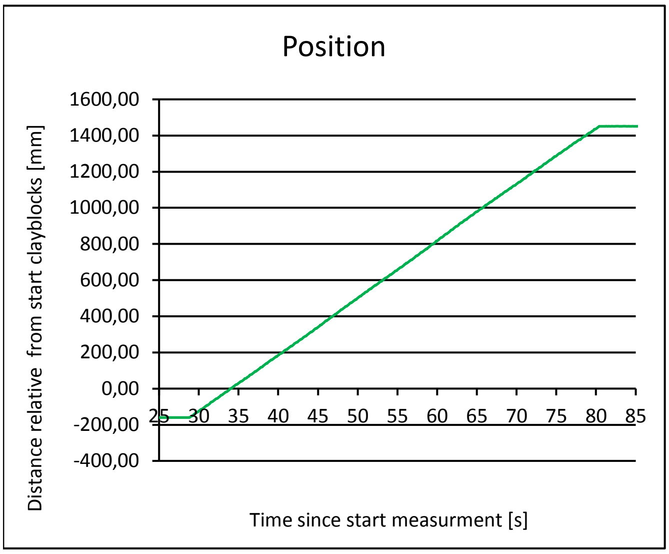
Field vane clay strength tests

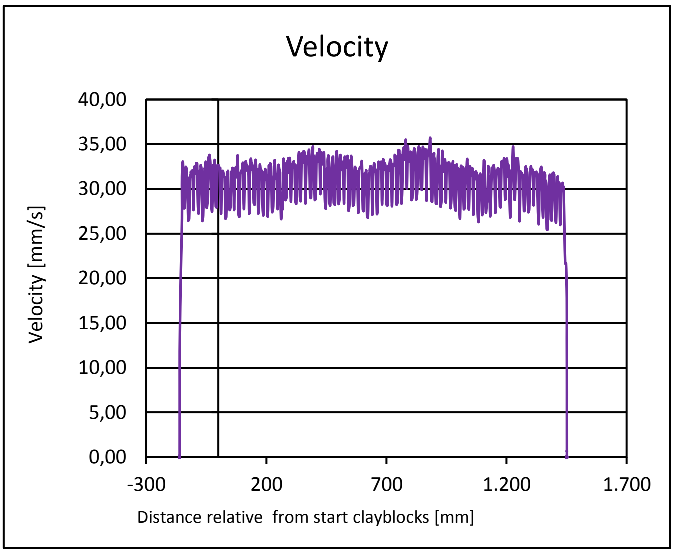
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	115	72	113	58
Left 2	116	89	115	62
Left 3	No test	No test	118	66
Right 1	124	69	121	62
Right 2	127	79	125	60
Right 3	No test	No test	122	54

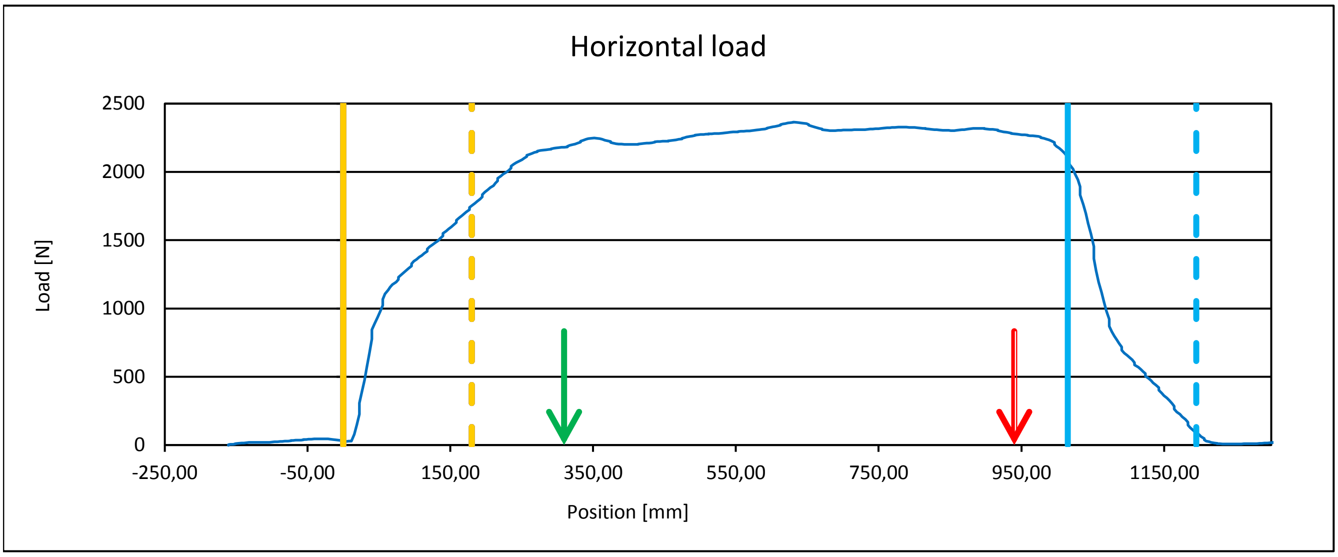
Averages in measuring length

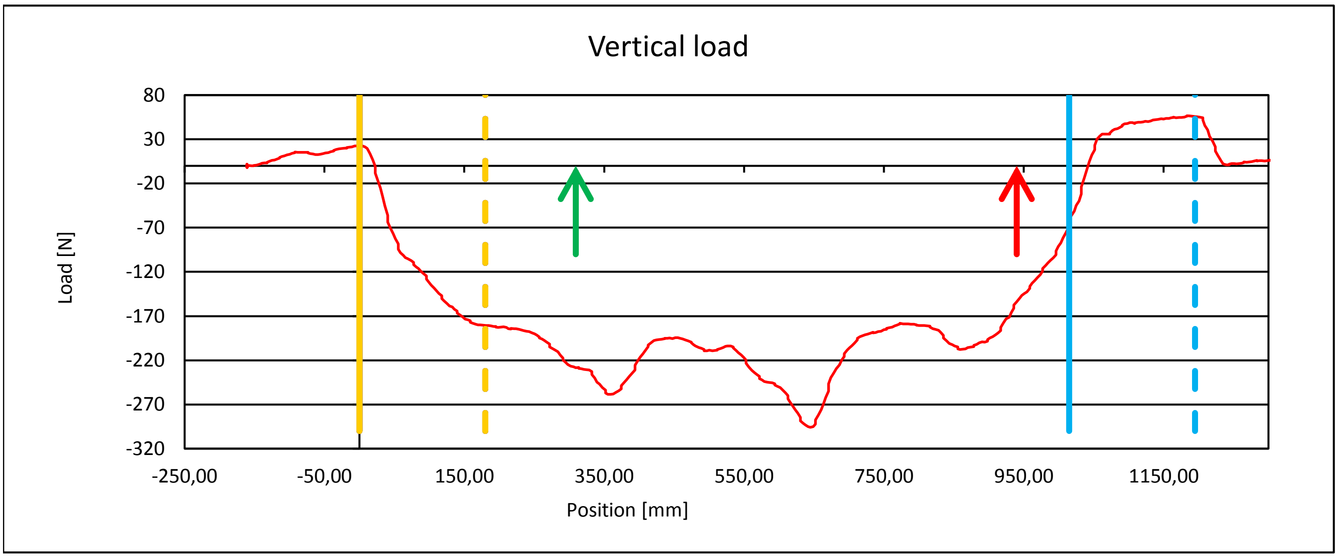
Start measuring length	309,4	mm
End measurement length	940,0	mm
Totaal length	630,6	mm
Average speed	31,9	mm/s
Average speed	115,0	m/h
Horizontal load cell	2286,0	N
Total Vertical load	-215,6	N
Total force	2296,1	N
Angle of total force	-5,4	Degree

Measured results

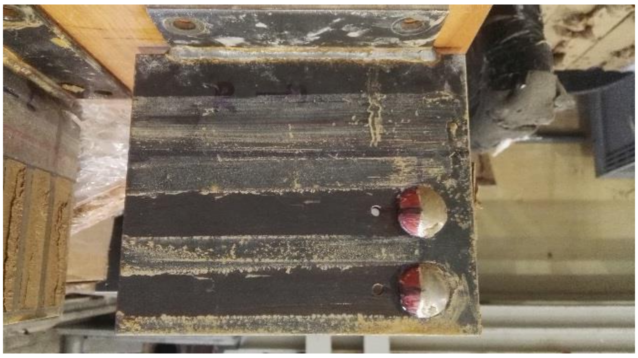








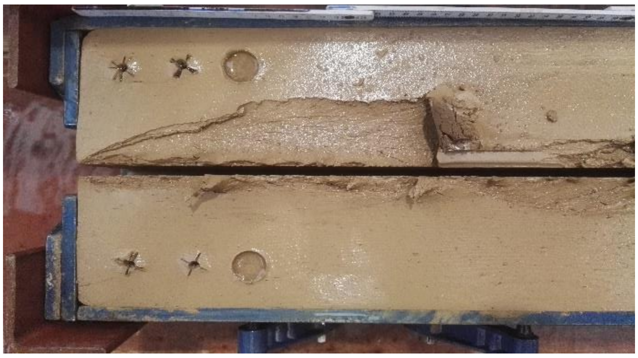
Left side of plough after trenching



Right side of plough after trenching

Frontview during trenching

Sideview during trenching



Top of first section

Top of middle section

Top of last section

Cross section

Sides of the trench

TEST REPORT 16

General information

Test number:	16	Length of clay box:	1015 mm
Date of test:	15-11-2016	Water on top of clay:	69 mm
Time of test:	17:00	Depth of the plough:	94 mm
Test profile:	ALPHA	Set motor velocity:	-6 [-]
		Clay type:	Hard

Particular during test

Particulars of the clay block:

0

Particular events during the test:

The gaps of the plough are filled with clay before the test. Plough did run into the metal plate at the back of the clay container. Stopped the test a short time, then continued.

Material properties of the clay

	Before	After	
Average shear strength:	121,0	121,2	kPa
Average residual shear strength:	80,5	64,8	kPa

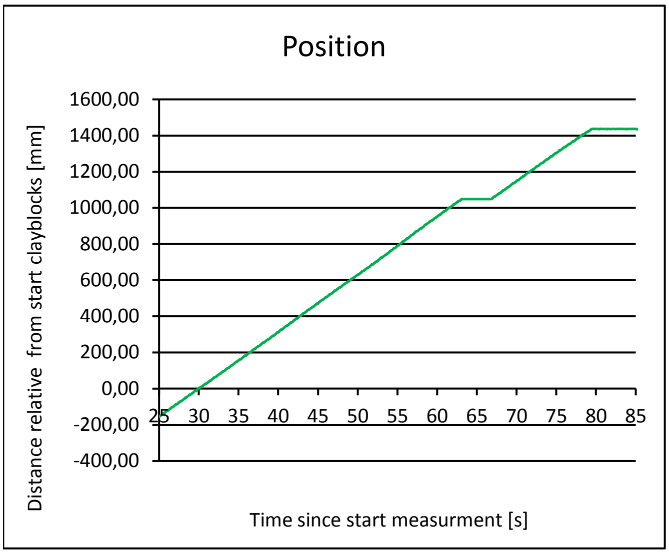
Field vane clay strength tests

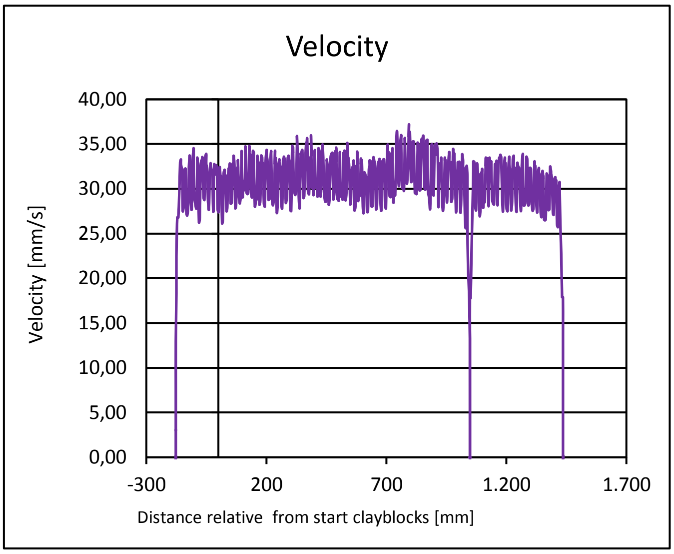
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	118	98	118	67
Left 2	116	84	118	91
Left 3	No test	No test	120	68
Right 1	122	63	123	57
Right 2	128	77	122	56
Right 3	No test	No test	126	50

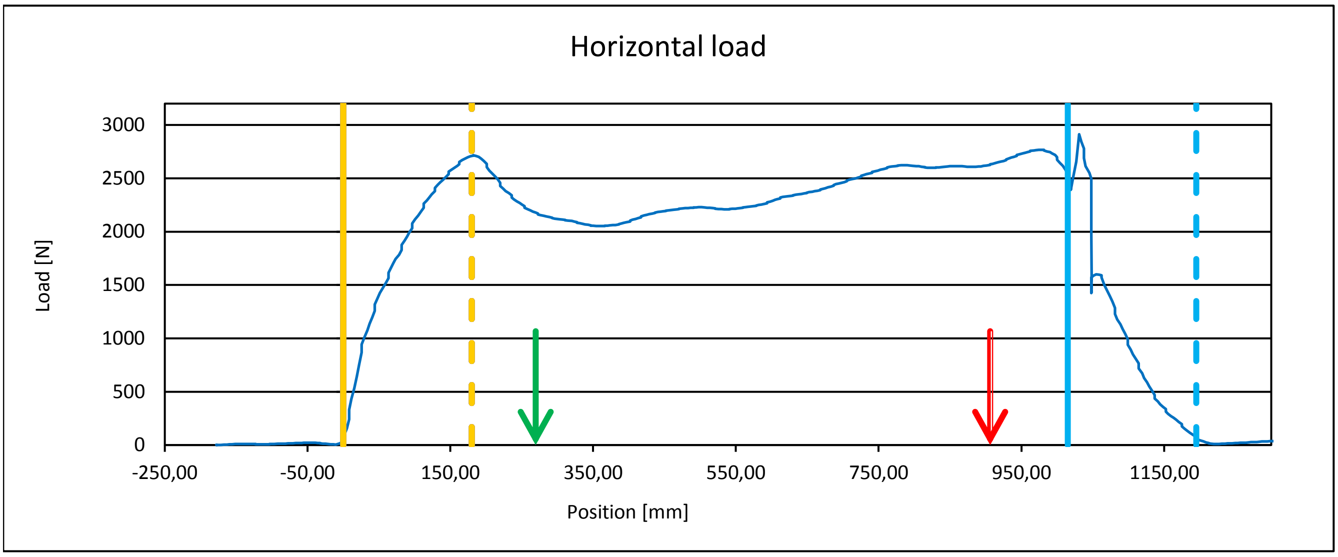
Averages in measuring length

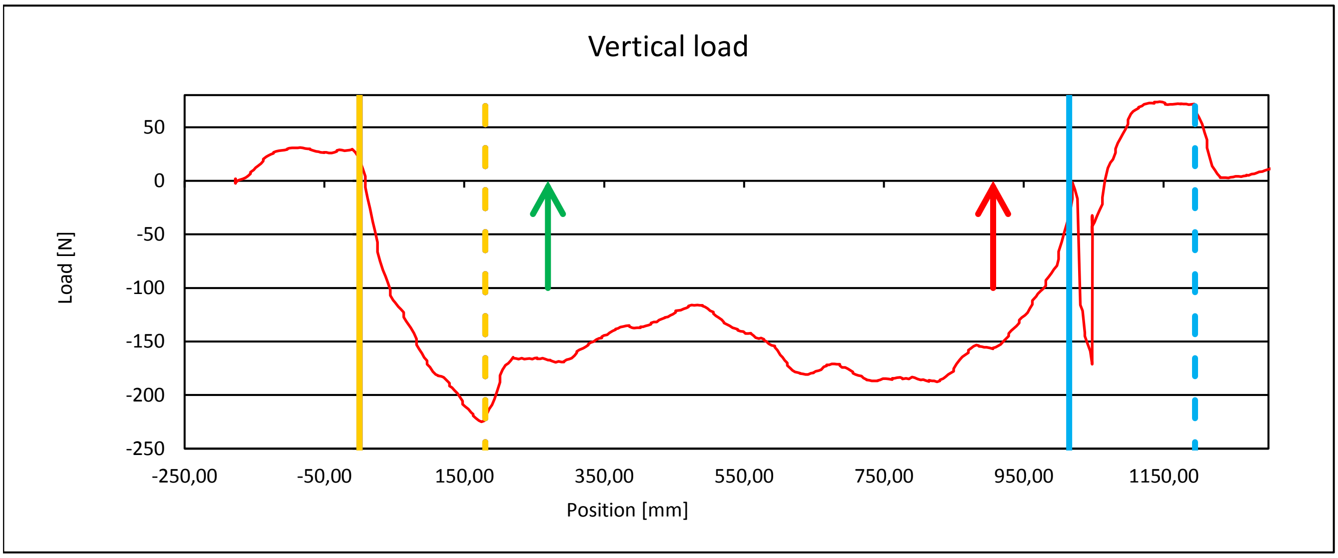
Start measuring length	269,6	mm
End measurement length	906,2	mm
Totaal length	636,7	mm
Average speed	32,0	mm/s
Average speed	115,1	m/h
Horizontal load cell	2330,6	N
Total Vertical load	-157,5	N
Total force	2335,9	N
Angle of total force	-3,9	Degree

Measured results



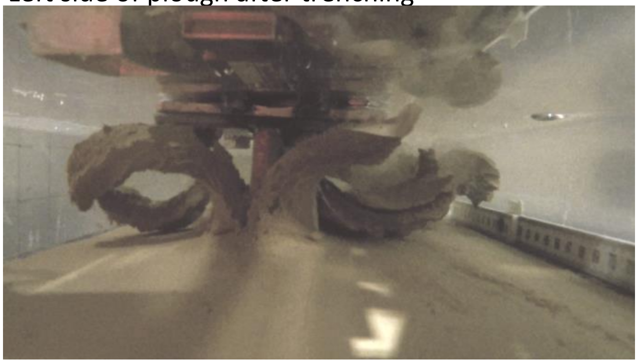


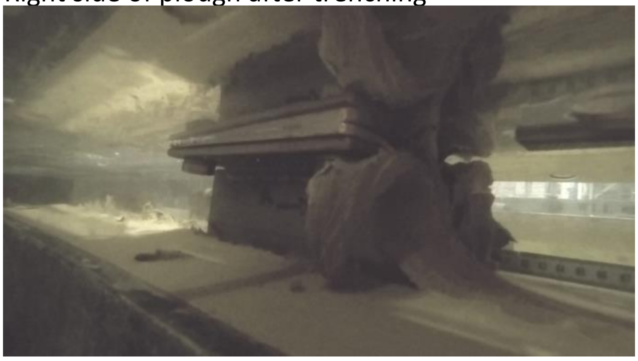





Left side of plough after trenching


Right side of plough after trenching


Frontview during trenching


Sideview during trenching


Top of first section


Top of middle section


Top of last section

Cross section

Sides of the trench

TEST REPORT 17

General information

Test number:	17	Length of clay box:	1015	mm
Date of test:	16-11-2016	Water on top of clay:	69	mm
Time of test:	12:00	Depth of the plough:	94	mm
Test profile:	BRAVO	Set motor velocity:	-6	[-]
		Clay type:	Hard	

Particular during test

Particulars of the clay block:

0

Particular events during the test:

BRAVO plough with convex height of 3mm. The top right convex got stuck in the clay at about 10 cm from the start of the clay container.

Material properties of the clay

	Before	After	
Average shear strength:	133,8	131,8	kPa
Average residual shear strength:	80,8	63,8	kPa

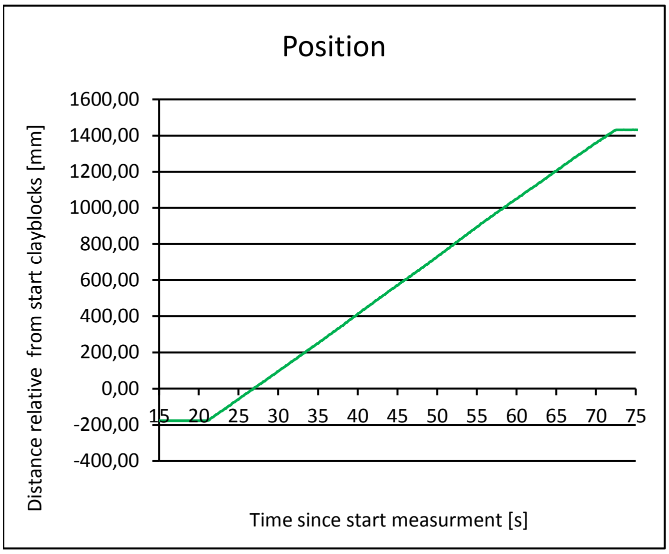
Field vane clay strength tests

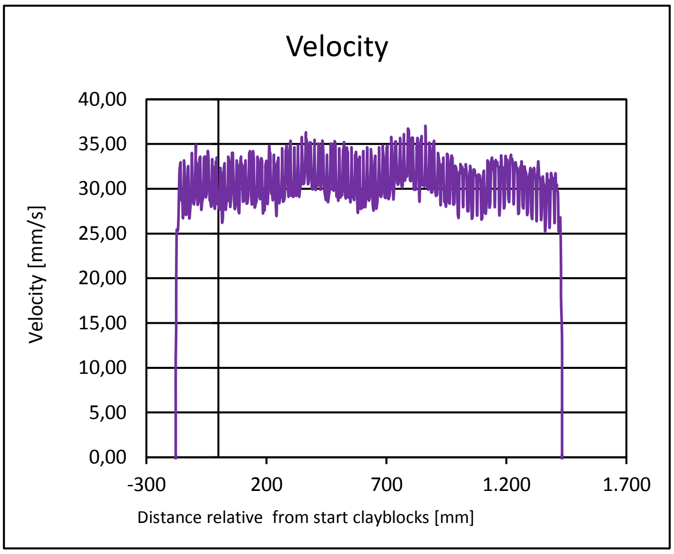
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	146	72	140	66
Left 2	135	74	140	68
Left 3	No test	No test	135	58
Right 1	126	87	126	62
Right 2	128	90	125	68
Right 3	No test	No test	125	61

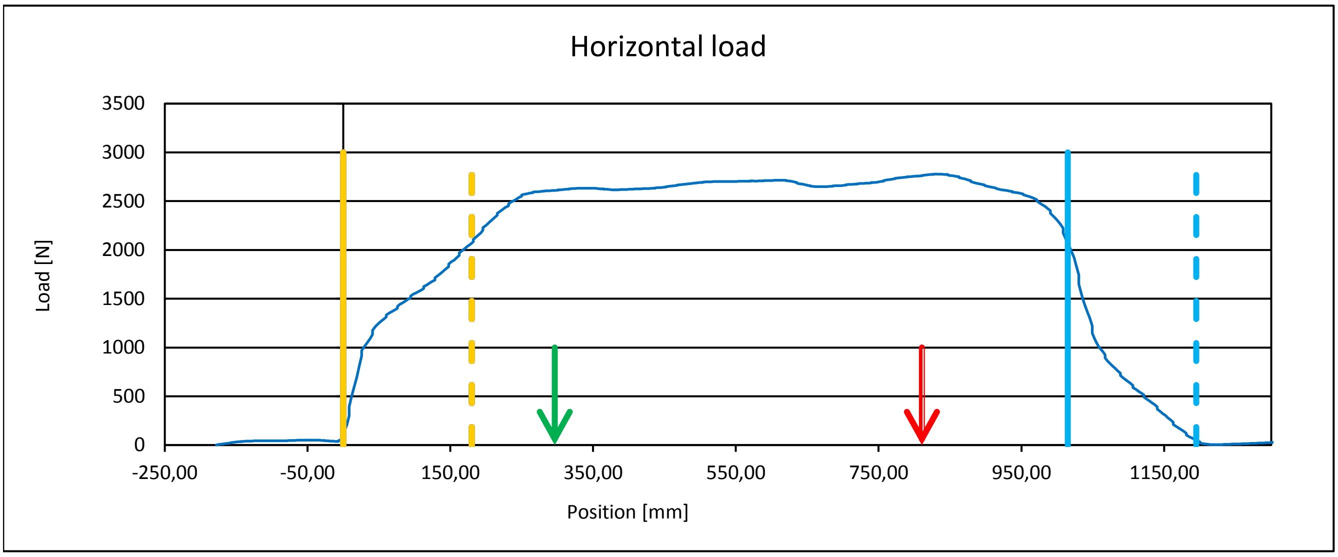
Averages in measuring length

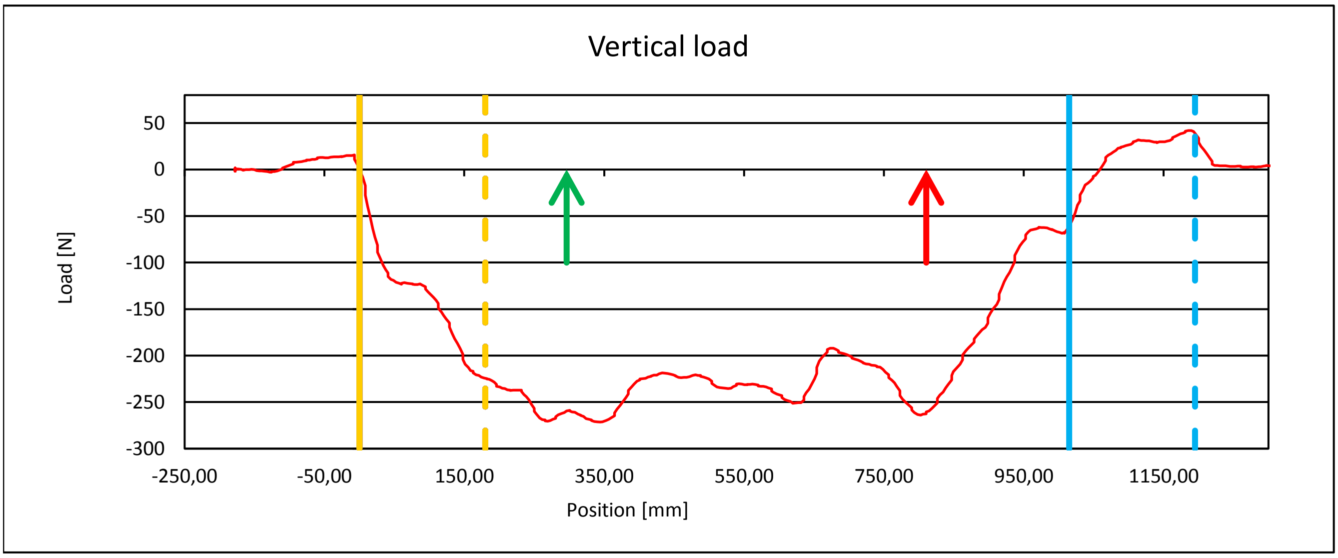
Start measuring length	296,3	mm
End measurement length	810,6	mm
Totaal length	514,3	mm
Average speed	32,1	mm/s
Average speed	115,5	m/h
Horizontal load cell	2672,9	N
Total Vertical load	-233,0	N
Total force	2683,1	N
Angle of total force	-5,0	Degree

Measured results









Left side of plough after trenching

Right side of plough after trenching

Frontview during trenching

Sideview during trenching

Top of first section

Top of middle section

Top of last section

Cross section

Sides of the trench

TEST REPORT 18

General information

Test number:	18	Length of clay box:	1015 mm
Date of test:	16-11-2016	Water on top of clay:	69 mm
Time of test:	15:00	Depth of the plough:	94 mm
Test profile:	L	Set motor velocity:	-6 [-]
		Clay type:	Hard

Particular during test

Particulars of the clay block:

0

Particular events during the test:

There was a hump in the clay of a couple mm at around 40 cm after the start of the clay container

Material properties of the clay

	Before	After	
Average shear strength:	129,0	125,2	kPa
Average residual shear strength:	66,8	63,8	kPa

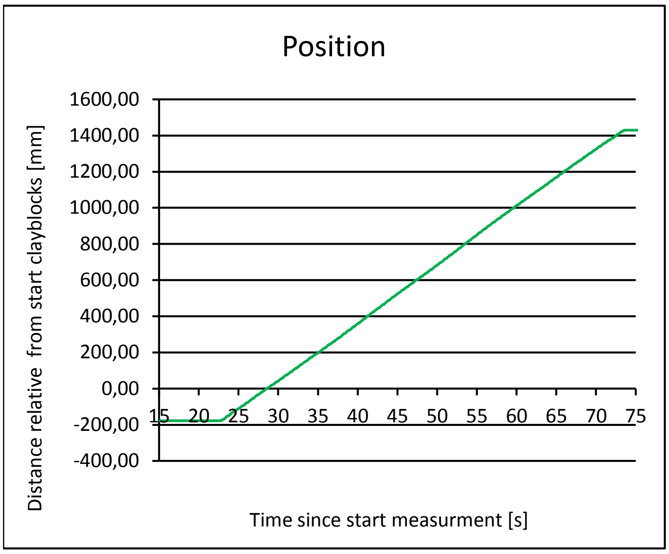
Field vane clay strength tests

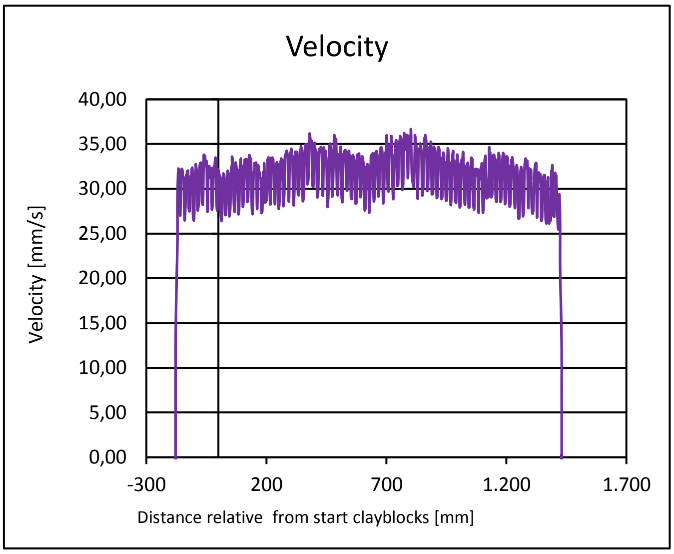
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	130	42	124	64
Left 2	135	59	133	69
Left 3	No test	No test	128	56
Right 1	124	82	125	66
Right 2	127	84	124	67
Right 3	No test	No test	117	61

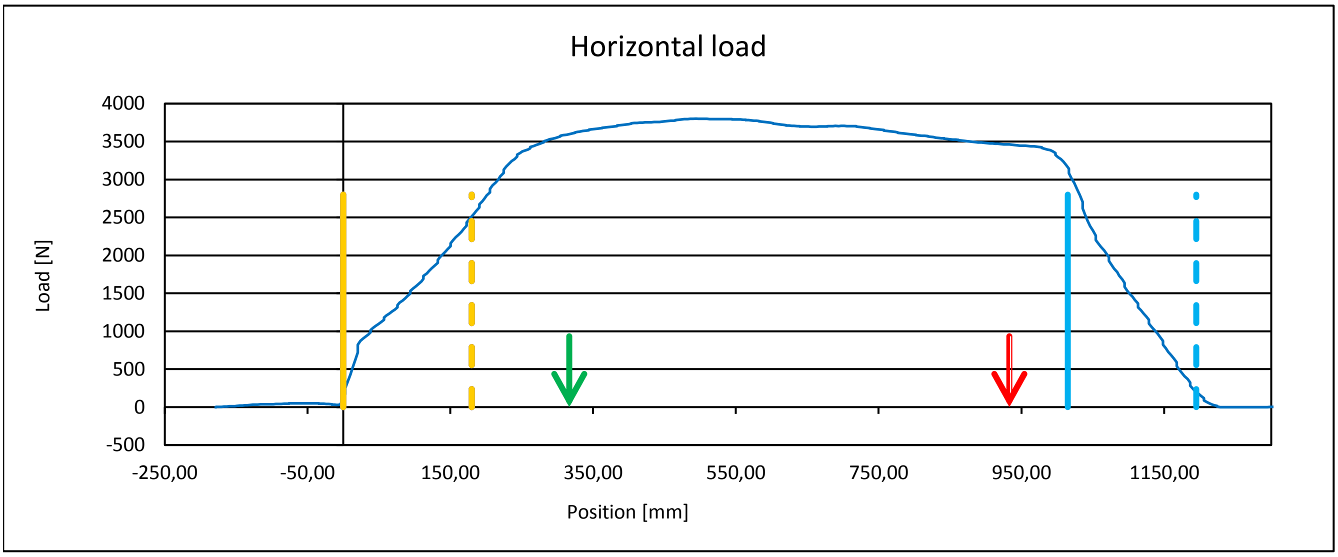
Averages in measuring length

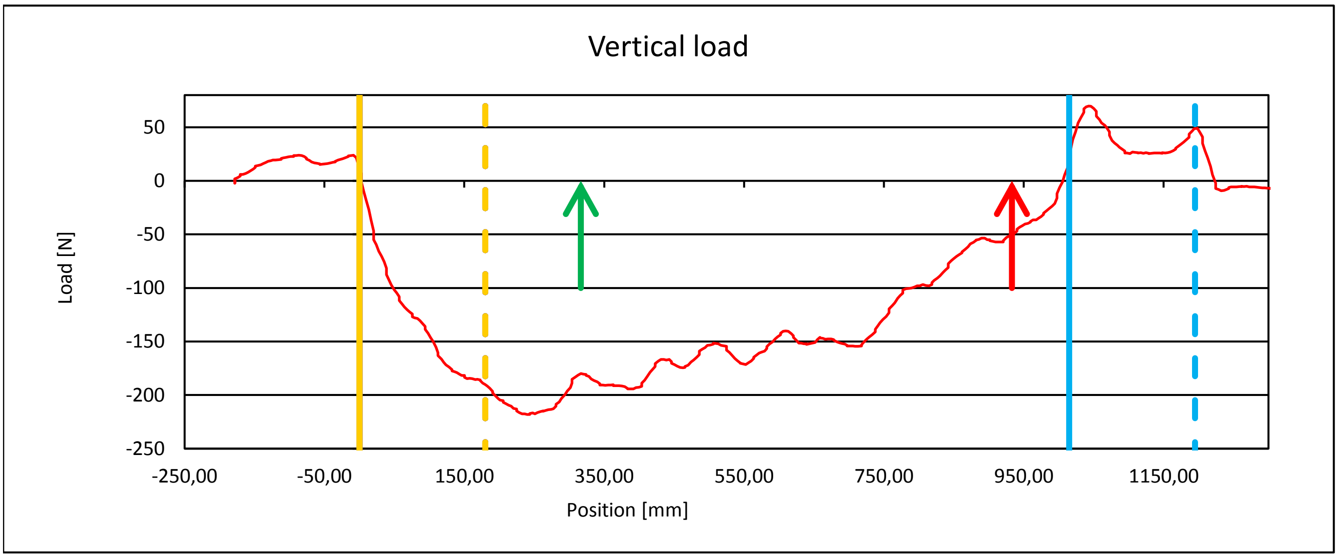
Start measuring length	316,6	mm
End measurement length	933,1	mm
Totaal length	616,5	mm
Average speed	32,8	mm/s
Average speed	118,0	m/h
Horizontal load cell	3675,6	N
Total Vertical load	-139,2	N
Total force	3678,2	N
Angle of total force	-2,2	Degree

Measured results









Left side of plough after trenching

Right side of plough after trenching

Frontview during trenching

Sideview during trenching

Top of first section

Top of middle section

Top of last section

Cross section

Sides of the trench

TEST REPORT 19

General information

Test number:	19	Length of clay box:	1015 mm
Date of test:	18-11-2016	Water on top of clay:	69 mm
Time of test:	11:00	Depth of the plough:	94 mm
Test profile:	SS4	Set motor velocity:	-6 [-]
		Clay type:	Hard

Particular during test

Particulars of the clay block:

0

Particular events during the test:

0

Material properties of the clay

	Before	After	
Average shear strength:	125,8	123,2	kPa
Average residual shear strength:	75,3	55,2	kPa

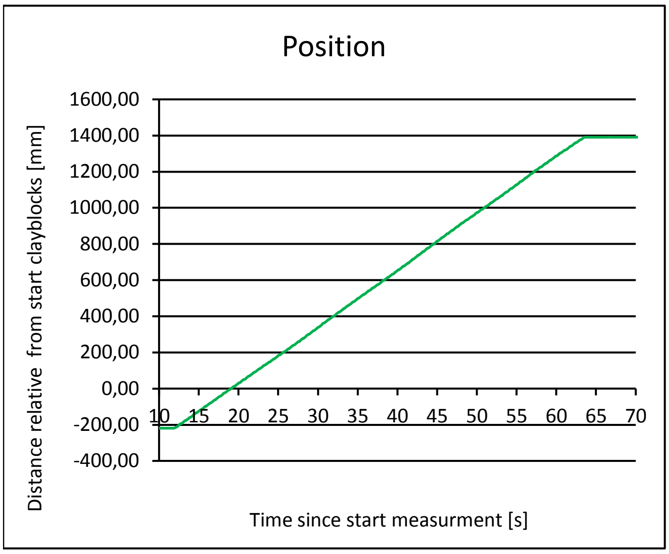
Field vane clay strength tests

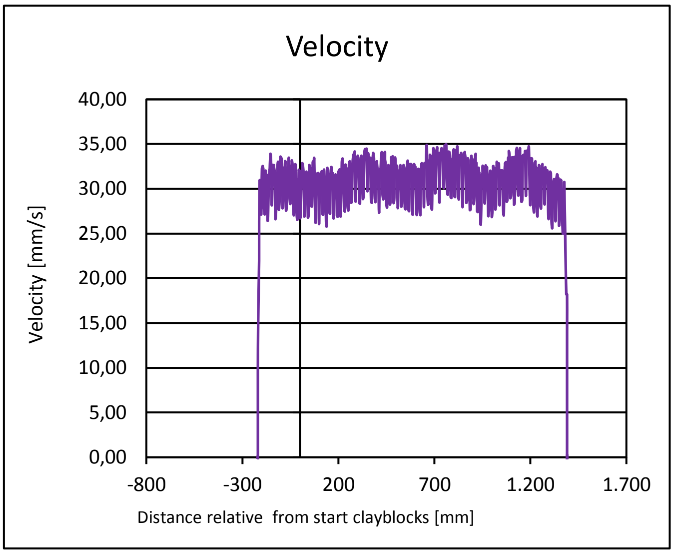
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	126	54	127	60
Left 2	132	74	132	57
Left 3	No test	No test	130	51
Right 1	124	83	118	61
Right 2	121	90	117	51
Right 3	No test	No test	115	51

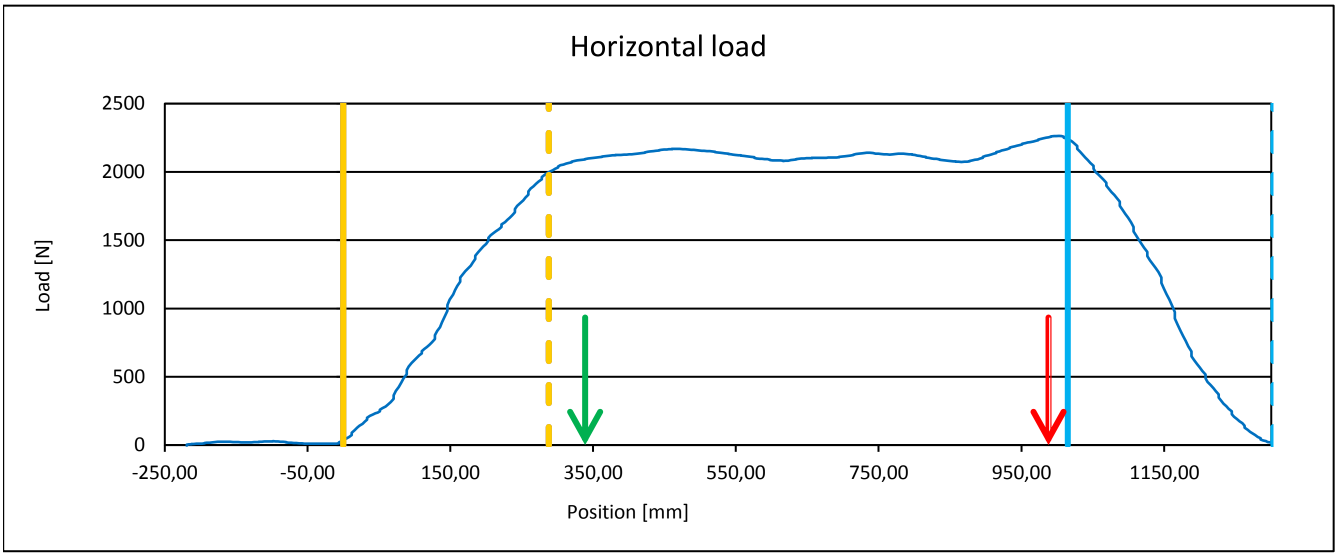
Averages in measuring length

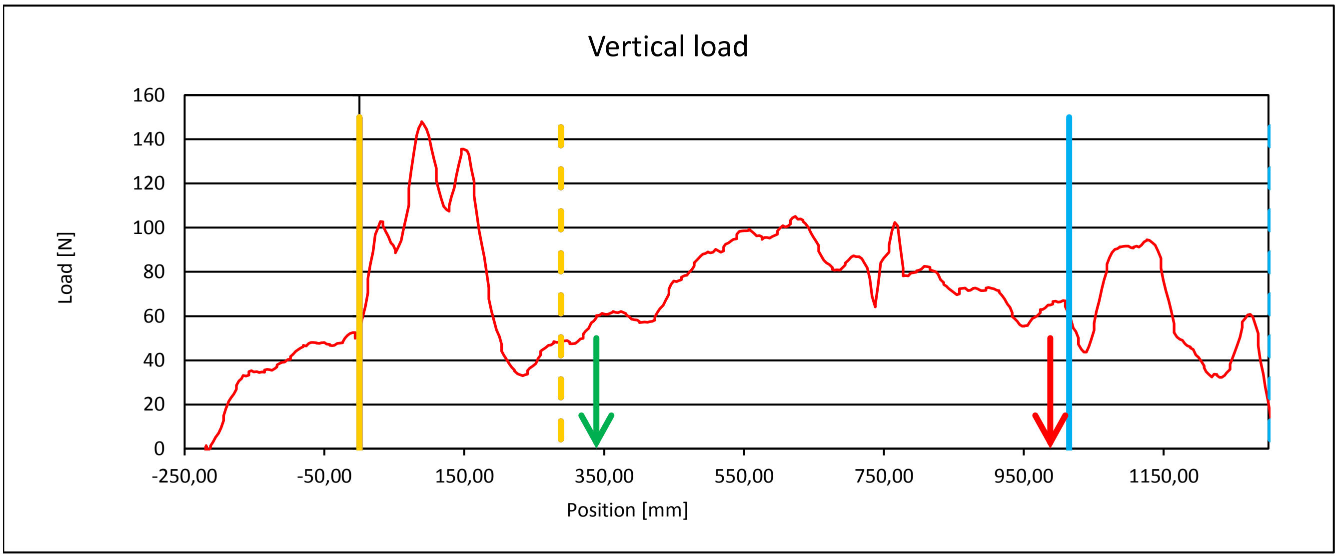
Start measuring length	338,8	mm
End measurement length	988,0	mm
Totaal length	649,1	mm
Average speed	31,7	mm/s
Average speed	114,1	m/h
Horizontal load cell	1985,9	N
Total Vertical load	76,1	N
Total force	1987,3	N
Angle of total force	2,2	Degree

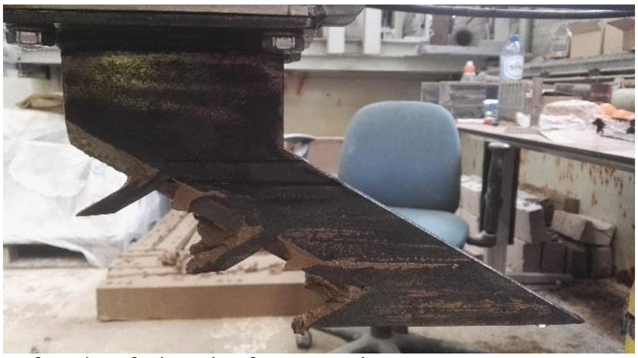
Measured results





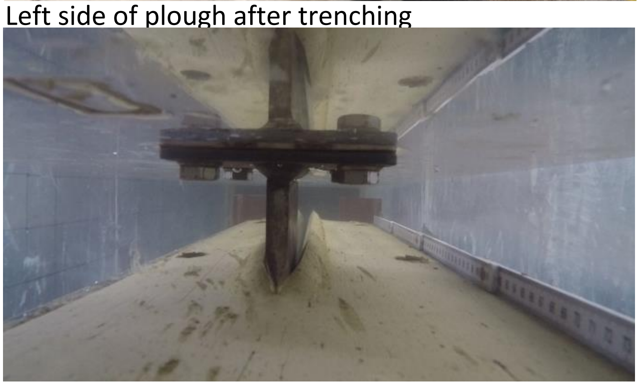






Left side of plough after trenching

Right side of plough after trenching



Frontview during trenching

Sideview during trenching

Top of first section

Top of middle section

Top of last section

Cross section

Sides of the trench

TEST REPORT 20

General information

Test number:	20
Date of test:	21-11-2016
Time of test:	11:00
Test profile:	L

Length of clay box:	1015	mm
Water on top of clay:	No water	mm
Depth of the plough:	94	mm
Set motor velocity:	-6	[-]
Clay type:	Hard	

Particular during test

Particulars of the clay block:

0

Particular events during the test:

Dry test

Material properties of the clay

	Before	After	
Average shear strength:	128,3	126,8	kPa
Average residual shear strength:	82,0	63,2	kPa

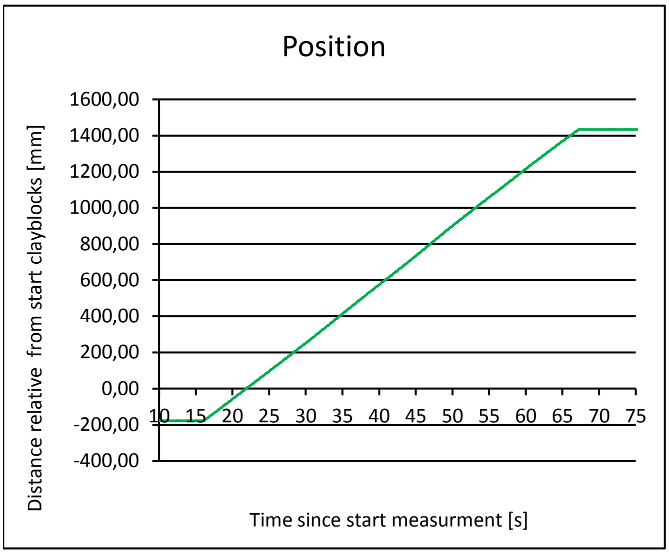
Field vane clay strength tests

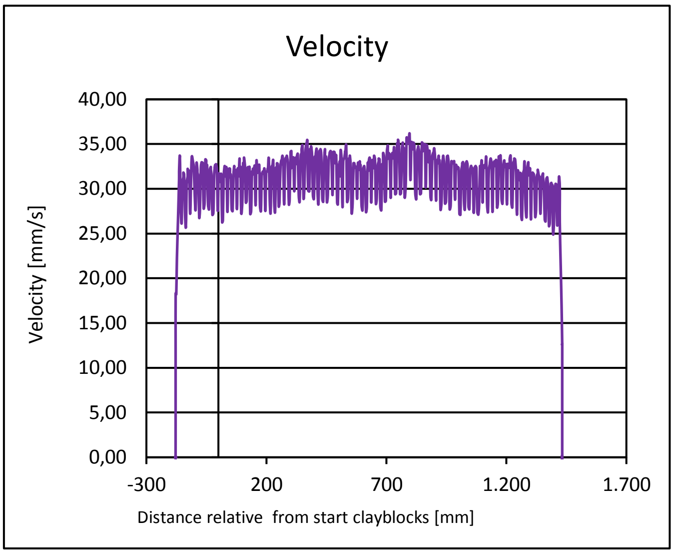
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	133	62	136	64
Left 2	140	72	135	58
Left 3	No test	No test	133	61
Right 1	120	98	116	70
Right 2	120	96	122	64
Right 3	No test	No test	119	62

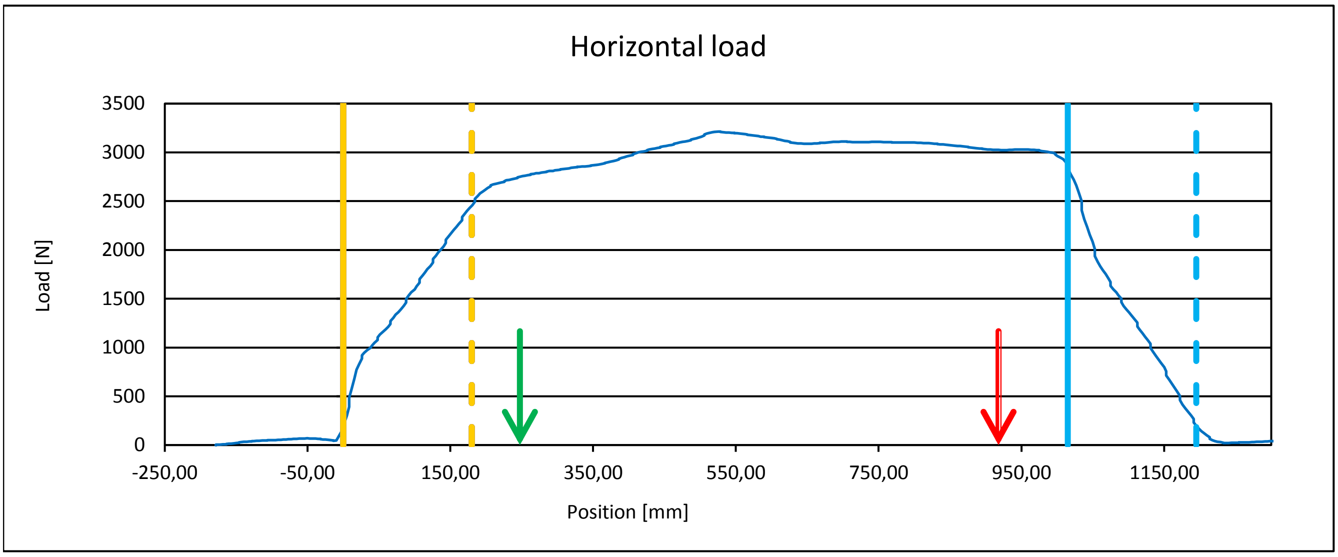
Averages in measuring length

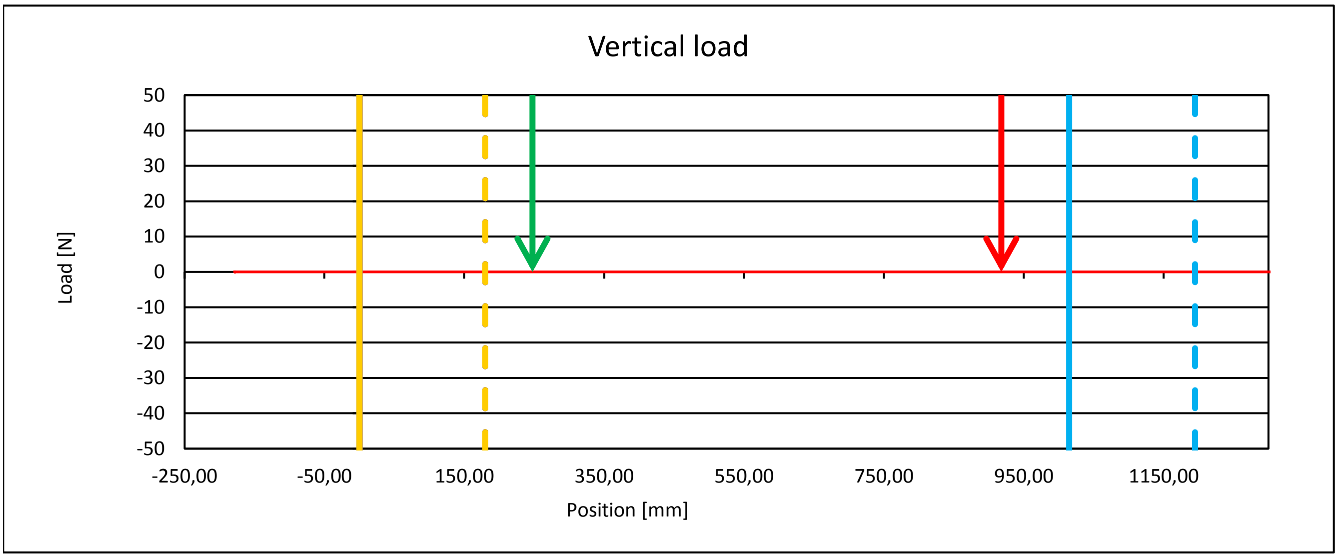
Start measuring length	247,5	mm
End measurement length	918,0	mm
Totaal length	670,5	mm
Average speed	32,1	mm/s
Average speed	115,7	m/h
Horizontal load cell	2856,6	N
Total Vertical load	Not available	N
Total force	Not available	N
Angle of total force	Not available	Degree

Measured results









Left side of plough after trenching

Right side of plough after trenching

Frontview during trenching

Sideview during trenching

Top of first section

Top of middle section

Top of last section

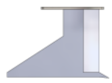
Cross section

Sides of the trench

TEST REPORT 21

General information

Test number:	21	Length of clay box:	1015 mm
Date of test:	21-11-2016	Water on top of clay:	69 mm
Time of test:	15:00	Depth of the plough:	94 mm
Test profile:	HD3	Set motor velocity:	-6 [-]
		Clay type:	Hard



Particular during test

Particulars of the clay block:

0

Particular events during the test:

0

Material properties of the clay

	Before	After	
Average shear strength:	126,0	124,0	kPa
Average residual shear strength:	76,8	56,0	kPa

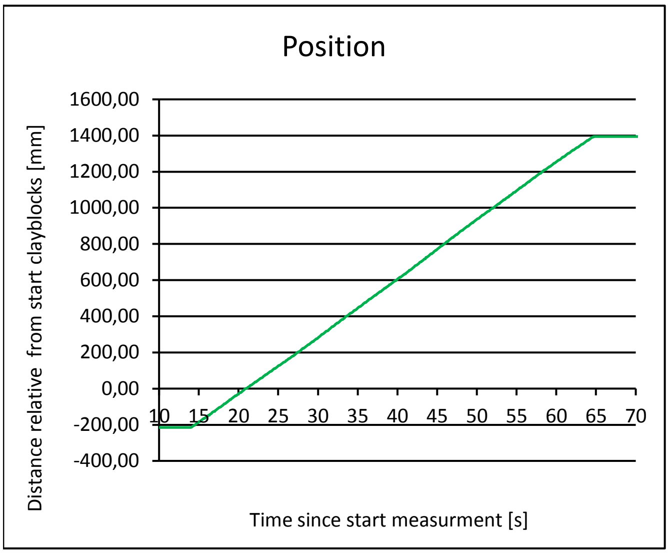
Field vane clay strength tests

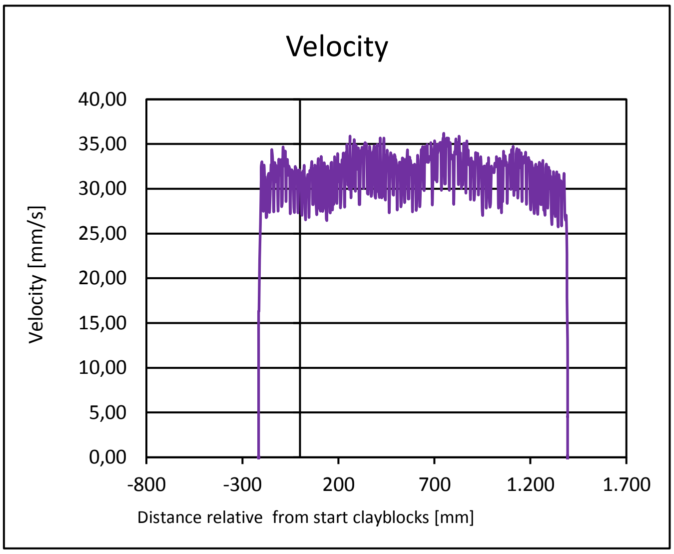
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	123	52	127	48
Left 2	131	55	125	51
Left 3	No test	No test	120	44
Right 1	122	100	123	66
Right 2	128	100	128	69
Right 3	No test	No test	121	58

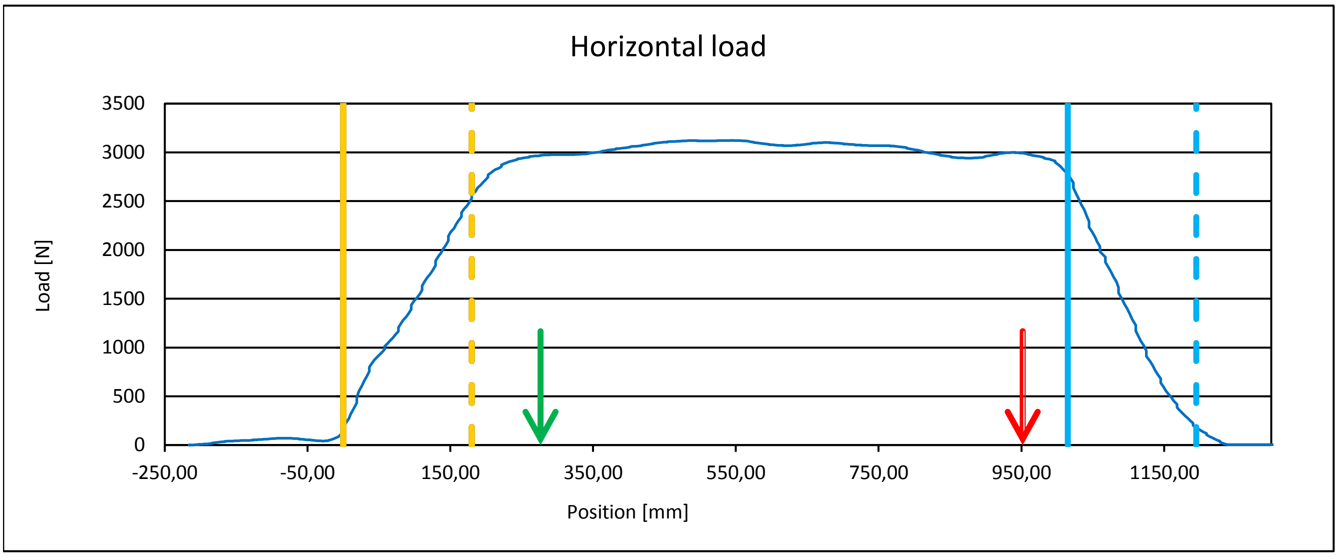
Averages in measuring length

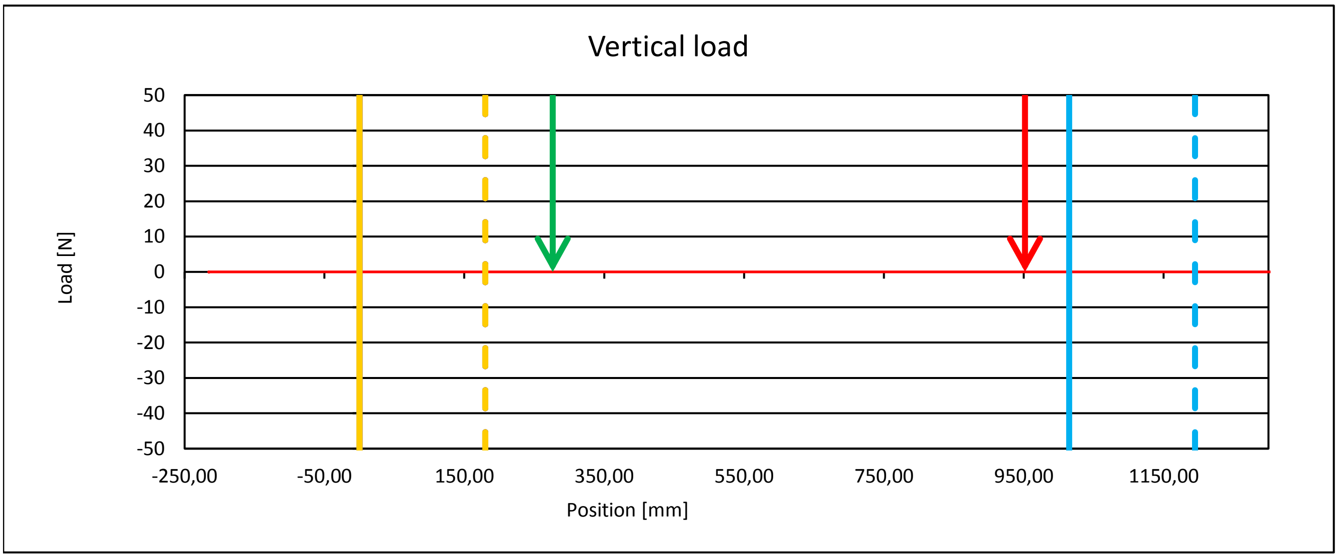
Start measuring length	276,4	mm
End measurement length	951,8	mm
Totaal length	675,4	mm
Average speed	32,7	mm/s
Average speed	117,6	m/h
Horizontal load cell	2750,1	N
Total Vertical load	Not available	N
Total force	Not available	N
Angle of total force	Not available	Degree

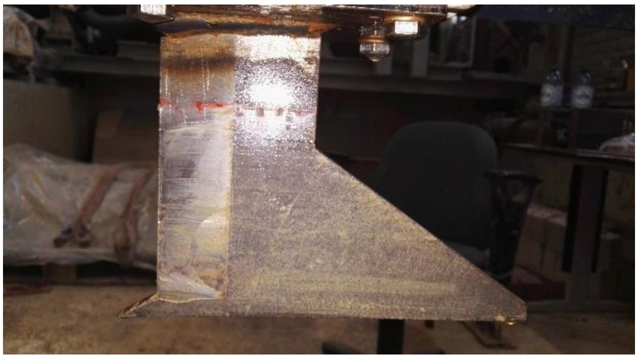
Measured results










Left side of plough after trenching


Right side of plough after trenching


Frontview during trenching


Sideview during trenching


Top of first section


Top of middle section


Top of last section

Cross section


Sides of the trench

TEST REPORT 22

General information

Test number:	22	Length of clay box:	1015 mm
Date of test:	23-11-2016	Water on top of clay:	69 mm
Time of test:	11:00	Depth of the plough:	94 mm
Test profile:	BRAVO	Set motor velocity:	-6 [-]
		Clay type:	Hard

Particular during test

Particulars of the clay block:

0

Particular events during the test:

BRAVO plough with convex height of 3mm

Material properties of the clay

	Before	After	
Average shear strength:	127,5	119,7	kPa
Average residual shear strength:	85,3	56,0	kPa

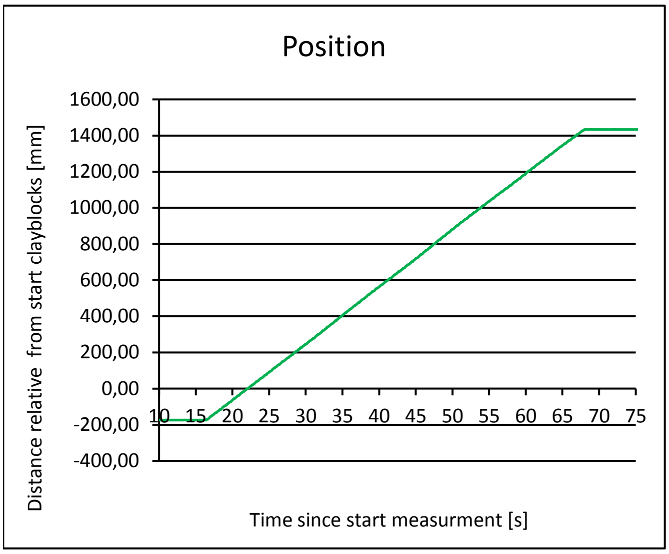
Field vane clay strength tests

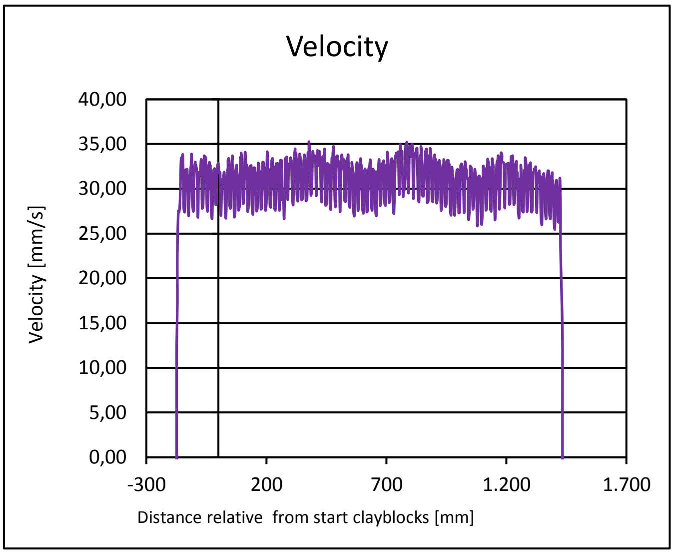
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	129	66	129	62
Left 2	133	86	132	60
Left 3	No test	No test	120	50
Right 1	122	94	111	52
Right 2	126	95	112	55
Right 3	No test	No test	114	57

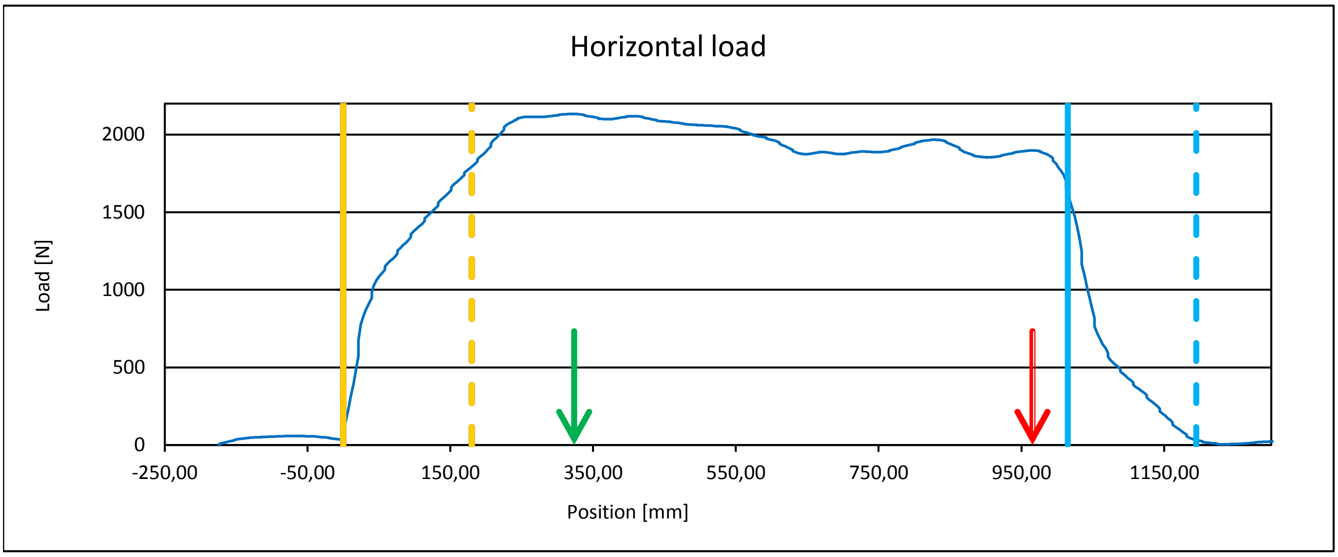
Averages in measuring length

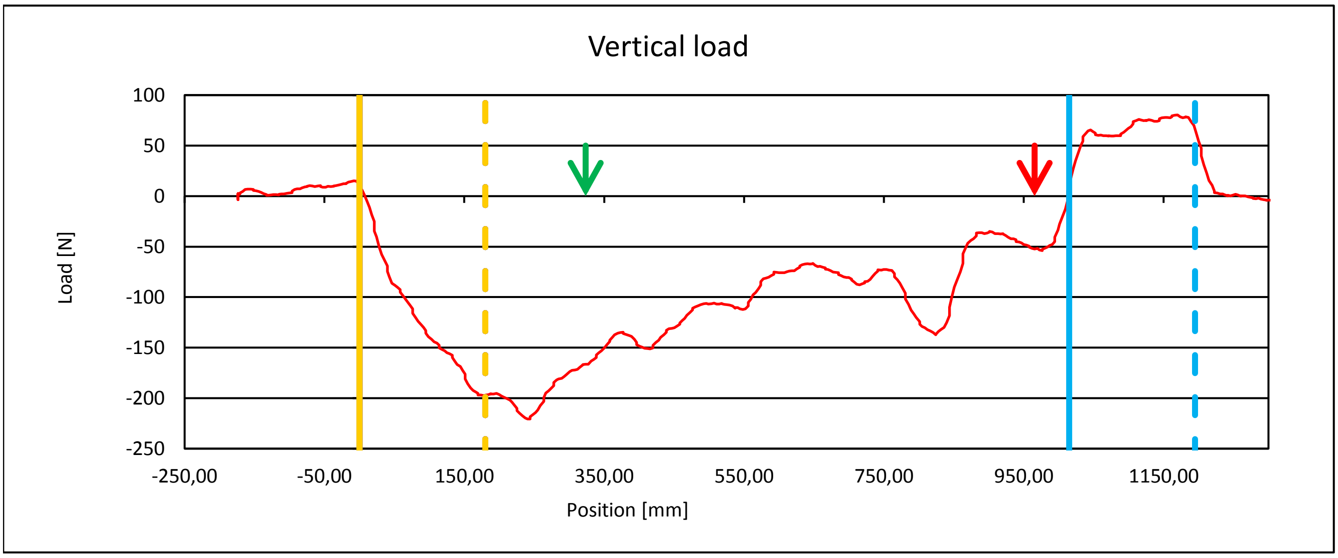
Start measuring length	323,5	mm
End measurement length	965,5	mm
Totaal length	642,0	mm
Average speed	31,7	mm/s
Average speed	114,3	m/h
Horizontal load cell	1974,4	N
Total Vertical load	-95,8	N
Total force	1976,7	N
Angle of total force	-2,8	Degree

Measured results









Left side of plough after trenching

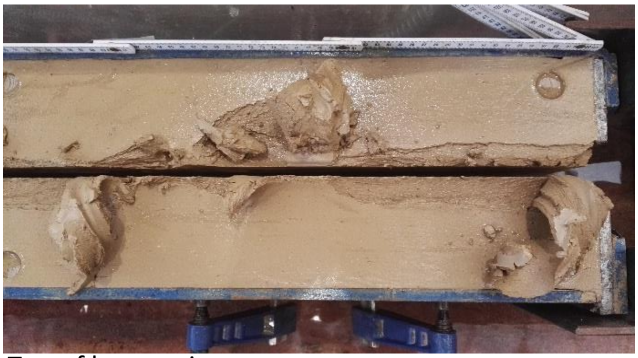
Right side of plough after trenching

Frontview during trenching

Sideview during trenching

Top of first section

Top of middle section



Top of last section

Cross section

Sides of the trench

TEST REPORT 23

General information

Test number:	23
Date of test:	23-11-2016
Time of test:	15:00
Test profile:	BRAVO

Length of clay box:	1015	mm
Water on top of clay:	69	mm
Depth of the plough:	94	mm
Set motor velocity:	-6	[-]
Clay type:	Hard	

Particular during test

Particulars of the clay block:

0

Particular events during the test:

BRAVO plough with convex height of 7mm

Material properties of the clay

	Before	After	
Average shear strength:	118,8	117,5	kPa
Average residual shear strength:	81,5	60,5	kPa

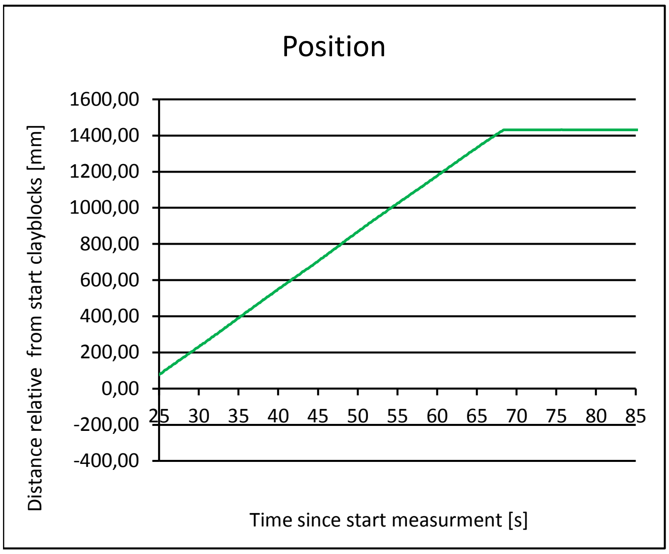
Field vane clay strength tests

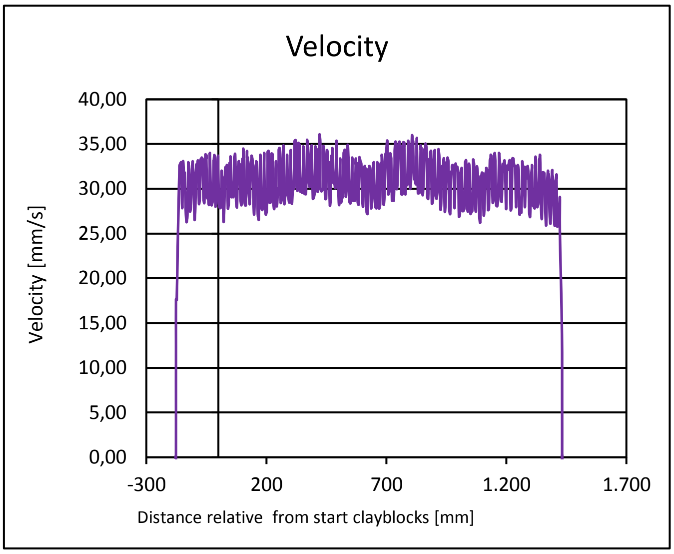
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	110	82	110	55
Left 2	116	76	114	81
Left 3	No test	No test	108	56
Right 1	128	87	126	60
Right 2	121	81	125	60
Right 3	No test	No test	122	51

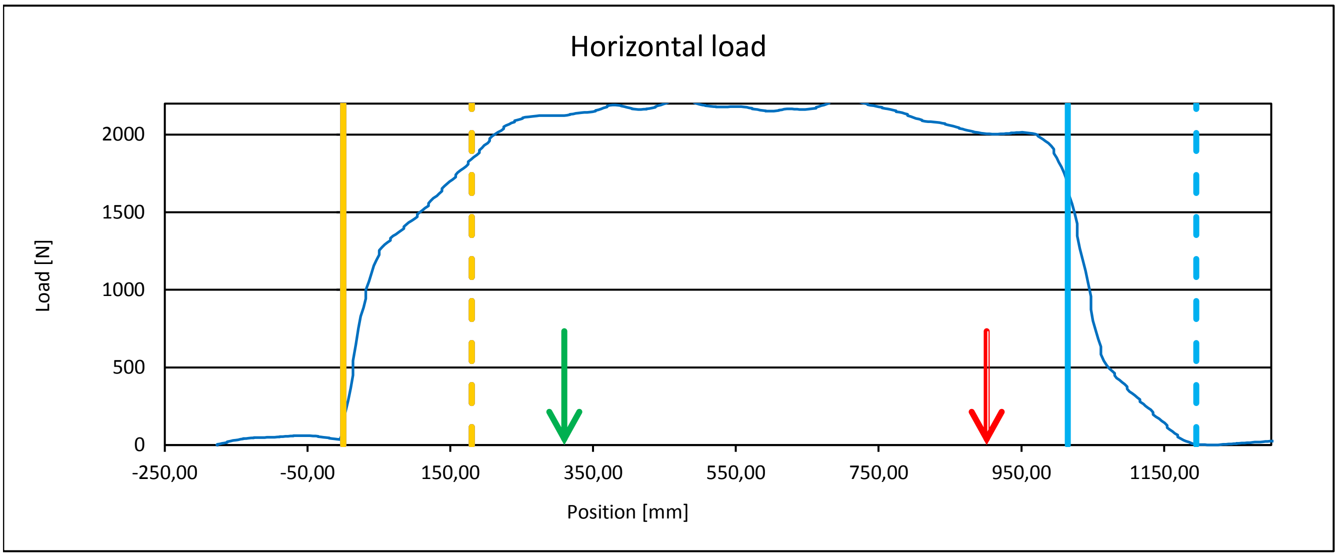
Averages in measuring length

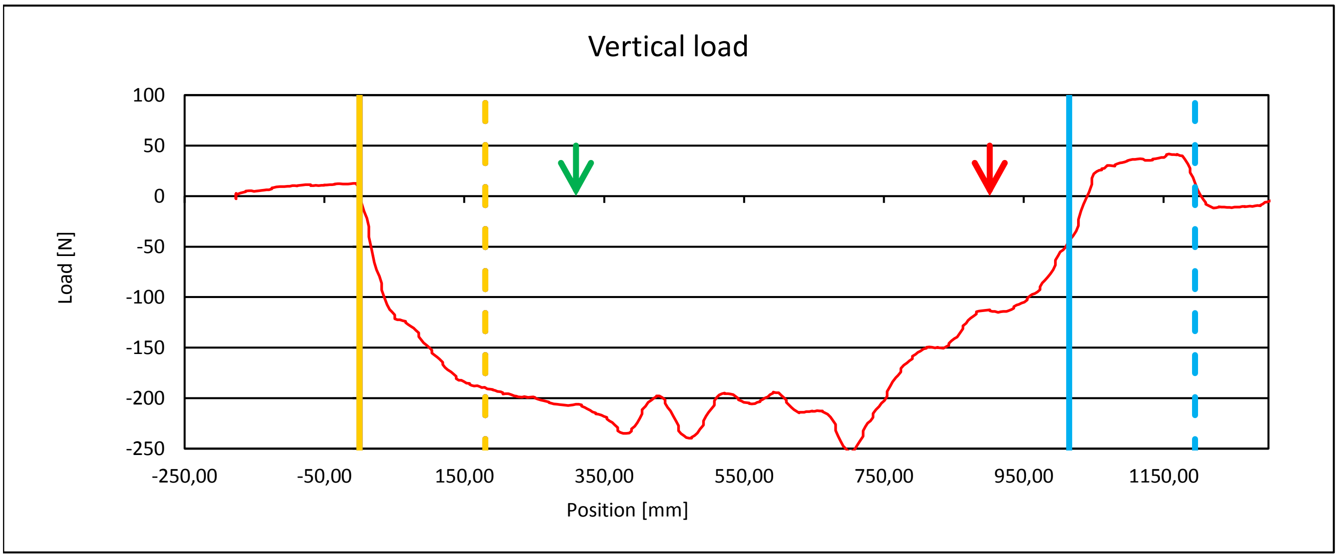
Start measuring length	309,7	mm
End measurement length	901,4	mm
Totaal length	591,7	mm
Average speed	31,9	mm/s
Average speed	114,8	m/h
Horizontal load cell	2156,6	N
Total Vertical load	-199,0	N
Total force	2165,7	N
Angle of total force	-5,3	Degree

Measured results







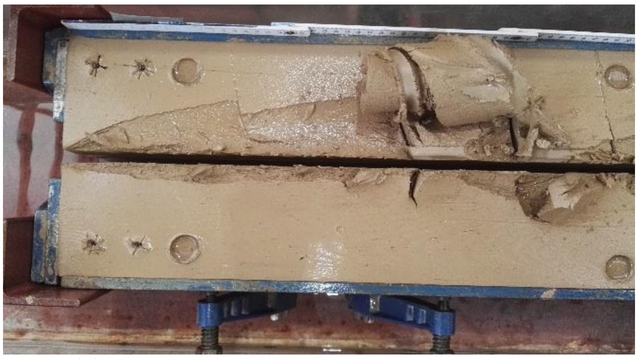


Left side of plough after trenching

Right side of plough after trenching

Frontview during trenching

Sideview during trenching

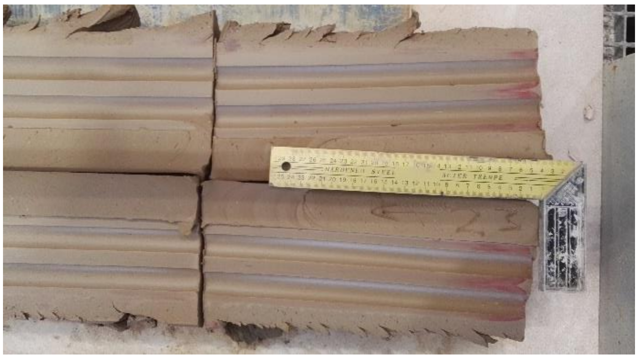


Top of first section

Top of middle section

Top of last section

Cross section



Sides of the trench

TEST REPORT 24

General information

Test number:	24	Length of clay box:	240 mm
Date of test:	25-11-2016	Water on top of clay:	69 mm
Time of test:	15:00	Depth of the plough:	94 mm
Test profile:	L	Set motor velocity:	-6 [-]
		Clay type:	Medium

Particular during test

Particulars of the clay block:

0

Particular events during the test:

0

Material properties of the clay

Average shear strength: 97 kPa

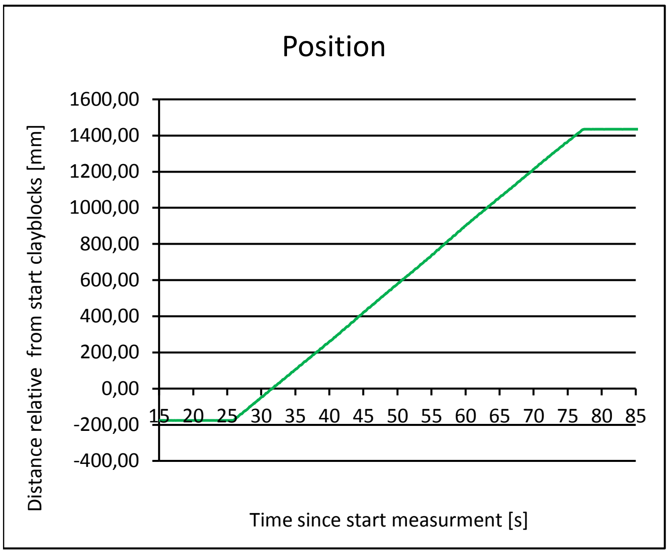
	Block 1	Block 2	Block 3	Block 4	
Handvane test before trenching:	75	70	95	97	kPa
	-	85	95	-	kPa

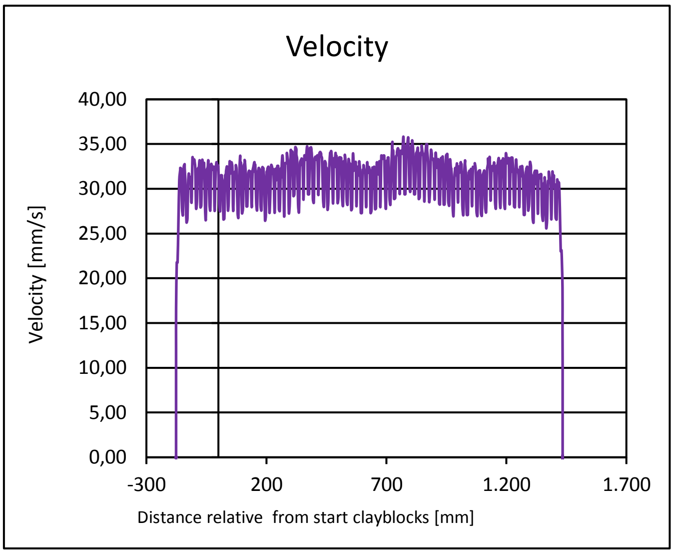
		Block 2	Block 3	
Handvane test after trenching:		52	53	kPa
Fieldvane test after trenching:	Shear 1	96	89	kPa
	Shear 2	124	94	kPa
	Residual 1	30	30	kPa
	Residual 2	32	44	kPa

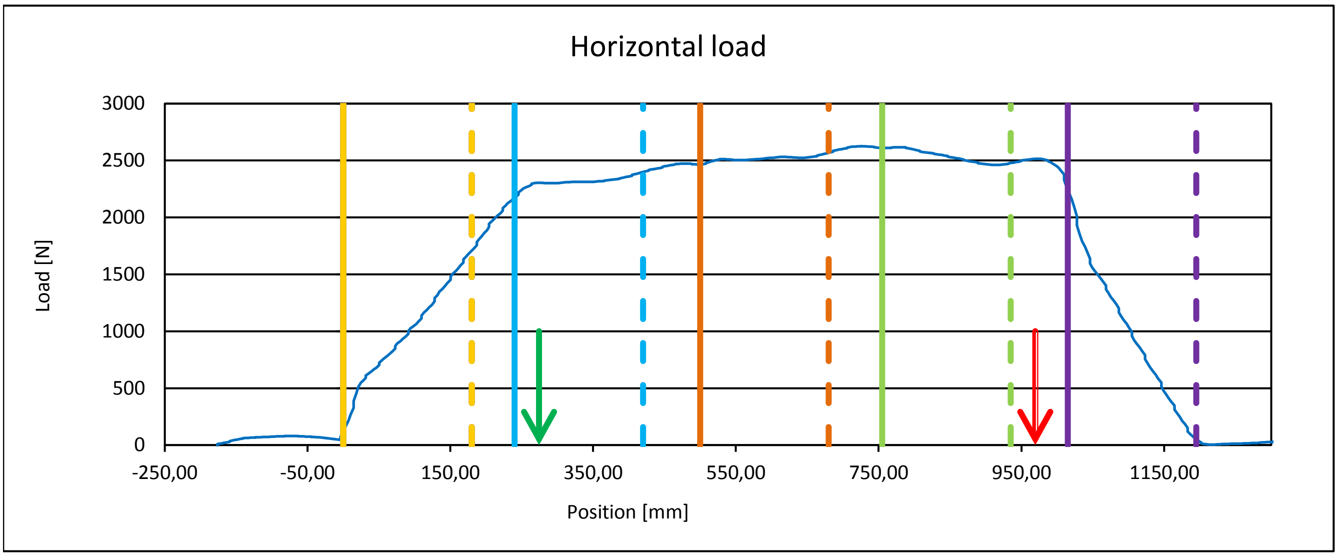
Averages in measuring length

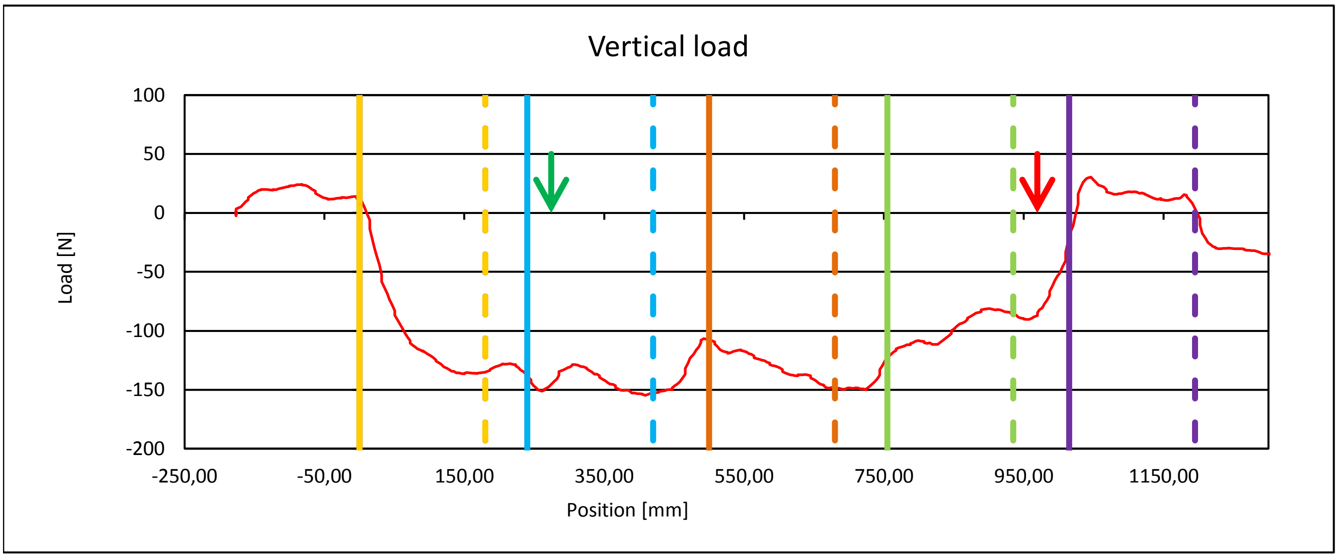
Start measuring length	274,2	mm
End measurement length	969,4	mm
Totaal length	695,2	mm
Average speed	32,1	mm/s
Average speed	115,4	m/h
Horizontal load cell	2483,4	N
Total Vertical load	-124,3	N
Total force	2486,5	N
Angle of total force	-2,9	Degree

Measured results










Left side of plough after trenching

Not available

Right side of plough after trenching


Frontview during trenching


Sideview during trenching


Top of first section


Top of middle section


Top of last section

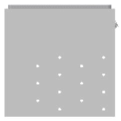

Cross section


Sides of the trench

TEST REPORT 25

General information

Test number:	25
Date of test:	30-11-2016
Time of test:	14:00
Test profile:	CHARLIE



Length of clay box:	1015	mm
Water on top of clay:	69	mm
Depth of the plough:	94	mm
Set motor velocity:	-6	[-]
Clay type:	Hard	

Particular during test

Particulars of the clay block:

0

Particular events during the test:

First tube connected with 3,5 Bar flowing water pressure. During trenching pressure was 4 bar. Other tubes blocked by srews.

Material properties of the clay

	Before	After	
Average shear strength:	128,5	128,0	kPa
Average residual shear strength:	68,3	70,0	kPa

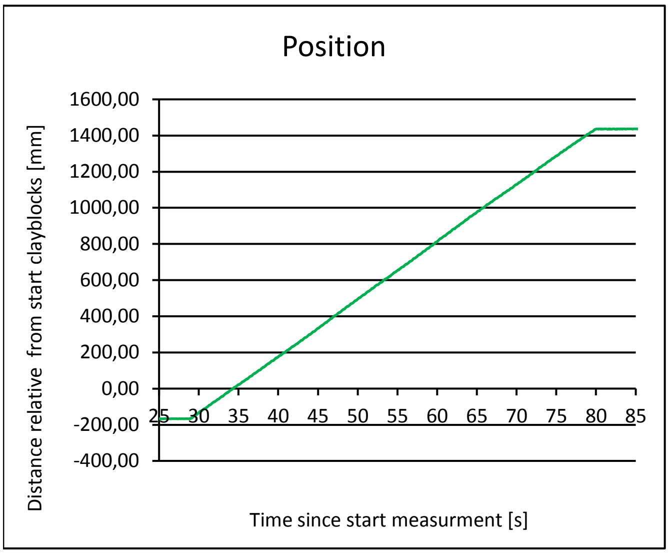
Field vane clay strength tests

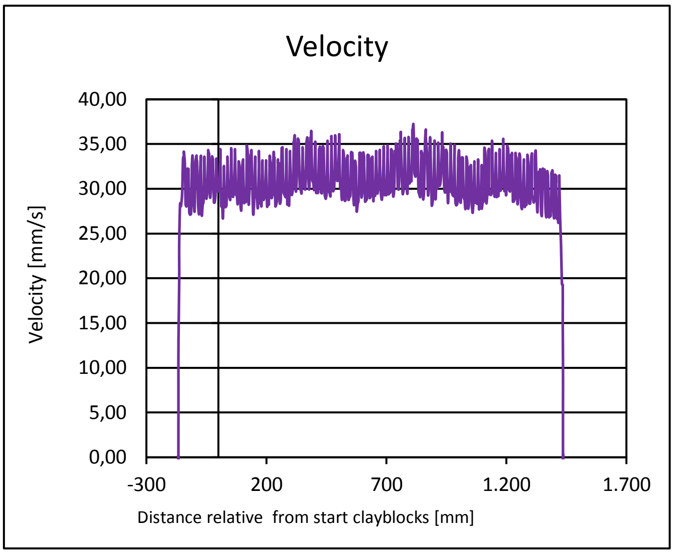
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	128	54	146	81
Left 2	137	58	136	66
Left 3	No test	No test	128	65
Right 1	124	74	122	68
Right 2	125	87	121	74
Right 3	No test	No test	115	66

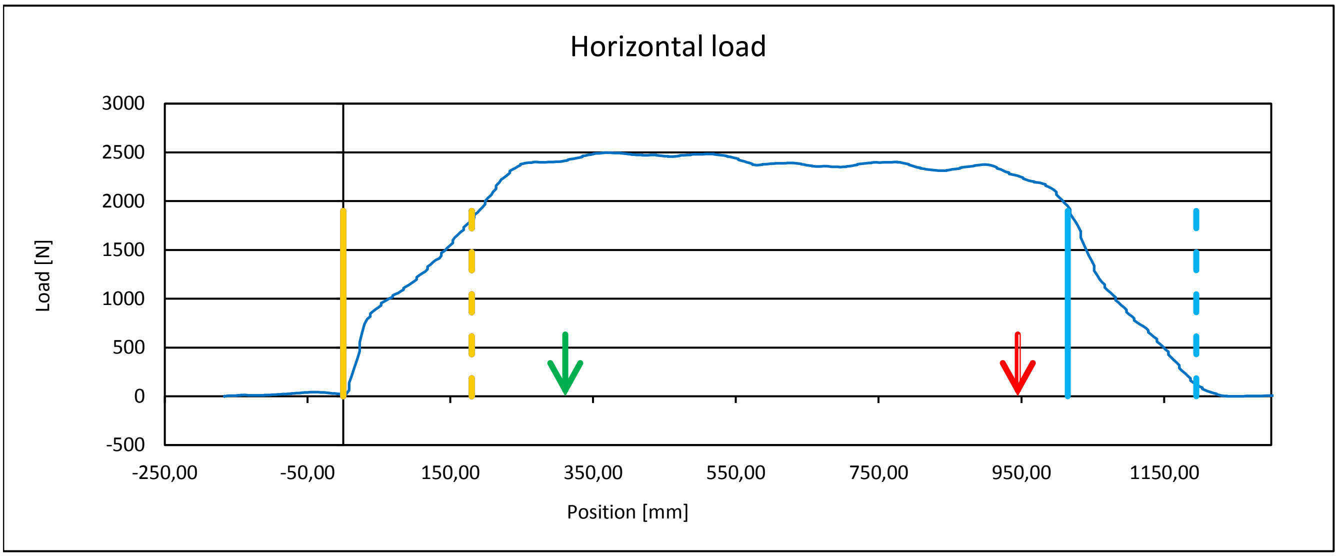
Averages in measuring length

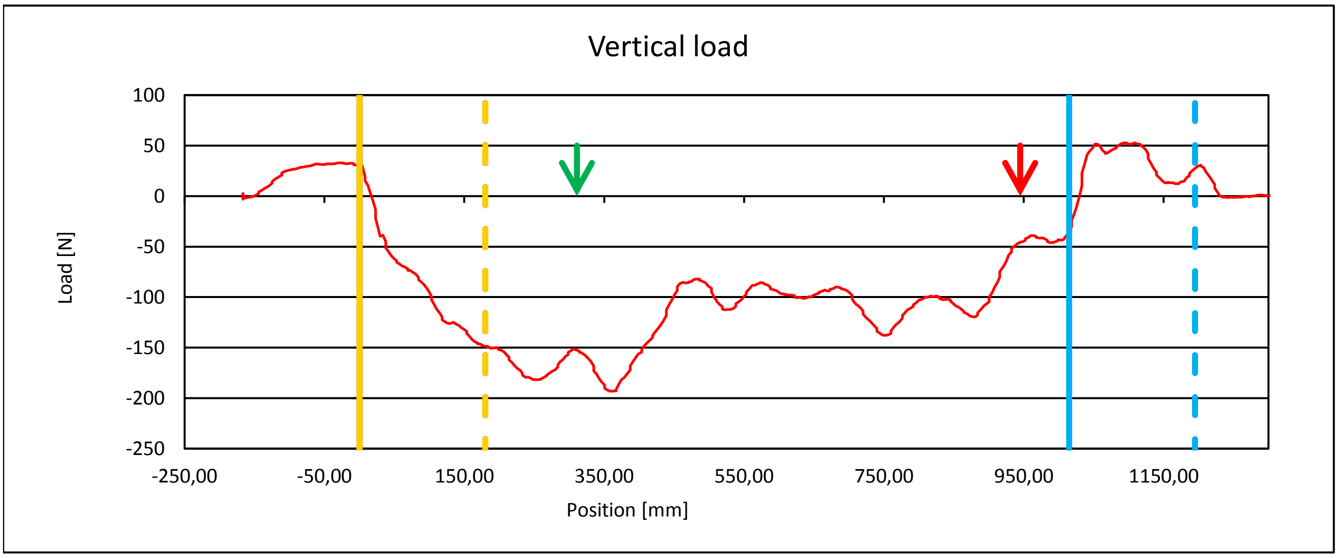
Start measuring length	311,0	mm
End measurement length	945,0	mm
Totaal length	633,9	mm
Average speed	32,2	mm/s
Average speed	115,9	m/h
Horizontal load cell	2403,6	N
Total Vertical load	-112,8	N
Total force	2406,3	N
Angle of total force	-2,7	Degree

Measured results










Front of plough after trenching


Right side of plough after trenching


Jets above water


Sideview during trenching


Top of first section


Top of middle section


Top of last section

Cross section


Sides of the trench

TEST REPORT 26

General information

Test number:	26	Length of clay box:	1015	mm
Date of test:	5-12-2016	Water on top of clay:	No water	mm
Time of test:	11:00	Depth of the plough:	94	mm
Test profile:	M	Set motor velocity:	-6	[-]
		Clay type:	Medium	

Particular during test

Particulars of the clay block:

0

Particular events during the test:

Dry test

Material properties of the clay

	Before	After	
Average shear strength:	125,3	130,8	kPa
Average residual shear strength:	73,8	74,8	kPa

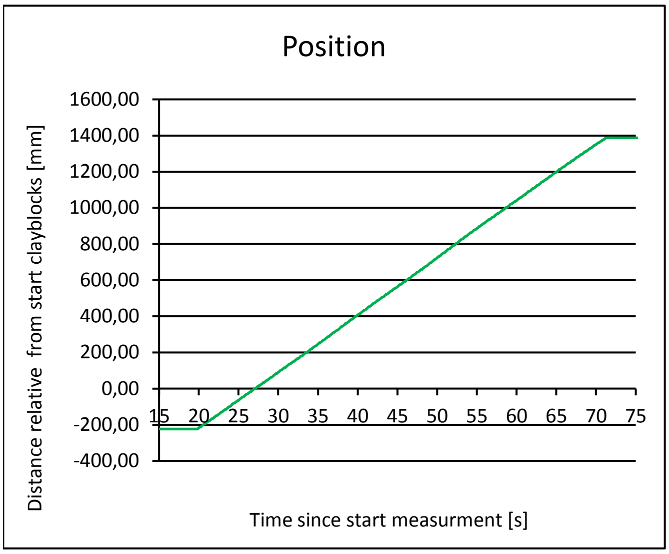
Field vane clay strength tests

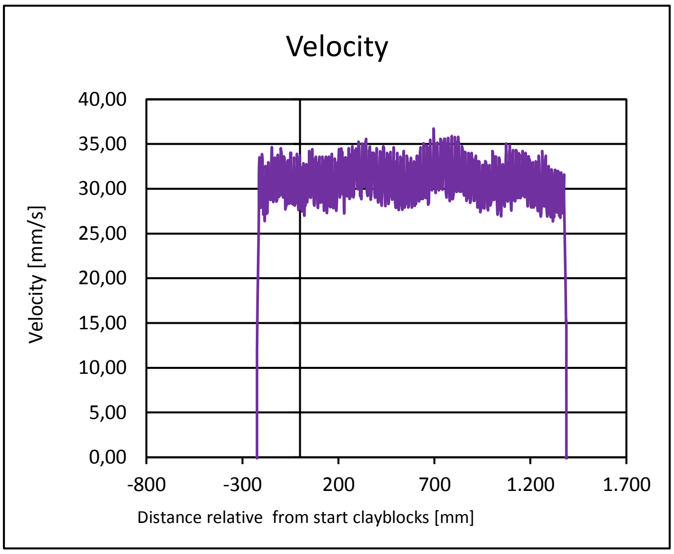
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	129	50	131	65
Left 2	128	51	135	74
Left 3	No test	No test	135	77
Right 1	122	100	126	70
Right 2	122	94	130	84
Right 3	No test	No test	128	79

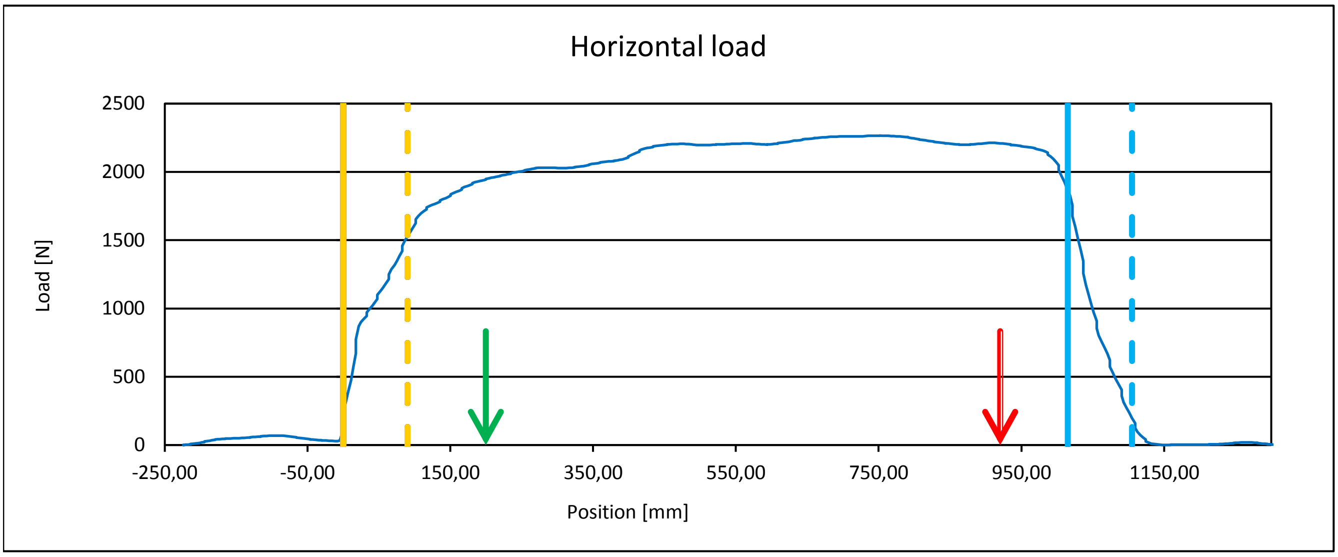
Averages in measuring length

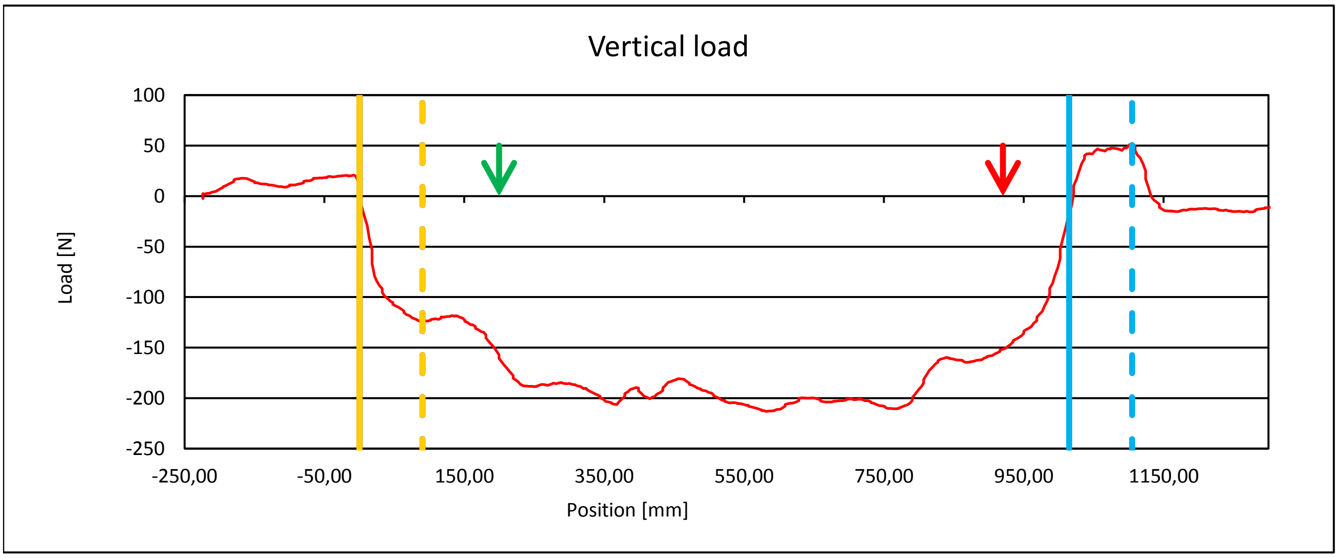
Start measuring length	199,7	mm
End measurement length	920,3	mm
Totaal length	720,6	mm
Average speed	32,0	mm/s
Average speed	115,2	m/h
Horizontal load cell	2165,6	N
Total Vertical load	-191,3	N
Total force	2174,0	N
Angle of total force	-5,0	Degree

Measured results

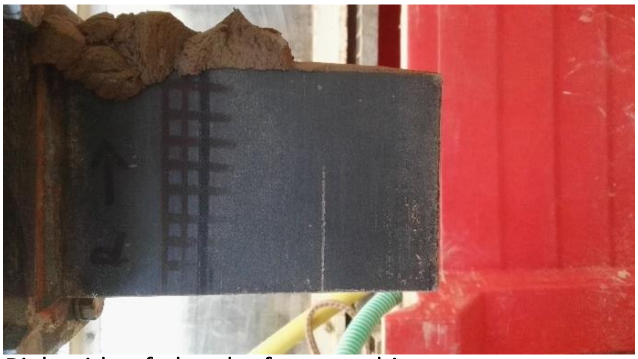









Left side of plough after trenching


Right side of plough after trenching


Frontview during trenching


Sideview during trenching


Top of first section


Top of middle section


Top of last section

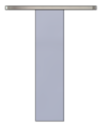
Cross section


Sides of the trench

TEST REPORT 27

General information

Test number:	27	Length of clay box:	1015	mm
Date of test:	5-12-2016	Water on top of clay:	No water	mm
Time of test:	15:00	Depth of the plough:	94	mm
Test profile:	S	Set motor velocity:	-6	[-]
		Clay type:	Hard	



Particular during test

Particulars of the clay block:

0

Particular events during the test:

Dry test

Material properties of the clay

	Before	After	
Average shear strength:	130,8	130,0	kPa
Average residual shear strength:	67,0	70,8	kPa

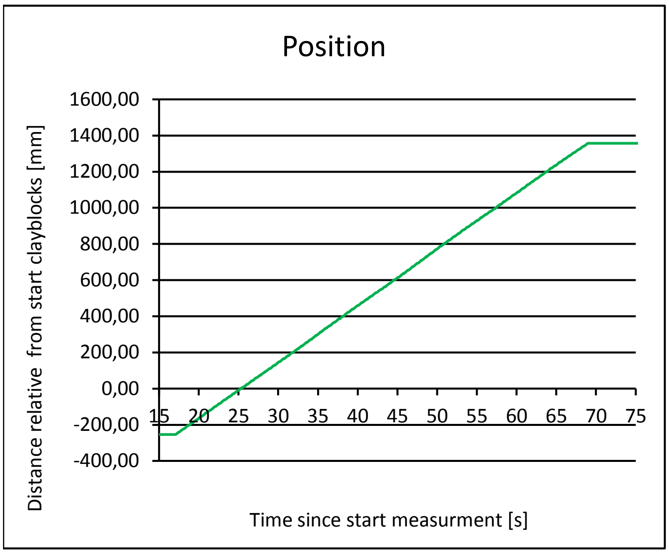
Field vane clay strength tests

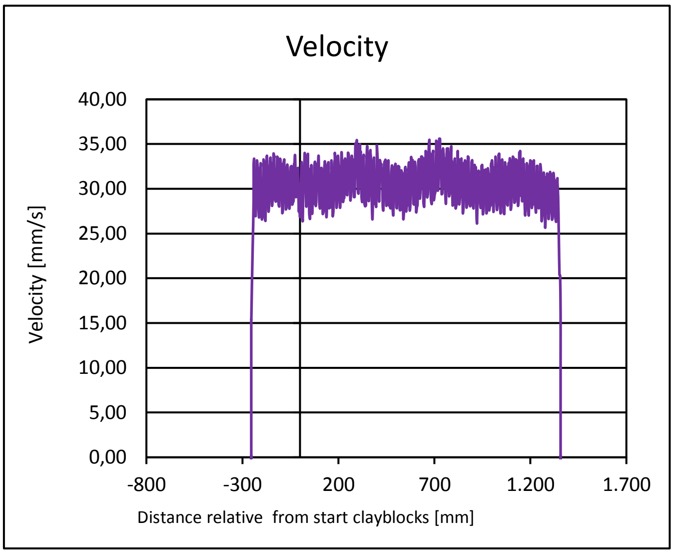
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	139	76	140	69
Left 2	136	74	138	76
Left 3	No test	No test	134	68
Right 1	120	44	118	70
Right 2	128	74	123	68
Right 3	No test	No test	127	74

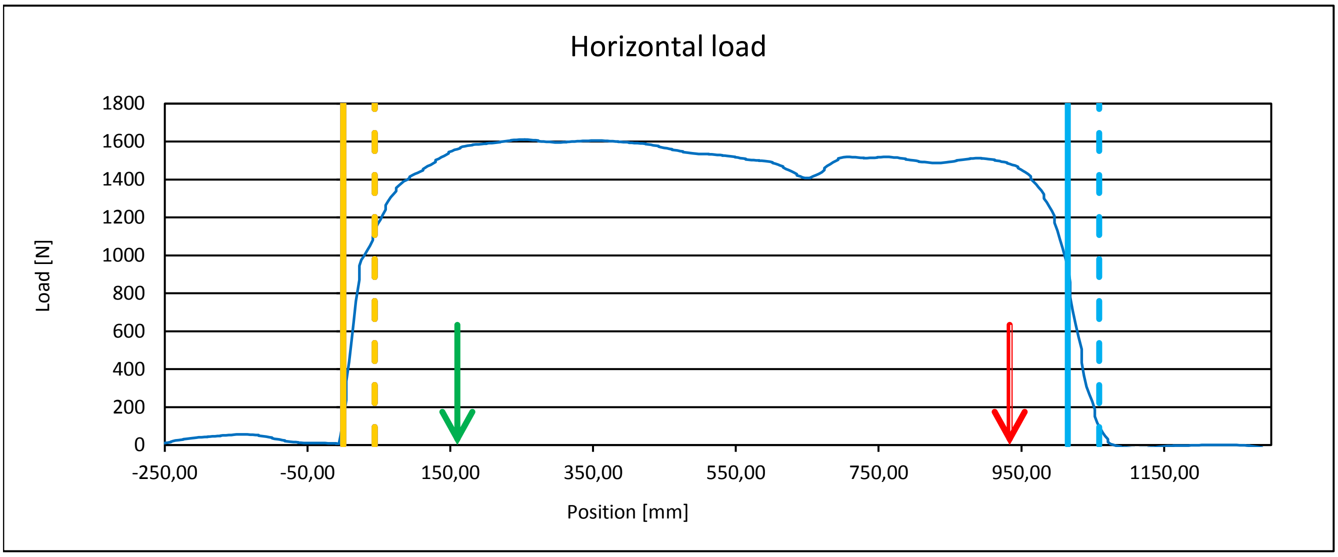
Averages in measuring length

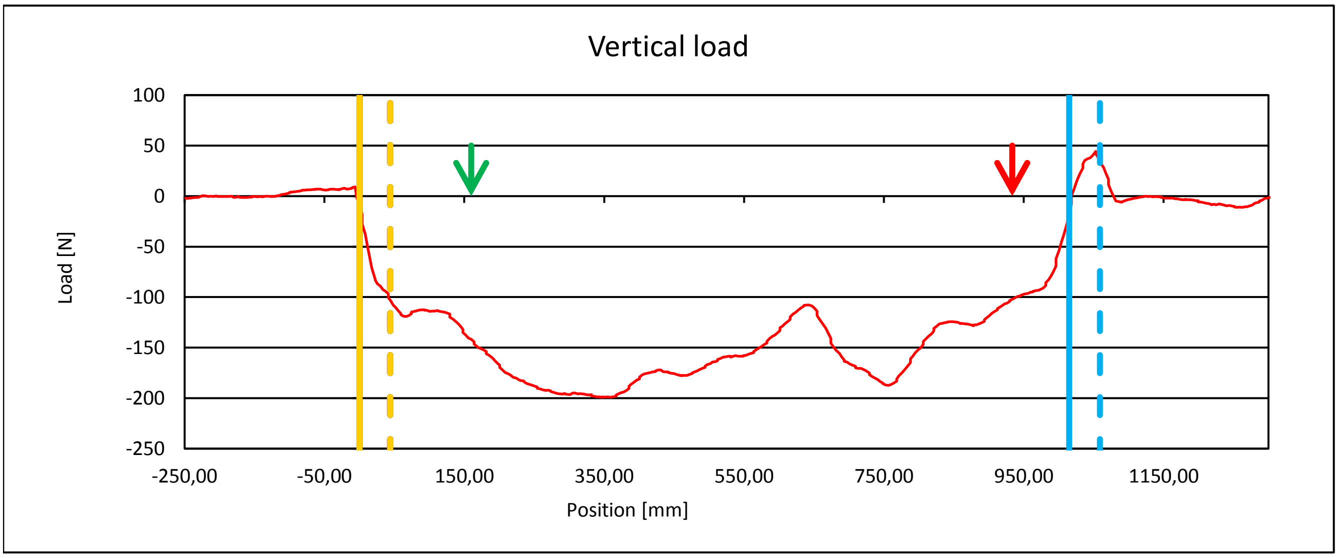
Start measuring length	159,8	mm
End measurement length	933,6	mm
Totaal length	773,7	mm
Average speed	31,4	mm/s
Average speed	113,1	m/h
Horizontal load cell	1536,1	N
Total Vertical load	-160,0	N
Total force	1544,4	N
Angle of total force	-5,9	Degree

Measured results

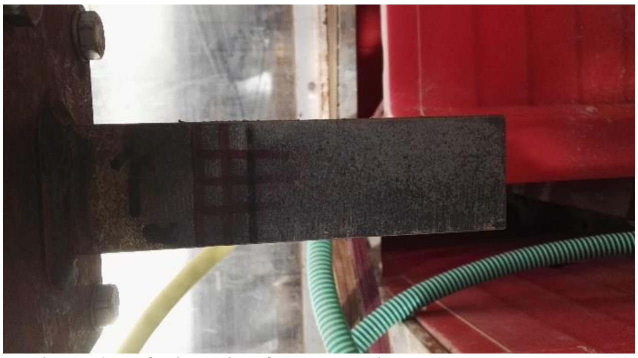









Left side of plough after trenching


Right side of plough after trenching


Frontview during trenching

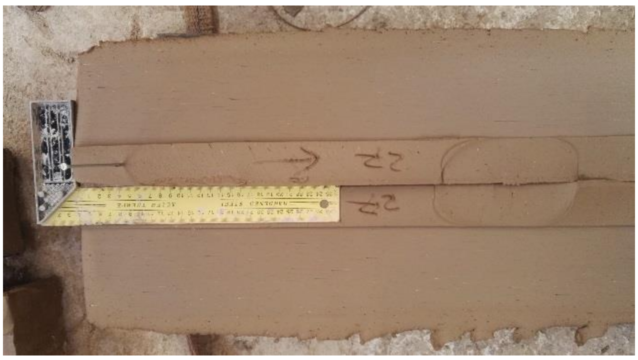

Sideview during trenching


Top of first section


Top of middle section


Top of last section

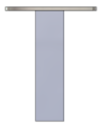

Cross section


Sides of the trench

TEST REPORT 28

General information

Test number:	28	Length of clay box:	1030 mm
Date of test:	6-12-2016	Water on top of clay:	69 mm
Time of test:	10:00	Depth of the plough:	94 mm
Test profile:	S	Set motor velocity:	-6 [-]
		Clay type:	Medium



Particular during test

Particulars of the clay block:

0

Particular events during the test:

0

Material properties of the clay

Average shear strength: 72 kPa

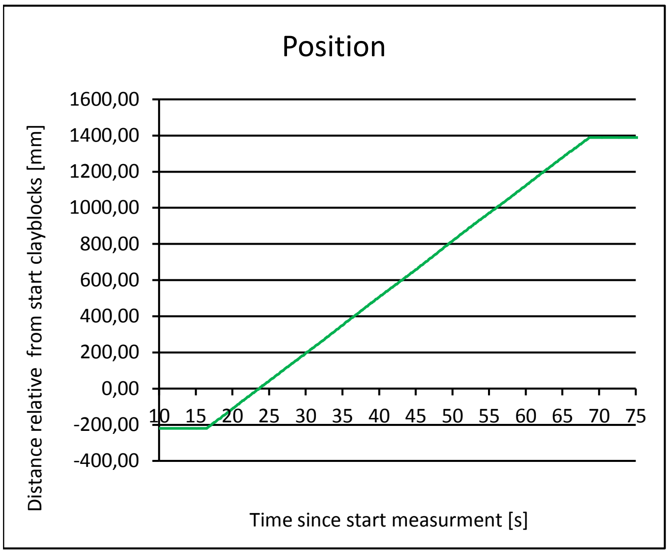
	Block 1	Block 2	Block 3	Block 4	
Handvane test before trenching:	52	50	60	97,5	kPa
	-	60	49	-	kPa

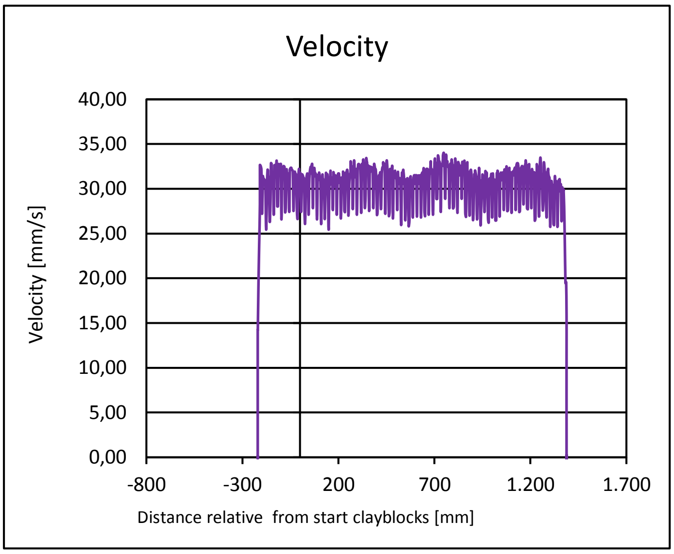
		Block 2	Block 3	
Handvane test after trenching:		50	40	kPa
Fieldvane test after trenching:	Shear 1	73	66	kPa
	Shear 2	66	66	kPa
	Residual 1	24	19	kPa
	Residual 2	28	18	kPa

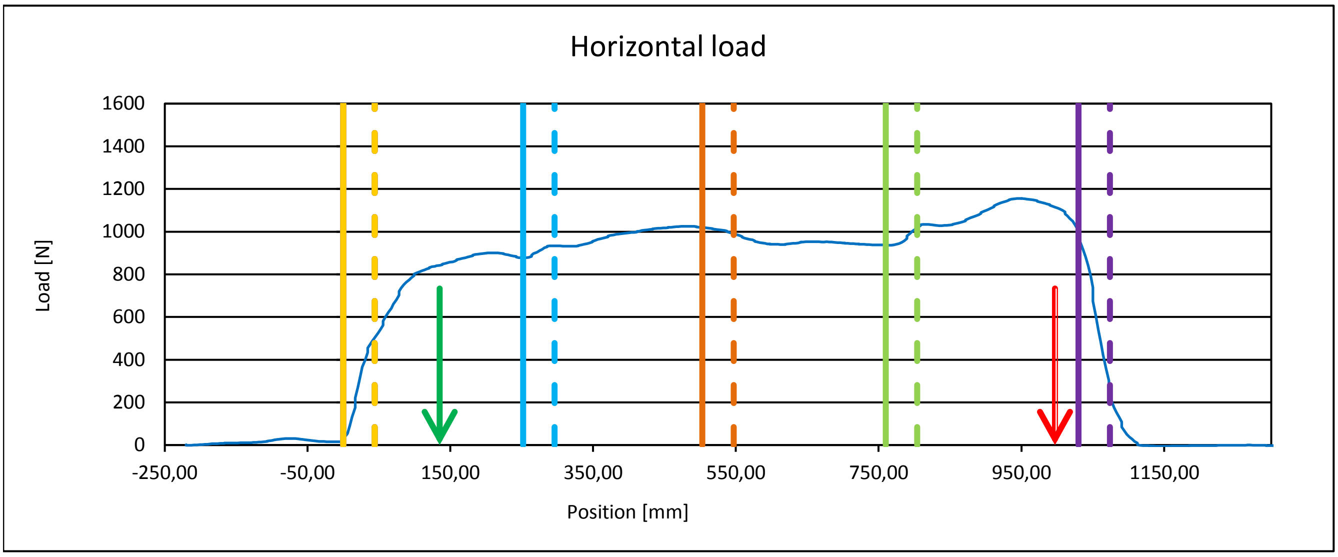
Averages in measuring length

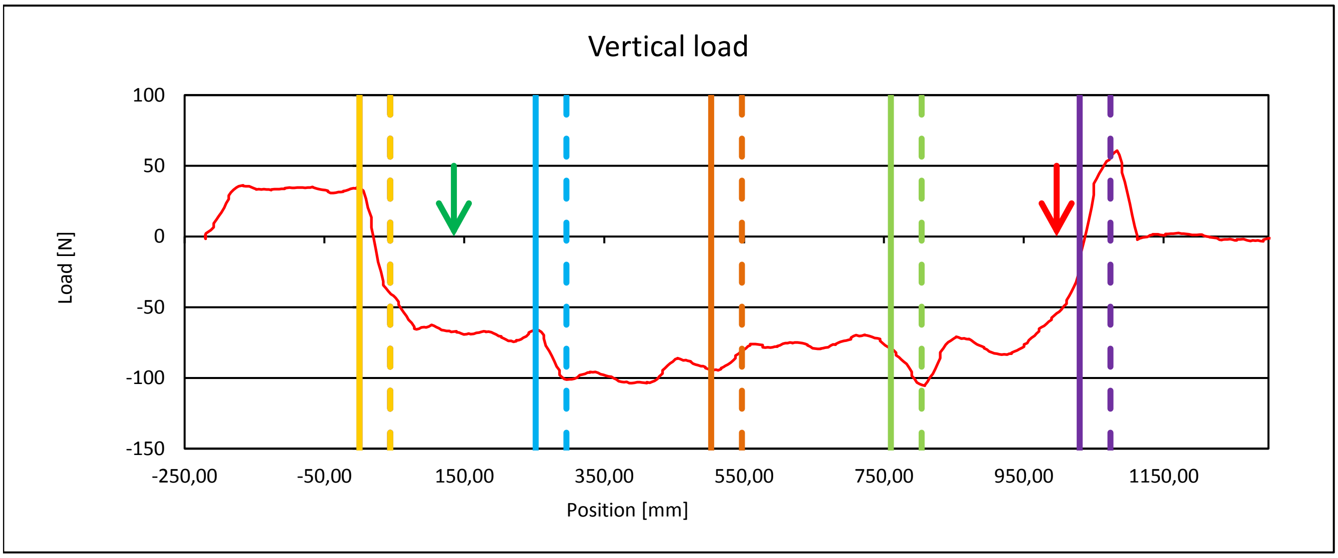
Start measuring length	135,0	mm
End measurement length	997,0	mm
Totaal length	862,0	mm
Average speed	31,0	mm/s
Average speed	111,4	m/h
Horizontal load cell	982,7	N
Total Vertical load	-82,1	N
Total force	986,1	N
Angle of total force	-4,8	Degree

Measured results

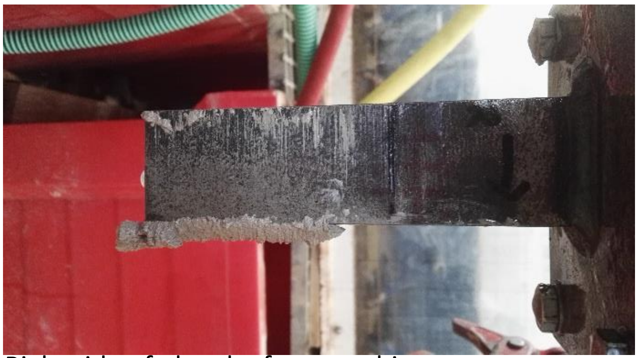









Left side of plough after trenching


Right side of plough after trenching


Frontview during trenching


Sideview during trenching


Top of first section


Top of middle section


Top of last section


Cross section


Sides of the trench

TEST REPORT 29

General information

Test number:	29	Length of clay box:	1030	mm
Date of test:	6-12-2016	Water on top of clay:	69	mm
Time of test:	15:00	Depth of the plough:	94	mm
Test profile:	BRAVO	Set motor velocity:	-6	[-]
		Clay type:	Medium	

Particular during test

Particulars of the clay block:

0

Particular events during the test:

BRAVO plough with convex height of 5mm

Material properties of the clay

Average shear strength: 62 kPa

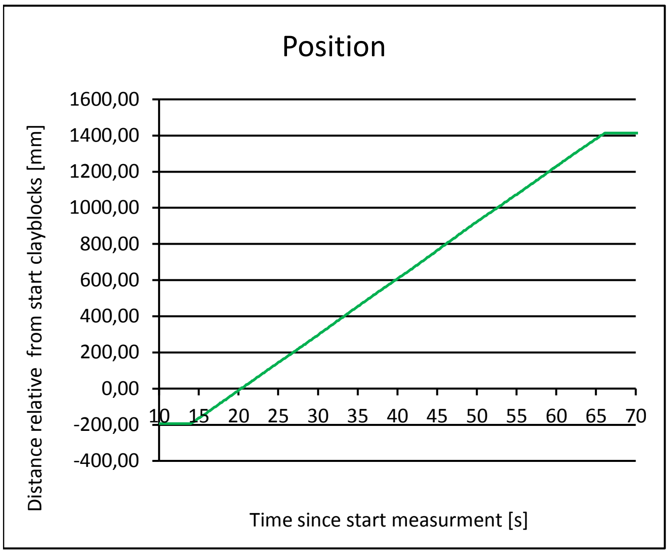
	Block 1	Block 2	Block 3	Block 4	
Handvane test before trenching:	50	65	60	63	kPa
	-	60	58	-	kPa

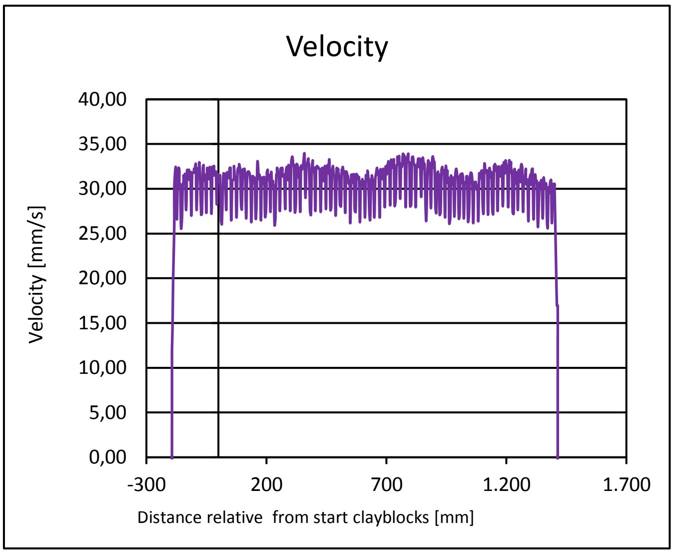
		Block 2	Block 3	
Handvane test after trenching:		49	55	kPa
Fieldvane test after trenching:	Shear 1	64	56	kPa
	Shear 2	64	66	kPa
	Residual 1	15	11	kPa
	Residual 2	16	13	kPa

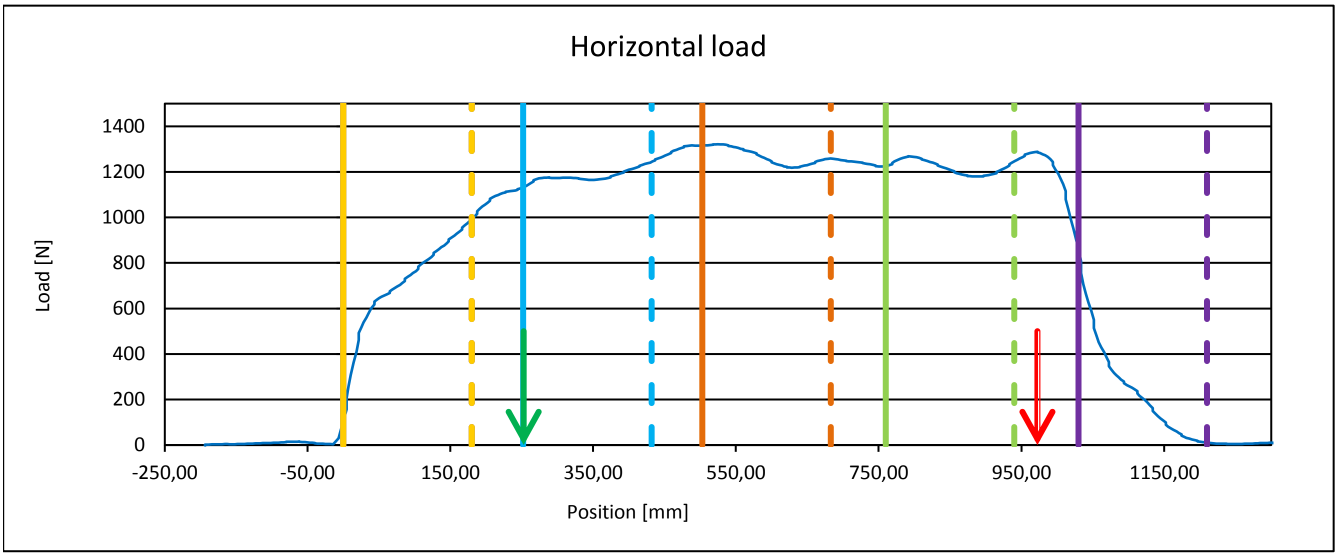
Averages in measuring length

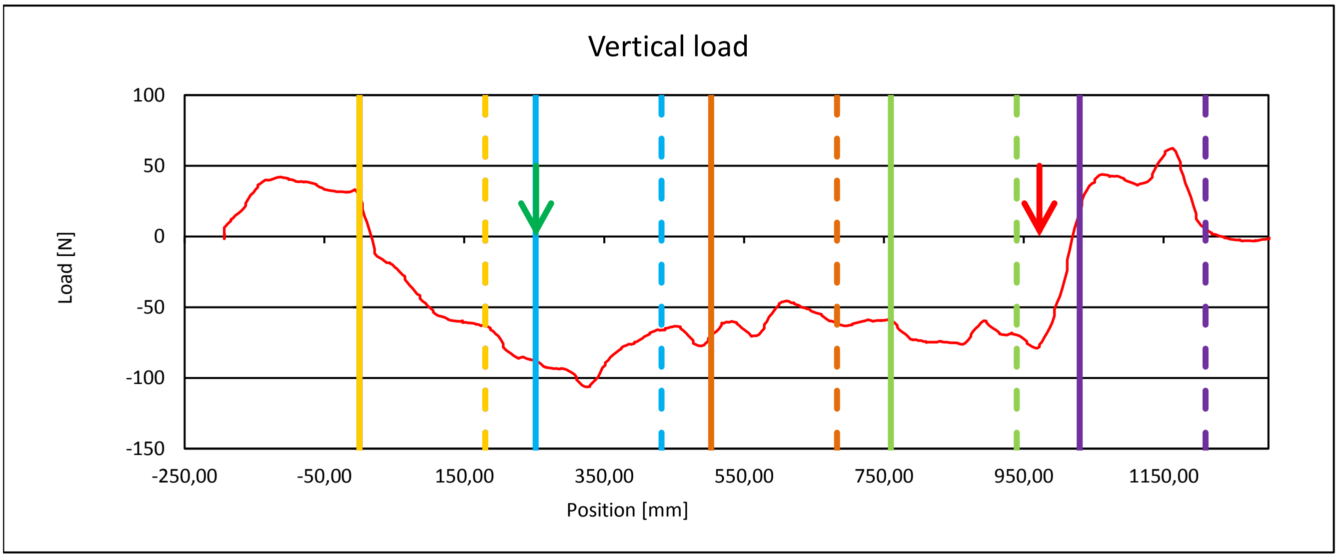
Start measuring length	252,7	mm
End measurement length	972,5	mm
Totaal length	719,7	mm
Average speed	31,2	mm/s
Average speed	112,4	m/h
Horizontal load cell	1234,9	N
Total Vertical load	-70,4	N
Total force	1236,9	N
Angle of total force	-3,3	Degree

Measured results

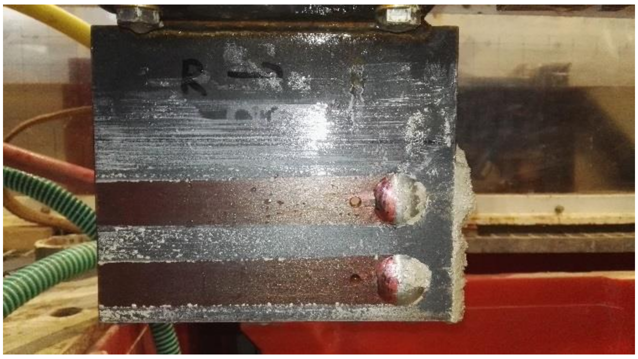








Left side of plough after trenching



Right side of plough after trenching

Frontview during trenching

Sideview during trenching

Top of first section

Top of middle section

Top of last section

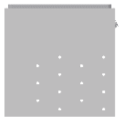
Cross section

Sides of the trench

TEST REPORT 30

General information

Test number:	30	
Date of test:	7-12-2016	
Time of test:	11:00	
Test profile:	CHARLIE	



Length of clay box:	1015	mm
Water on top of clay:	69	mm
Depth of the plough:	94	mm
Set motor velocity:	-6	[-]
Clay type:	Hard	

Particular during test

Particulars of the clay block:

0

Particular events during the test:

The first two columns of nozzles are fed with 2 tubes at a pressure of 4 bar just before the T-junction of the 2 tubes.

Material properties of the clay

	Before	After	
Average shear strength:	134,5	124,7	kPa
Average residual shear strength:	83,0	65,0	kPa

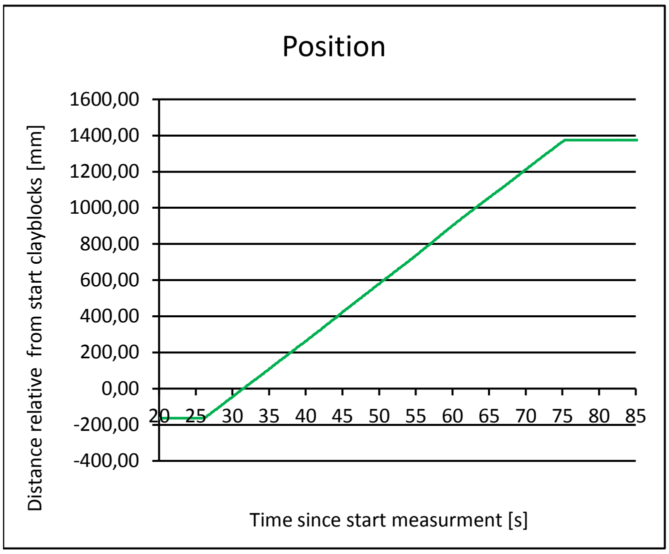
Field vane clay strength tests

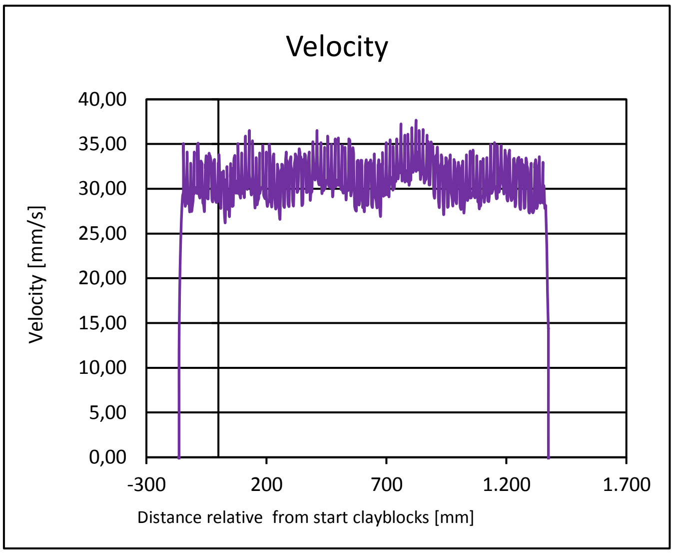
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	147	80	135	68
Left 2	144	74	130	68
Left 3	No test	No test	128	56
Right 1	124	88	122	60
Right 2	123	90	120	64
Right 3	No test	No test	113	74

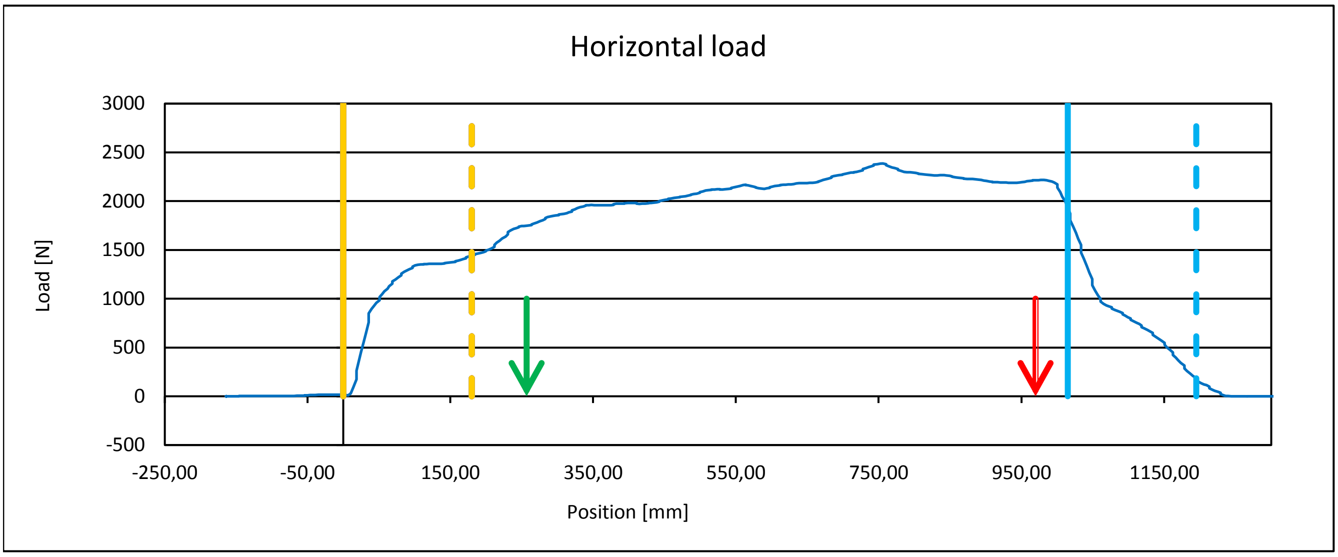
Averages in measuring length

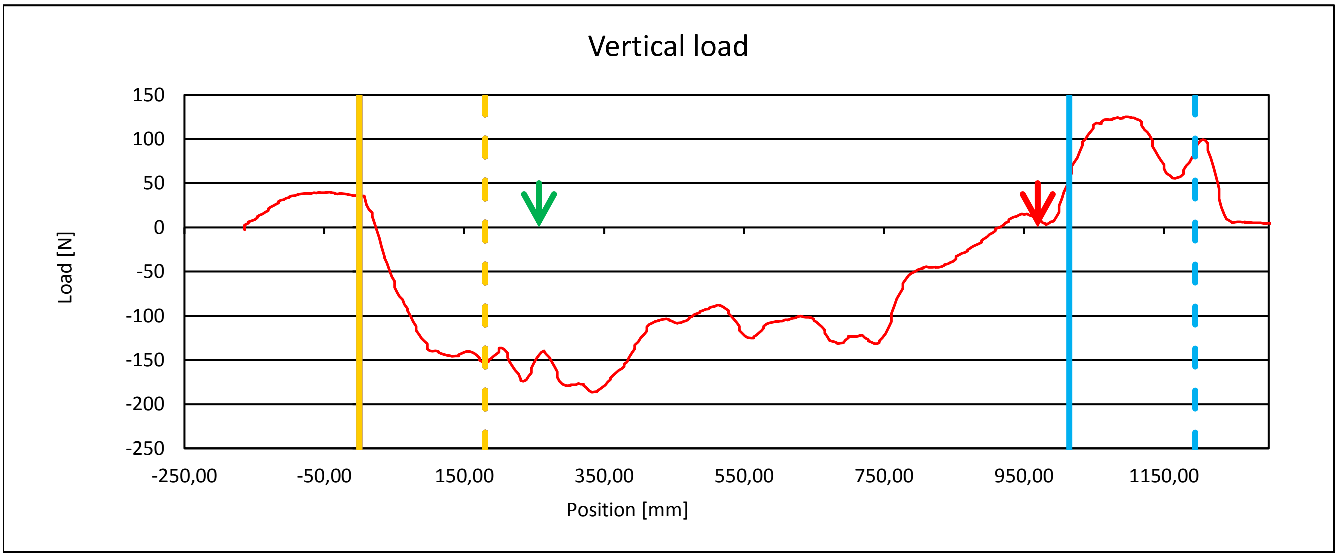
Start measuring length	256,9	mm
End measurement length	969,8	mm
Totaal length	713,0	mm
Average speed	31,9	mm/s
Average speed	114,8	m/h
Horizontal load cell	2126,7	N
Total Vertical load	-97,1	N
Total force	2129,0	N
Angle of total force	-2,6	Degree

Measured results





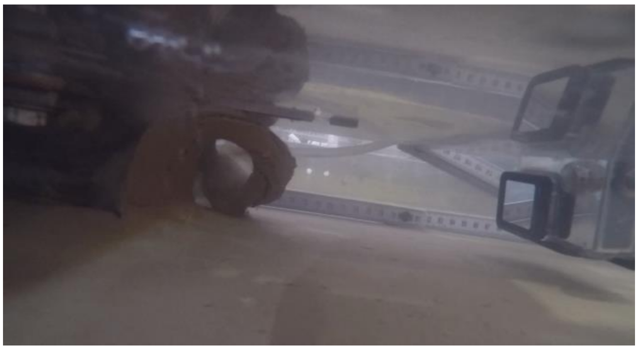





Left side of plough after trenching

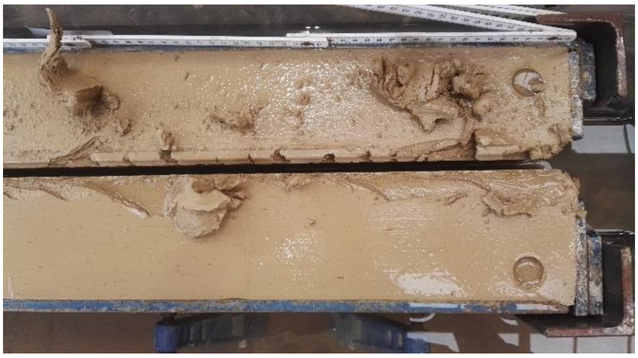

Right side of plough after trenching


Frontview during trenching


Sideview during trenching


Top of first section


Top of middle section


Top of last section

Cross section

Sides of the trench

TEST REPORT 31

General information

Test number:	31	Length of clay box:	1015 mm
Date of test:	7-12-2016	Water on top of clay:	69 mm
Time of test:	15:00	Depth of the plough:	94 mm
Test profile:	L	Set motor velocity:	-6 [-]
		Clay type:	Hard

Particular during test

Particulars of the clay block:

The clay bread is cut into 4 blocks just like the medium clay. The goal is to see what the influence is of the seems between the blocks.

Particular events during the test:

0

Material properties of the clay

Average shear strength: 125 kPa

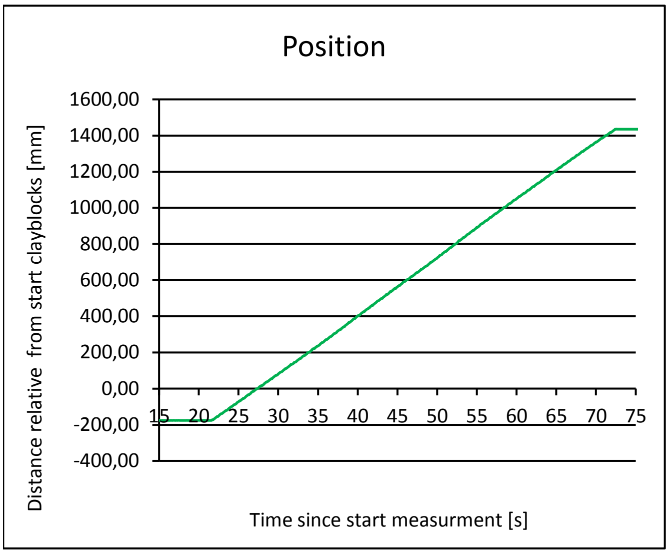
	Block 1	Block 2	Block 3	Block 4	
Handvane test before trenching:	115	116	112	110	kPa
	-	120	110	-	kPa

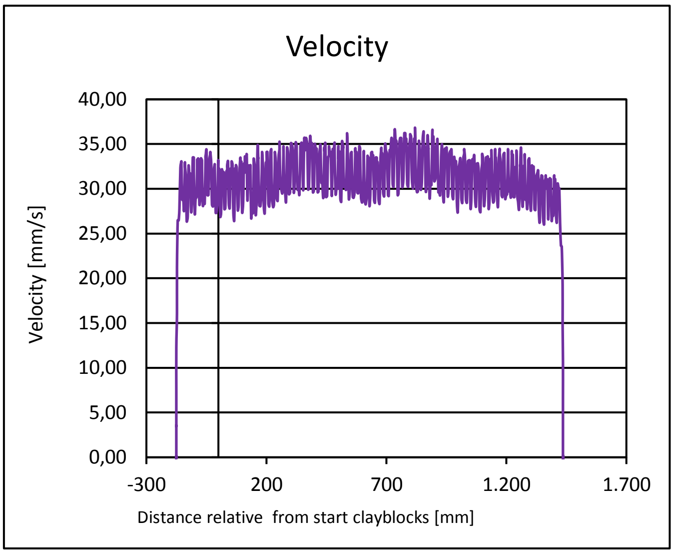
		Block 2	Block 3	
Handvane test after trenching:		100	103	kPa
Fieldvane test after trenching:	Shear 1	133	130	kPa
	Shear 2	119	118	kPa
	Residual 1	56	68	kPa
	Residual 2	58	57	kPa

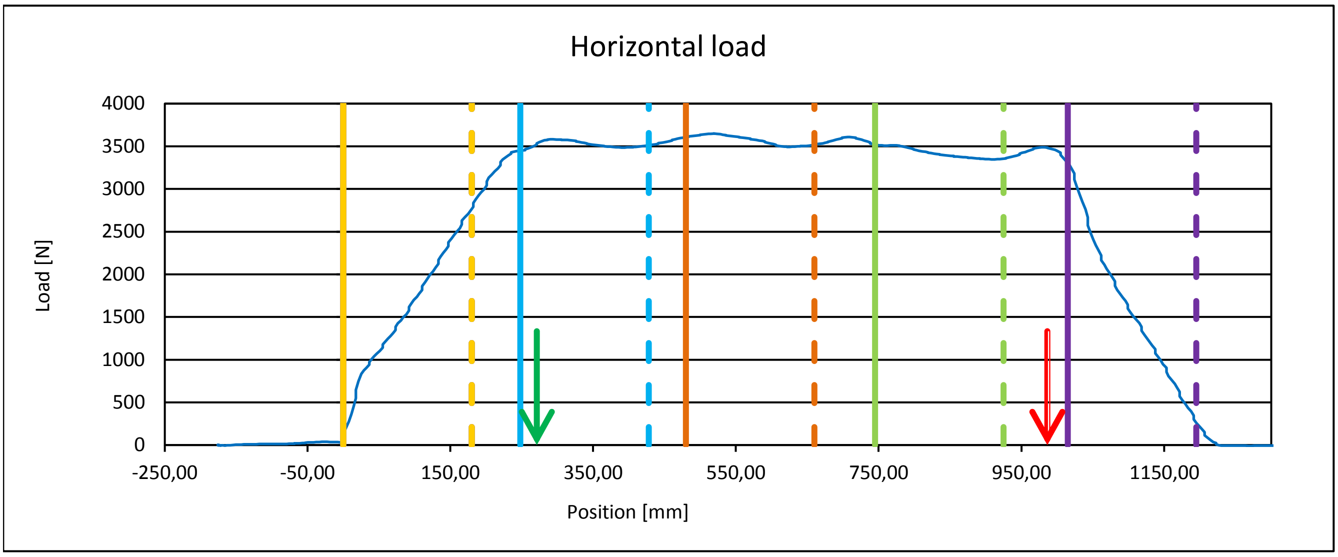
Averages in measuring length

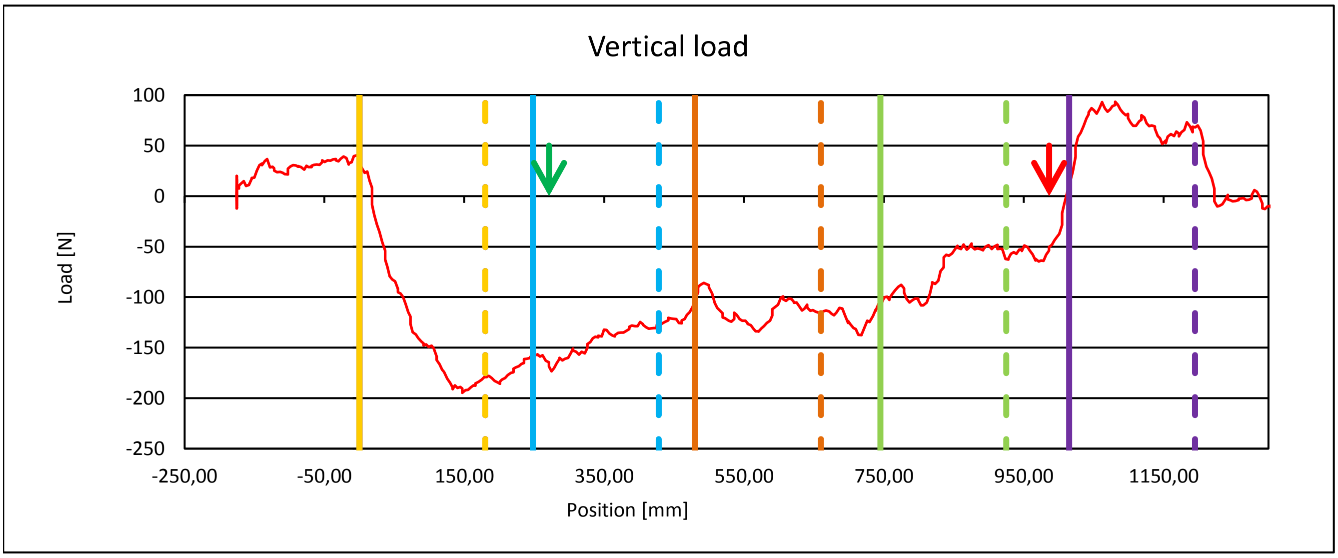
Start measuring length	271,1	mm
End measurement length	986,4	mm
Totaal length	715,2	mm
Average speed	32,7	mm/s
Average speed	117,7	m/h
Horizontal load cell	3511,4	N
Total Vertical load	-106,8	N
Total force	3513,0	N
Angle of total force	-1,7	Degree

Measured results









Left side of plough after trenching

Right side of plough after trenching

Frontview during trenching

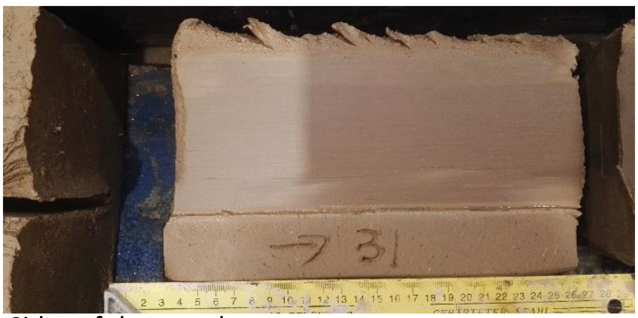
Sideview during trenching

Top of first section

Top of middle section

Top of last section

Cross section



Sides of the trench

TEST REPORT 32

General information

Test number:	32	Length of clay box:	1015 mm
Date of test:	8-12-2016	Water on top of clay:	No water mm
Time of test:	11:00	Depth of the plough:	94 mm
Test profile:	L	Set motor velocity:	-6 [-]
		Clay type:	Soft

Particular during test

Particulars of the clay block:

0

Particular events during the test:

Dry test

Material properties of the clay

Average shear strength*: 24,8 kPa

Average residual shear strength*: 15,6 kPa

**average of field vane test before trenching block 3 to 7*

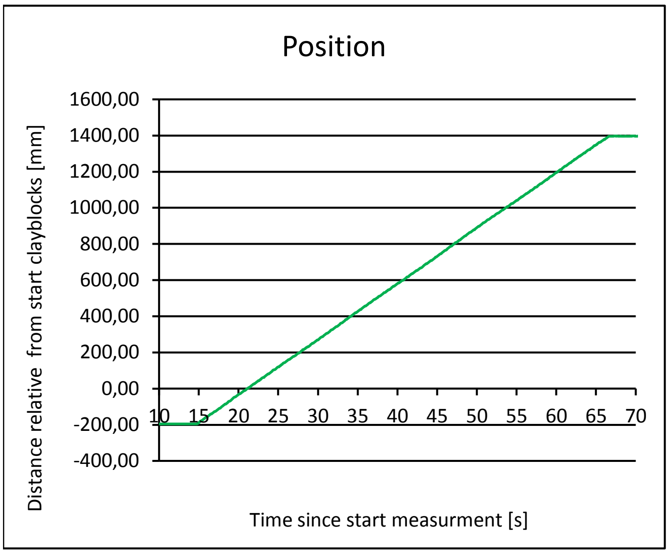
Field vane clay strength tests	**Block 1**	**Block 2**	**Block 3**	**Block 4**	
Shear strength test before trenching:	23	23	24	25	kPa
Residual strength test before trenching:	12	14	14	16	kPa
Shear strength test after trenching:	23	26	24	23	kPa

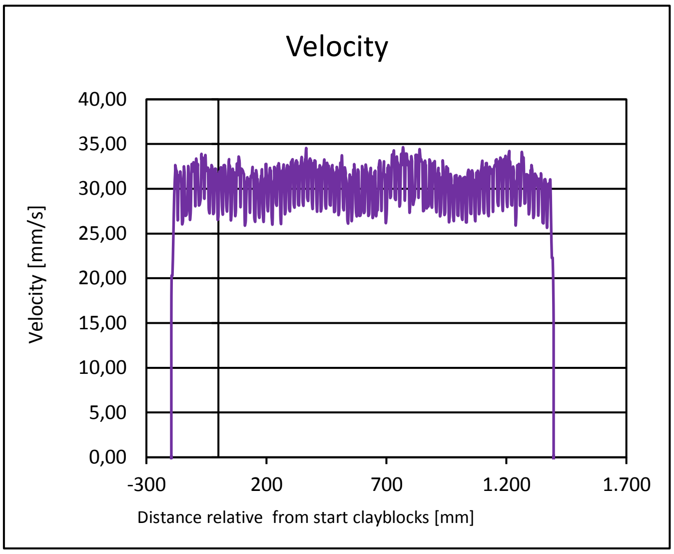
	Block 5	**Block 6**	**Block 7**	**Block 8**	
Shear strength test before trenching:	25	25	26	26	kPa
Residual strength test before trenching:	15	16	17	18	kPa
Shear strength test after trenching:	24	23	25	24	kPa

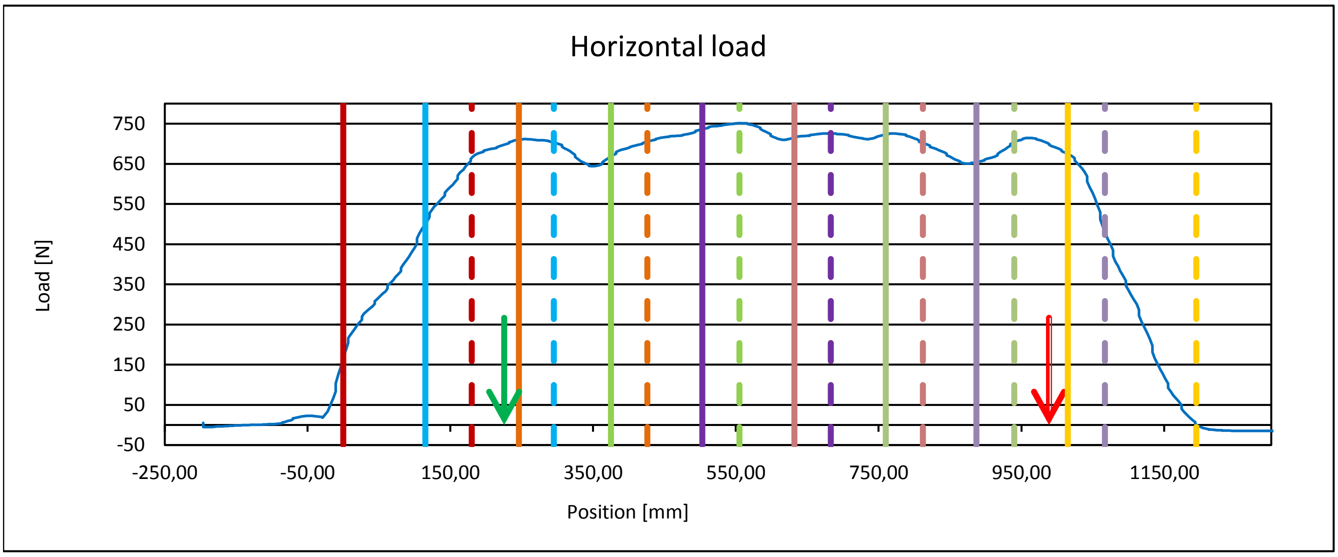
Averages in measuring length

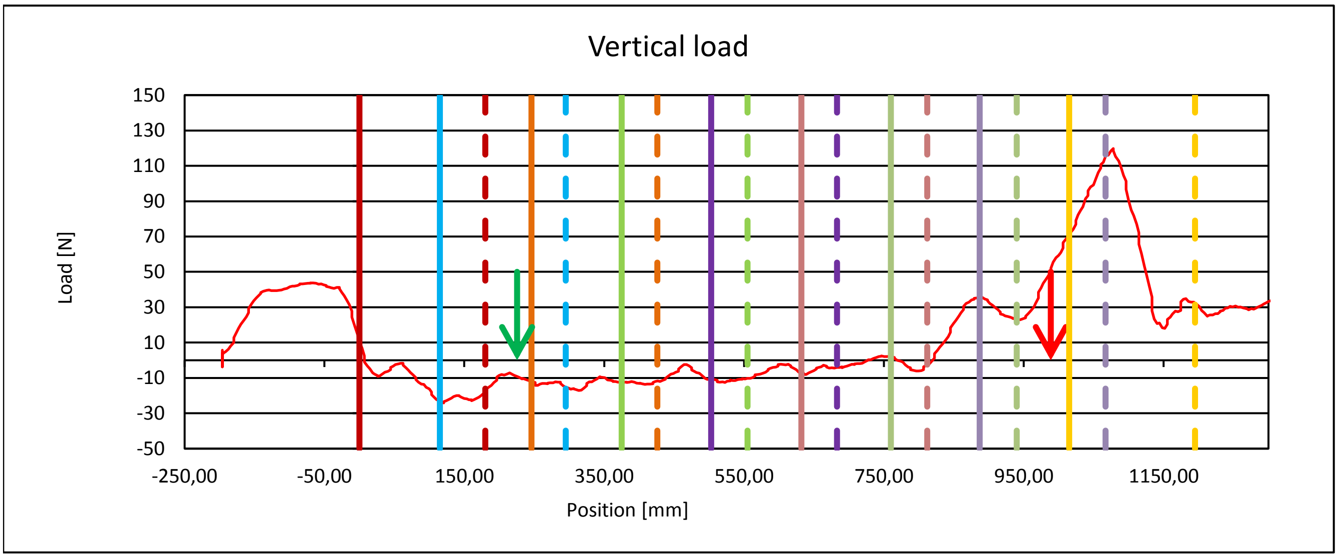
Start measuring length	225,4	mm
End measurement length	988,7	mm
Totaal length	763,3	mm
Average speed	30,8	mm/s
Average speed	111,1	m/h
Horizontal load cell	705,4	N
Total Vertical load	-0,1	N
Total force	705,4	N
Angle of total force	0,0	Degree

Measured results









Left side of plough after trenching

Right side of plough after trenching

Frontview during trenching

Sideview during trenching

Top of first section

Top of middle section

Top of last section

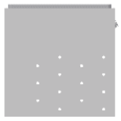
Cross section

Sides of the trench

TEST REPORT 33

General information

Test number:	33	Length of clay box:	1025 mm
Date of test:	8-12-2016	Water on top of clay:	69 mm
Time of test:	15:00	Depth of the plough:	94 mm
Test profile:	CHARLIE	Set motor velocity:	-6 [-]
		Clay type:	Soft



Particular during test

Particulars of the clay block:

0

Particular events during the test:

The first two columns of nozzles are fed with 2 tubes at a pressure of 4 bar just before the T-junction of the 2 tubes.

Material properties of the clay

<u>Average shear strength*:</u> <u>25,8</u> kPa

<u>Average residual shear strength*:</u> <u>16,0</u> kPa

**average of field vane test before trenching block 3 to 7*

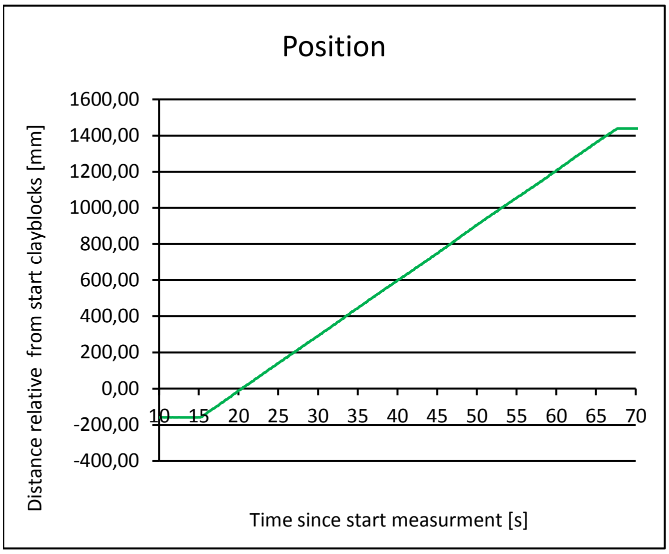
Field vane clay strength tests	**Block 1**	**Block 2**	**Block 3**	**Block 4**	
Shear strength test before trenching:	24	25	26	26	kPa
Residual strength test before trenching:	14	16	17	15	kPa
Shear strength test after trenching:	24	24	25	25	kPa

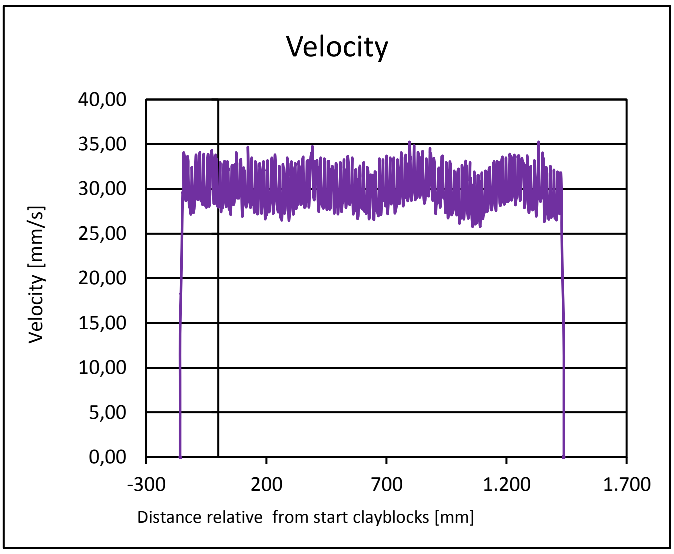
	Block 5	**Block 6**	**Block 7**	**Block 8**	
Shear strength test before trenching:	26	26	26	27	kPa
Residual strength test before trenching:	16	16	16	15	kPa
Shear strength test after trenching:	24	24	25	24	kPa

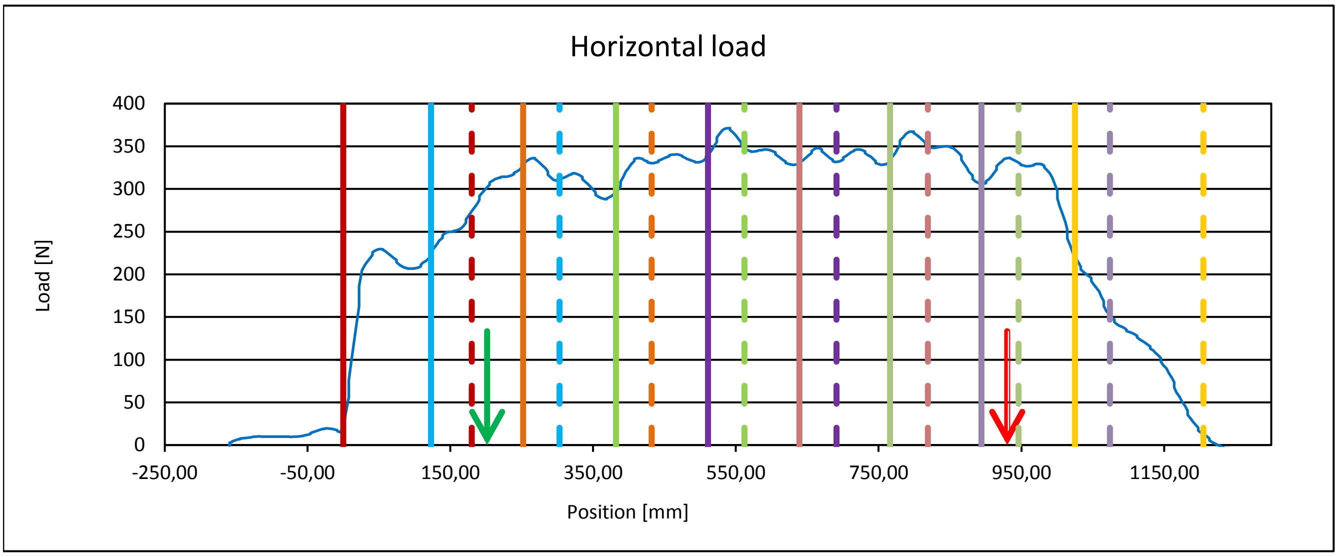
Averages in measuring length

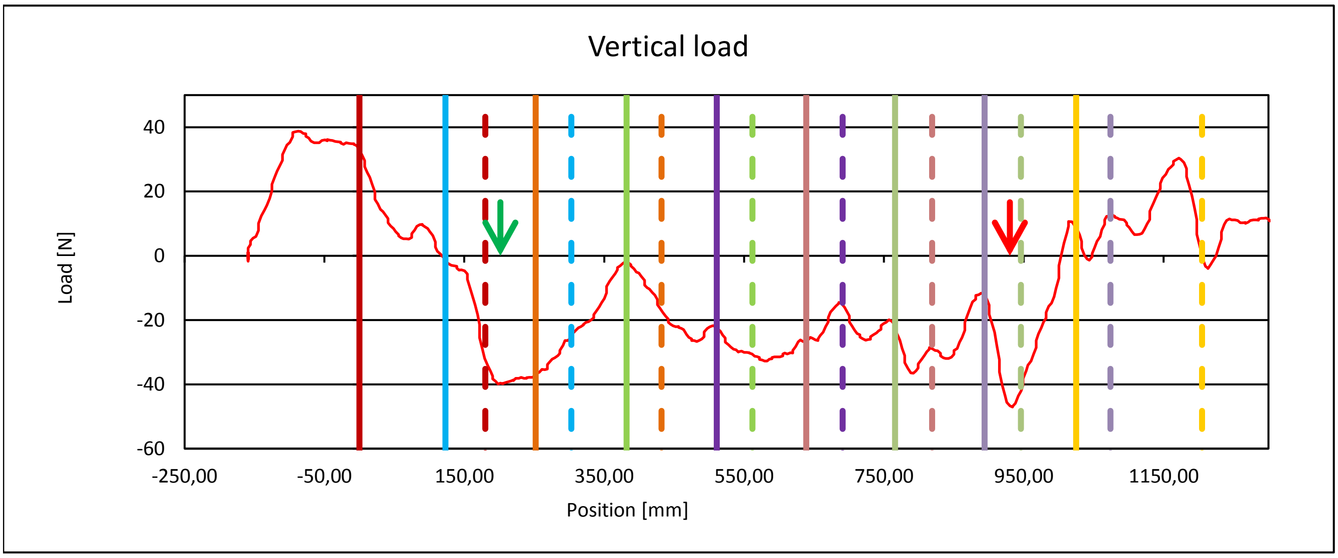
Start measuring length	201,6	mm
End measurement length	930,2	mm
Totaal length	728,6	mm
Average speed	30,6	mm/s
Average speed	110,2	m/h
Horizontal load cell	332,5	N
Total Vertical load	-24,9	N
Total force	333,4	N
Angle of total force	-4,3	Degree

Measured results









Left side of plough after trenching

Right side of plough after trenching

Frontview during trenching

Sideview during trenching

Top of first section

Top of middle section

Top of last section

Cross section

Sides of the trench

TEST REPORT 34

General information

Test number:	34	Length of clay box:	1015 mm
Date of test:	12-12-2016	Water on top of clay:	69 mm
Time of test:	11:00	Depth of the plough:	94 mm
Test profile:	L	Set motor velocity:	-6 [-]
		Clay type:	Hard

Particular during test

Particulars of the clay block:

Clay was clamped with the maximum torque I could generate on the frame clamp. The purpuse is to check if a larger normal force on the plough generates a larger friction.

Particular events during the test:

0

Material properties of the clay

	Before	After	
Average shear strength:	136,0	131,2	kPa
Average residual shear strength:	95,8	66,0	kPa

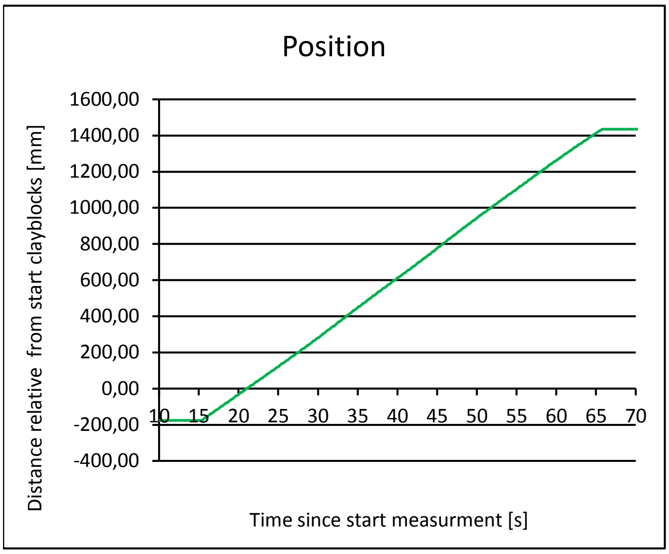
Field vane clay strength tests

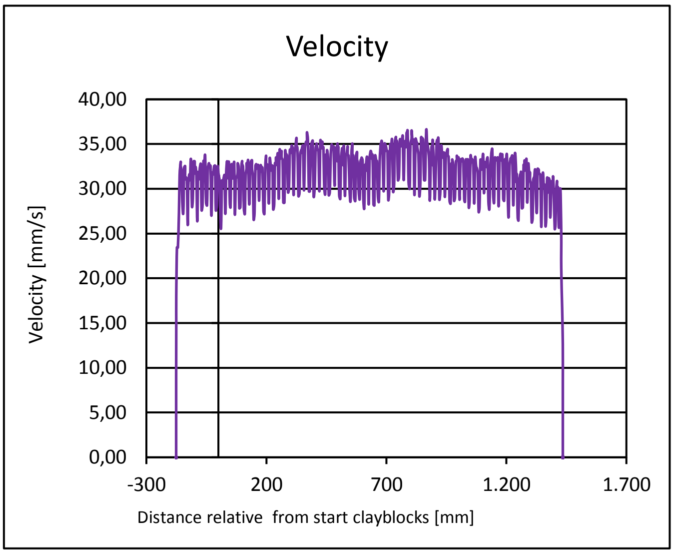
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	142	69	140	72
Left 2	145	101	133	70
Left 3	No test	No test	138	67
Right 1	127	109	123	57
Right 2	130	104	128	66
Right 3	No test	No test	125	64

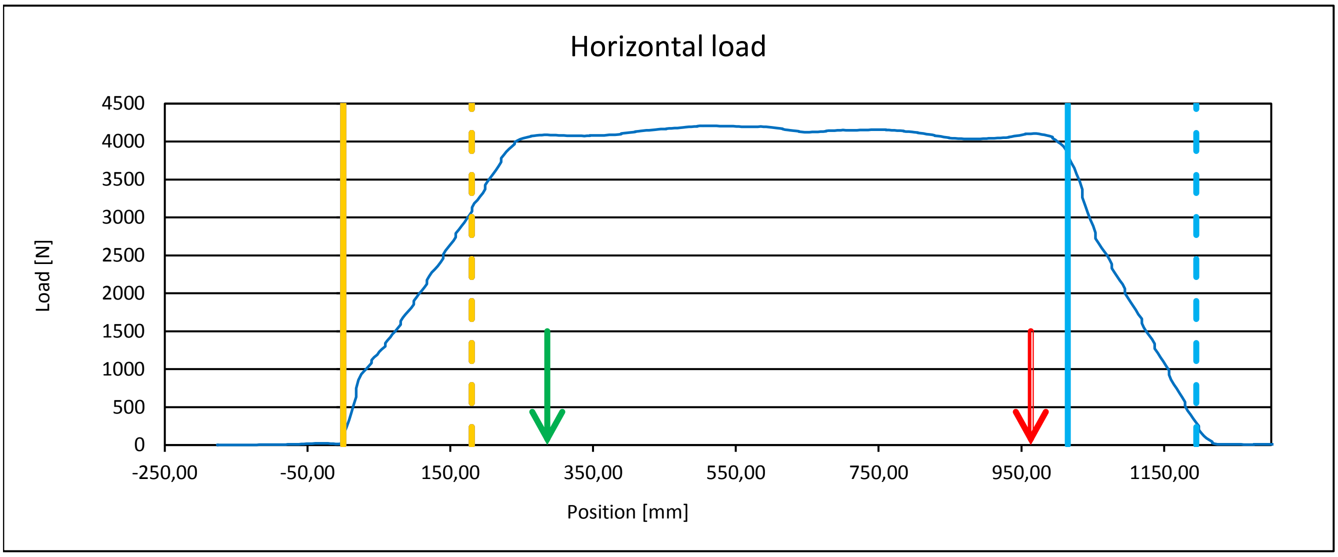
Averages in measuring length

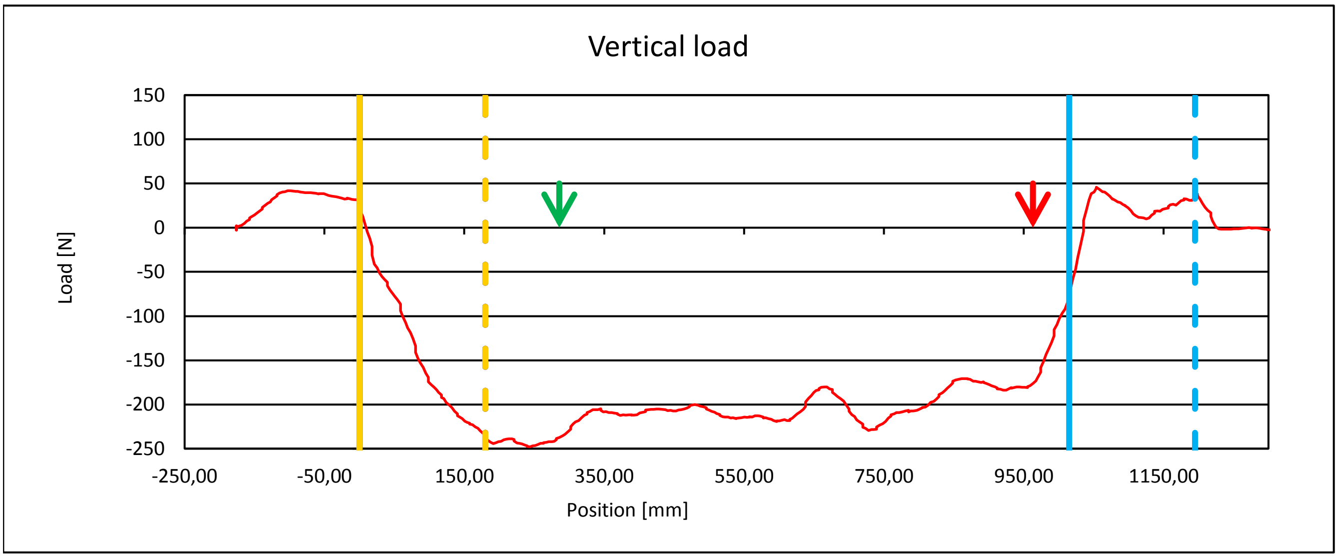
Start measuring length	285,8	mm
End measurement length	963,2	mm
Totaal length	677,4	mm
Average speed	33,1	mm/s
Average speed	119,3	m/h
Horizontal load cell	4126,5	N
Total Vertical load	-203,0	N
Total force	4131,4	N
Angle of total force	-2,8	Degree

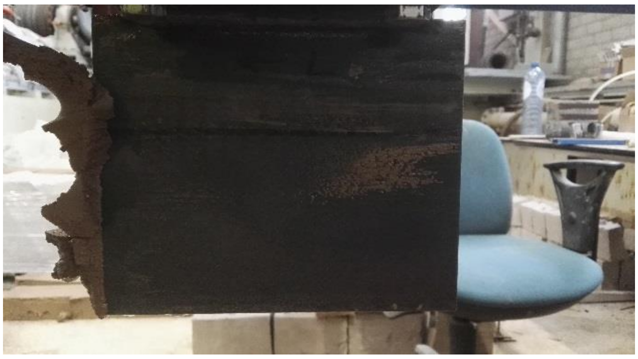
Measured results










Left side of plough after trenching


Right side of plough after trenching


Frontview during trenching


Sideview during trenching


Top of first section


Top of middle section


Top of last section

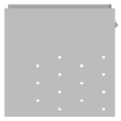
Cross section

Sides of the trench

TEST REPORT 35

General information

Test number:	35	Length of clay box:	1015 mm
Date of test:	13-12-2016	Water on top of clay:	69 mm
Time of test:	11:00	Depth of the plough:	94 mm
Test profile:	CHARLIE	Set motor velocity:	-6 [-]
		Clay type:	Hard



Particular during test

Particulars of the clay block:

0

Particular events during the test:

The first two columns of nozzles are fed with 2 tubes at a pressure of 5 bar just before the T-junction of the 2 tubes.

Material properties of the clay

	Before	After	
Average shear strength:	123,8	124,0	kPa
Average residual shear strength:	70,5	67,3	kPa

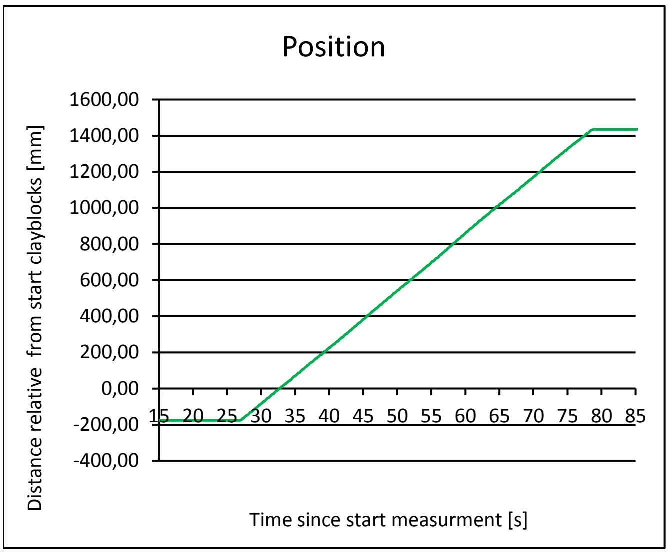
Field vane clay strength tests

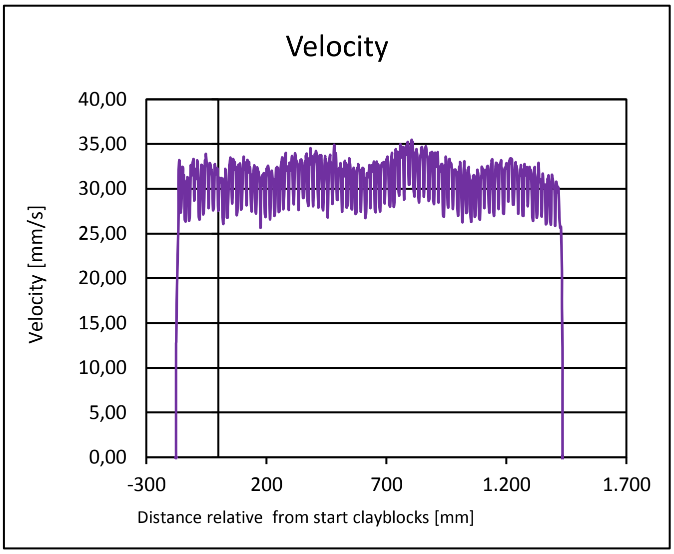
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	130	60	128	80
Left 2	132	66	133	66
Left 3	No test	No test	131	68
Right 1	116	77	117	60
Right 2	117	79	120	64
Right 3	No test	No test	115	66

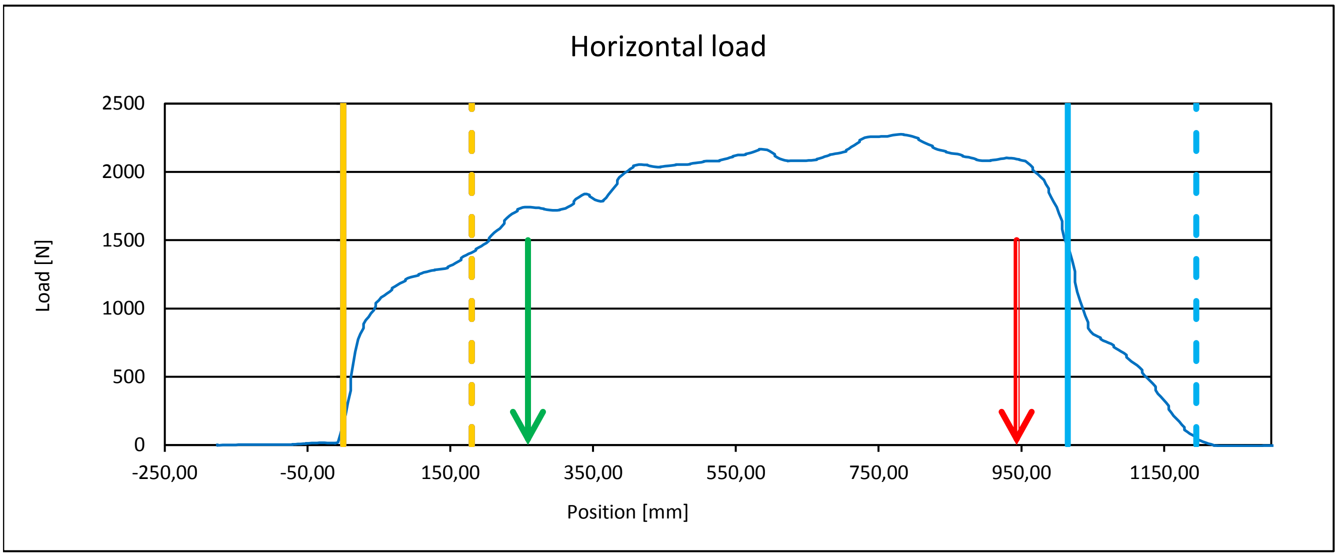
Averages in measuring length

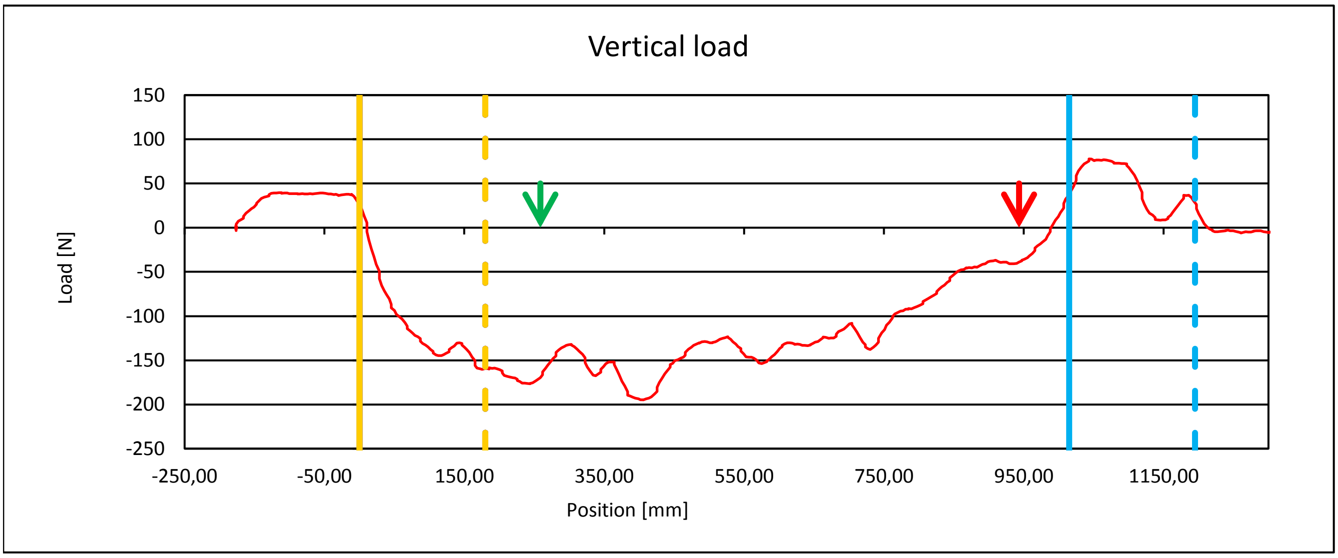
Start measuring length	258,8	mm
End measurement length	943,3	mm
Totaal length	684,6	mm
Average speed	31,9	mm/s
Average speed	114,7	m/h
Horizontal load cell	2058,8	N
Total Vertical load	-122,0	N
Total force	2062,4	N
Angle of total force	-3,4	Degree

Measured results










Left side of plough after trenching


Right side of plough after trenching


Frontview during trenching


Sideview during trenching


Top of first section


Top of middle section


Top of last section

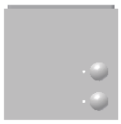
Cross section


Sides of the trench

TEST REPORT 36

General information

Test number:	36	Length of clay box:	1015 mm
Date of test:	13-12-2016	Water on top of clay:	69 mm
Time of test:	16:00	Depth of the plough:	94 mm
Test profile:	BRAVO	Set motor velocity:	-6 [-]
		Clay type:	Hard



Particular during test

Particulars of the clay block:

0

Particular events during the test:

2mm strips where attached to the sides of the BRAVO plough.

Material properties of the clay

	Before	After	
Average shear strength:	121,5	121,5	kPa
Average residual shear strength:	71,5	65,2	kPa

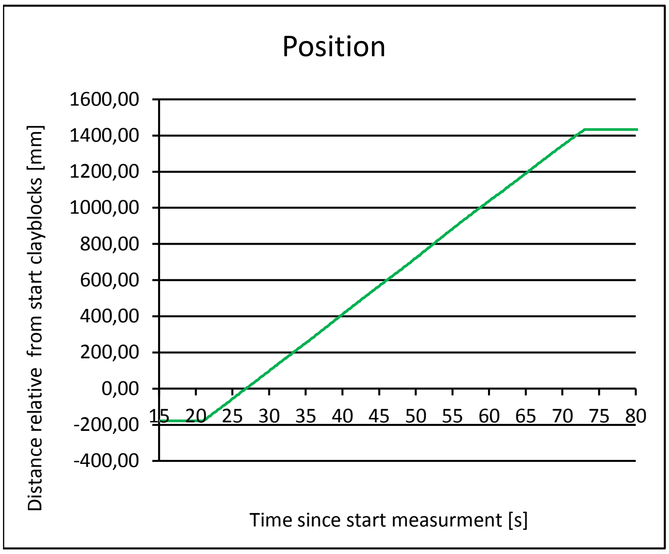
Field vane clay strength tests

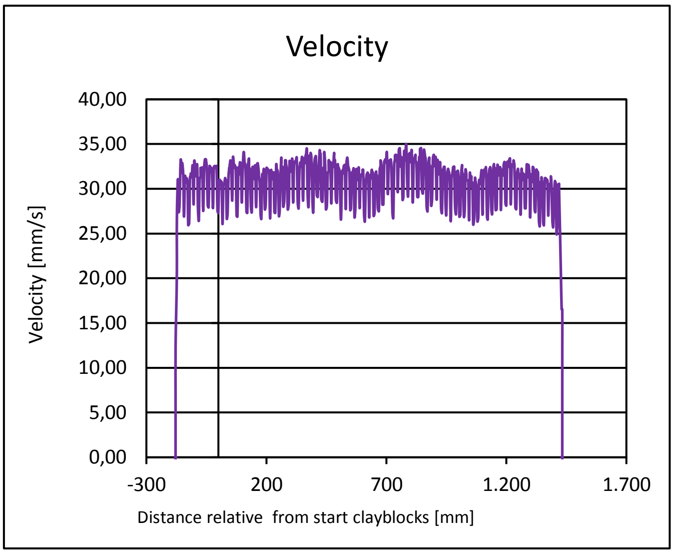
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	126	48	128	62
Left 2	131	75	138	70
Left 3	No test	No test	124	74
Right 1	115	70	112	48
Right 2	114	93	114	75
Right 3	No test	No test	113	62

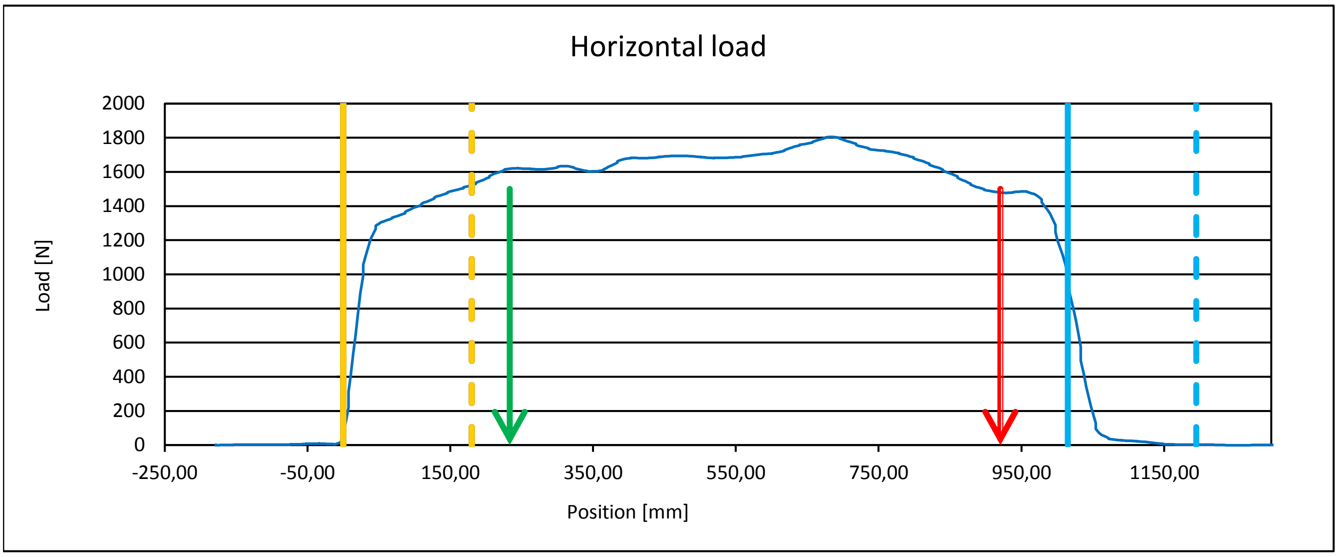
Averages in measuring length

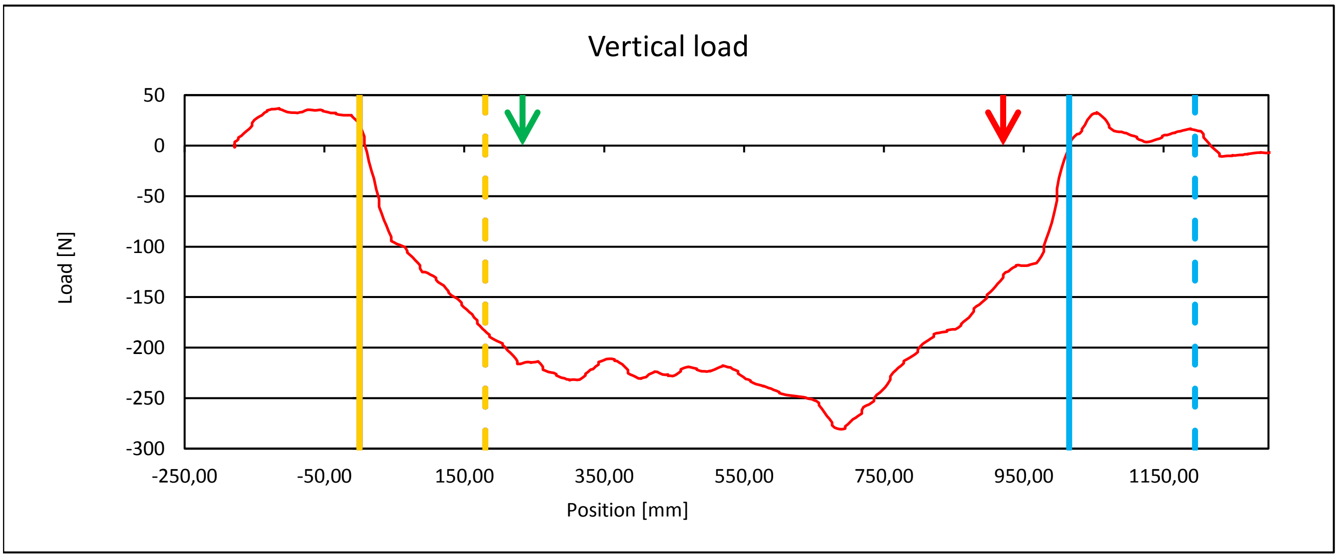
Start measuring length	233,2	mm
End measurement length	920,6	mm
Totaal length	687,3	mm
Average speed	31,6	mm/s
Average speed	113,6	m/h
Horizontal load cell	1670,0	N
Total Vertical load	-222,5	N
Total force	1684,8	N
Angle of total force	-7,6	Degree

Measured results

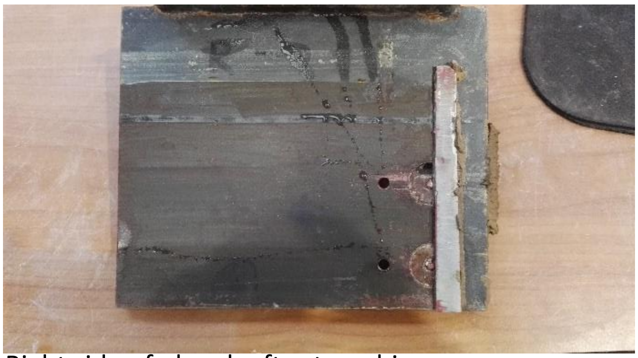








Left side of plough after trenching



Right side of plough after trenching

Frontview during trenching

Sideview during trenching

Top of first section

Top of middle section

Top of last section

Cross section

Sides of the trench

TEST REPORT 37

General information

Test number:	37	Length of clay box:	1015 mm
Date of test:	14-12-2016	Water on top of clay:	69 mm
Time of test:	11:00	Depth of the plough:	94 mm
Test profile:	L	Set motor velocity:	-3 [-]
		Clay type:	Hard

Particular during test

Particulars of the clay block:

0

Particular events during the test:

Velocity of 63 meters per hour

Material properties of the clay

	Before	After	
Average shear strength:	125,8	124,5	kPa
Average residual shear strength:	54,3	61,8	kPa

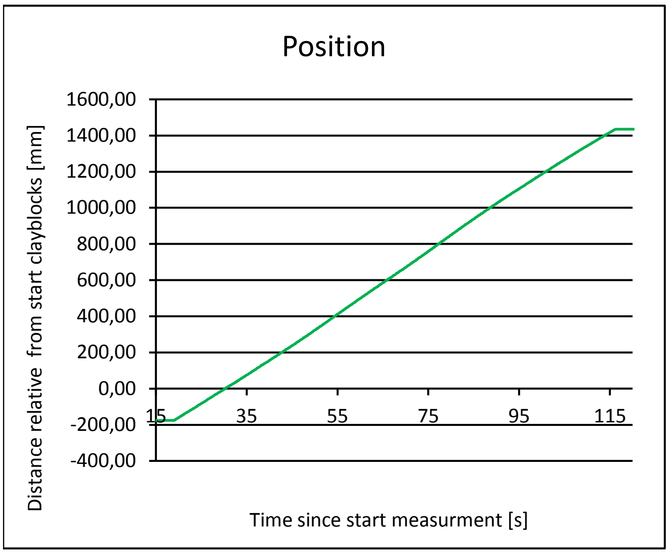
Field vane clay strength tests

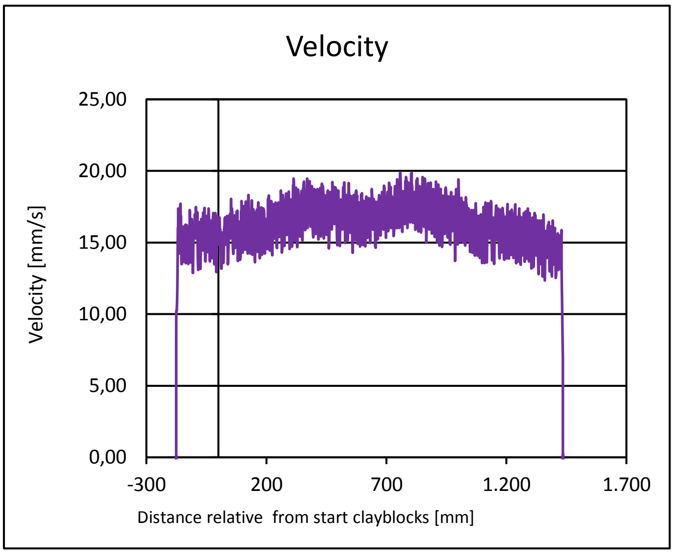
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	128	47	131	60
Left 2	130	54	130	58
Left 3	No test	No test	128	58
Right 1	122	56	119	60
Right 2	123	60	120	64
Right 3	No test	No test	119	71

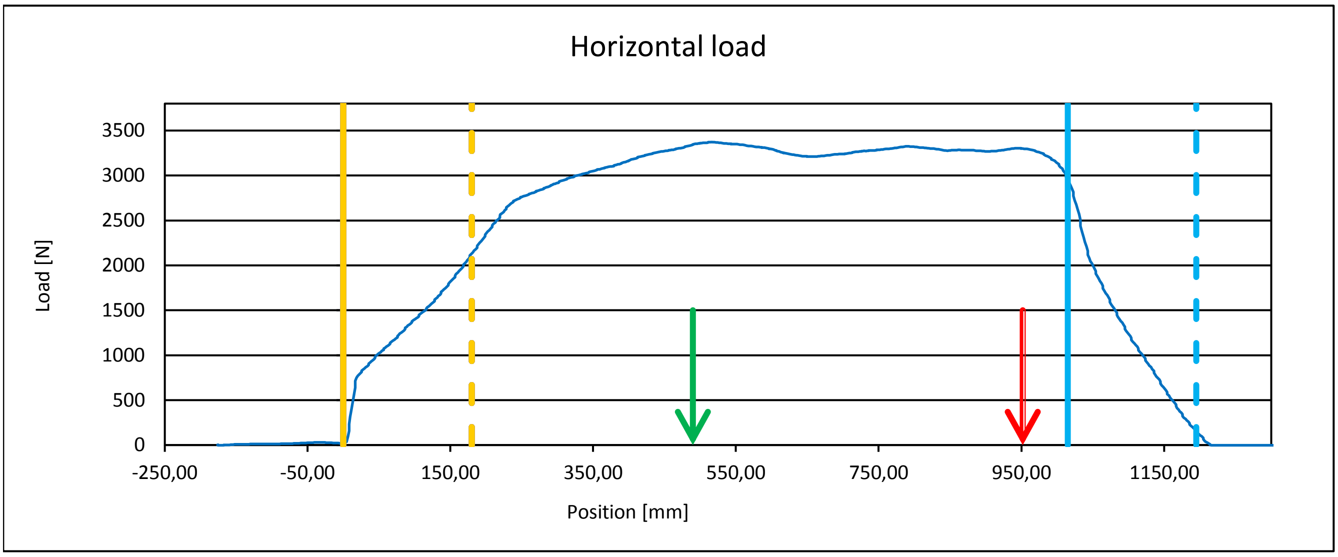
Averages in measuring length

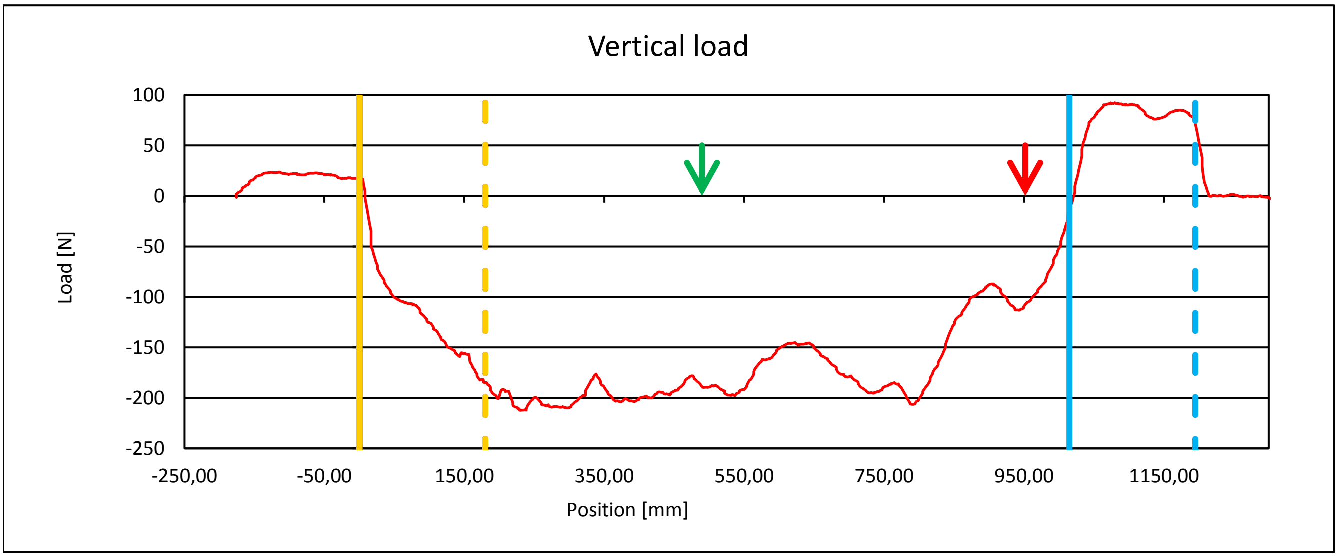
Start measuring length	489,8	mm
End measurement length	951,9	mm
Totaal length	462,1	mm
Average speed	17,6	mm/s
Average speed	63,3	m/h
Horizontal load cell	3288,5	N
Total Vertical load	-162,5	N
Total force	3292,5	N
Angle of total force	-2,8	Degree

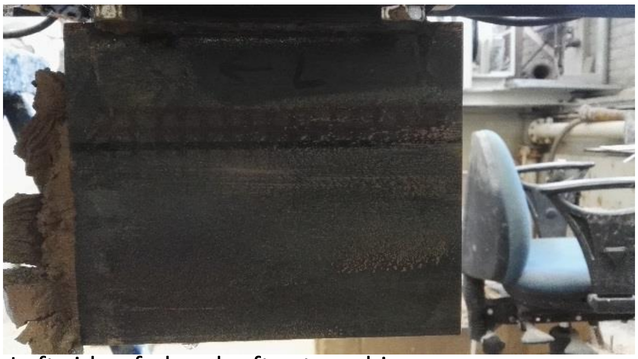
Measured results









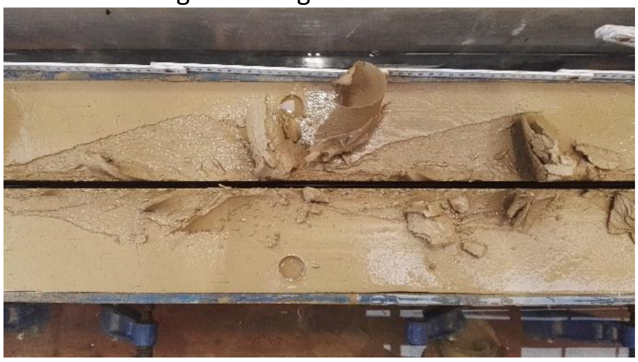

Left side of plough after trenching


Right side of plough after trenching


Frontview during trenching


Sideview during trenching


Top of first section


Top of middle section


Top of last section


Cross section


Sides of the trench

TEST REPORT 38

General information

Test number:	38	
Date of test:	14-12-2016	
Time of test:	16:00	
Test profile:	ALPHA	
Length of clay box:	1015	mm
Water on top of clay:	69	mm
Depth of the plough:	94	mm
Set motor velocity:	-6	[-]
Clay type:	Hard	

Particular during test

Particulars of the clay block:

0

Particular events during the test:

The gaps in the ALFA plough are not filled with clay during this test. The gaps are filled during ploughing, the clay is scraped off the sidewall of the trench.

Material properties of the clay

	Before	After	
Average shear strength:	131,0	122,7	kPa
Average residual shear strength:	78,0	68,8	kPa

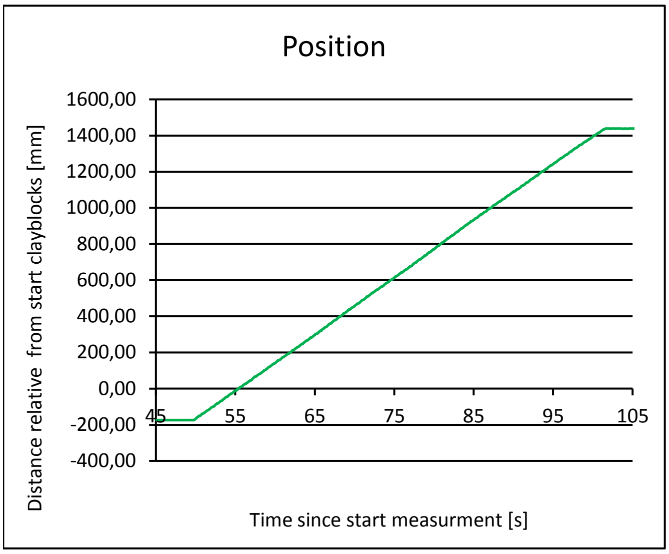
Field vane clay strength tests

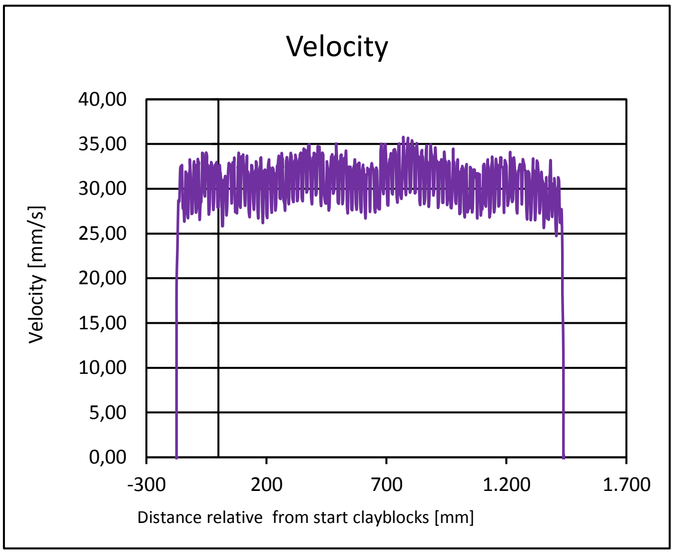
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	129	55	131	78
Left 2	135	77	137	72
Left 3	No test	No test	112	61
Right 1	132	90	113	74
Right 2	128	90	124	58
Right 3	No test	No test	119	70

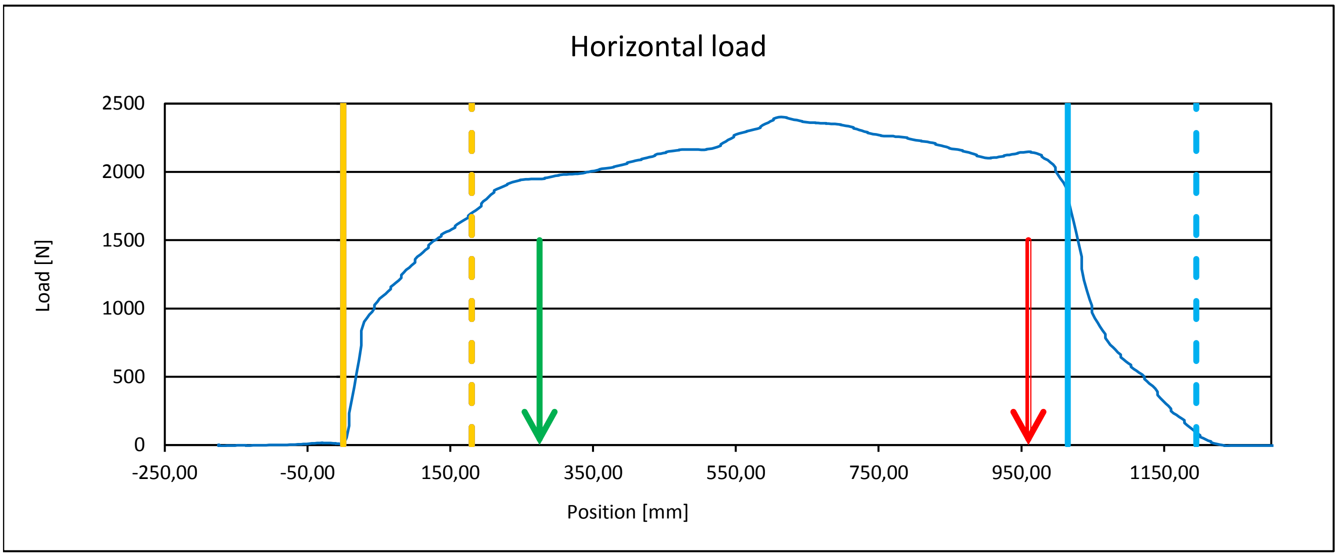
Averages in measuring length

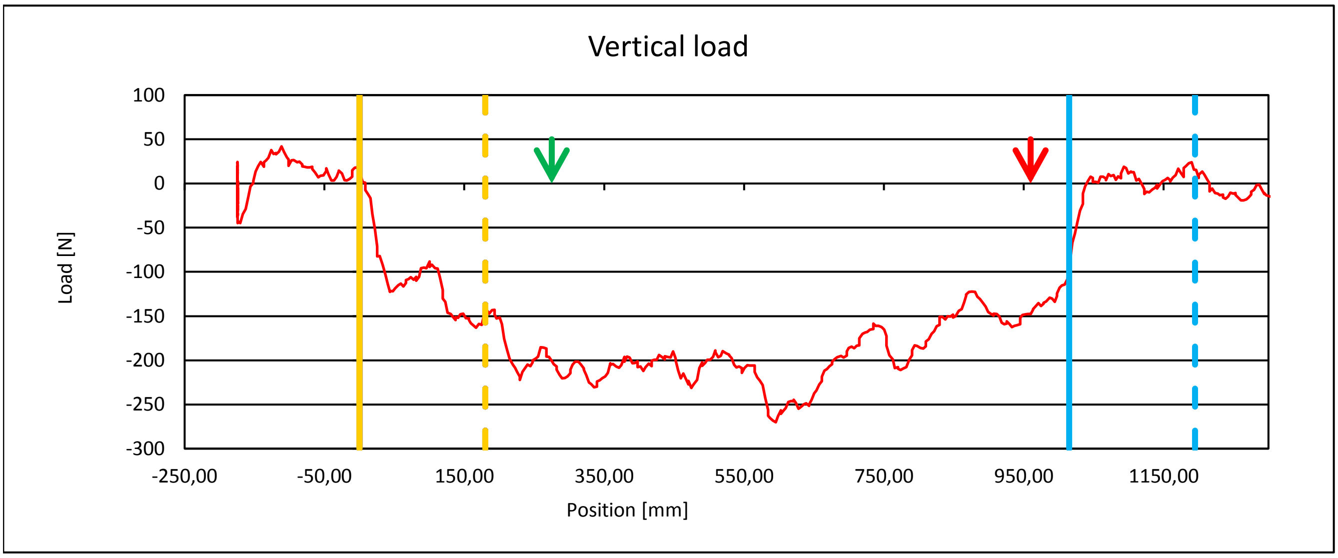
Start measuring length	275,0	mm
End measurement length	959,8	mm
Totaal length	684,8	mm
Average speed	31,8	mm/s
Average speed	114,5	m/h
Horizontal load cell	2188,0	N
Total Vertical load	-196,2	N
Total force	2196,8	N
Angle of total force	-5,1	Degree

Measured results










Left side of plough after trenching


Right side of plough after trenching


Frontview during trenching


Sideview during trenching


Top of first section


Top of middle section


Top of last section

Cross section


Sides of the trench

TEST REPORT 39

General information

Test number:	39	Length of clay box:	1025 mm
Date of test:	15-12-2016	Water on top of clay:	No water mm
Time of test:	11:00	Depth of the plough:	94 mm
Test profile:	M	Set motor velocity:	-6 [-]
		Clay type:	Soft

Particular during test

Particulars of the clay block:

0

Particular events during the test:

Dry test

Material properties of the clay

Average shear strength*: 25,2 kPa

Average residual shear strength*: 16,2 kPa

**average of field vane test before trenching block 3 to 7*

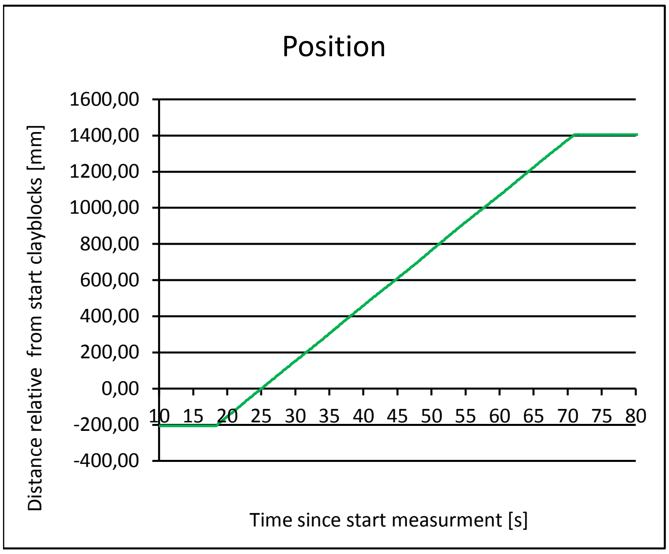
Field vane clay strength tests	**Block 1**	**Block 2**	**Block 3**	**Block 4**	
Shear strength test before trenching:	24	25	25	25	kPa
Residual strength test before trenching:	17	16	16	16	kPa
Shear strength test after trenching:	24	24	25	26	kPa

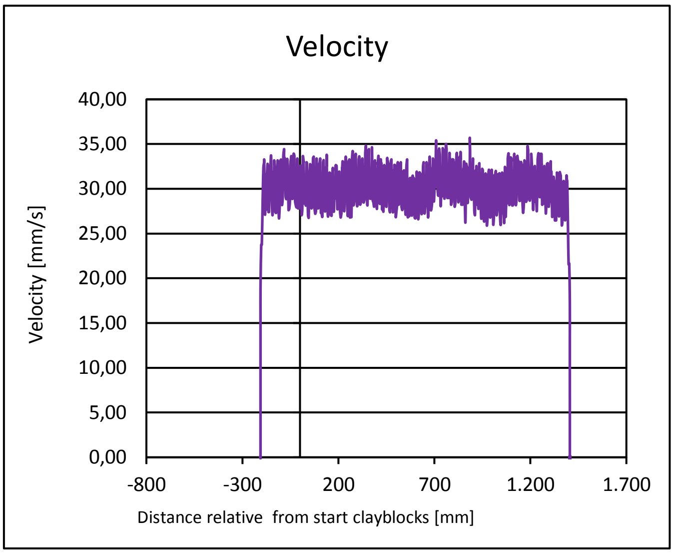
	Block 5	**Block 6**	**Block 7**	**Block 8**	
Shear strength test before trenching:	25	25	26	26	kPa
Residual strength test before trenching:	16	17	16	16	kPa
Shear strength test after trenching:	26	25	24	25	kPa

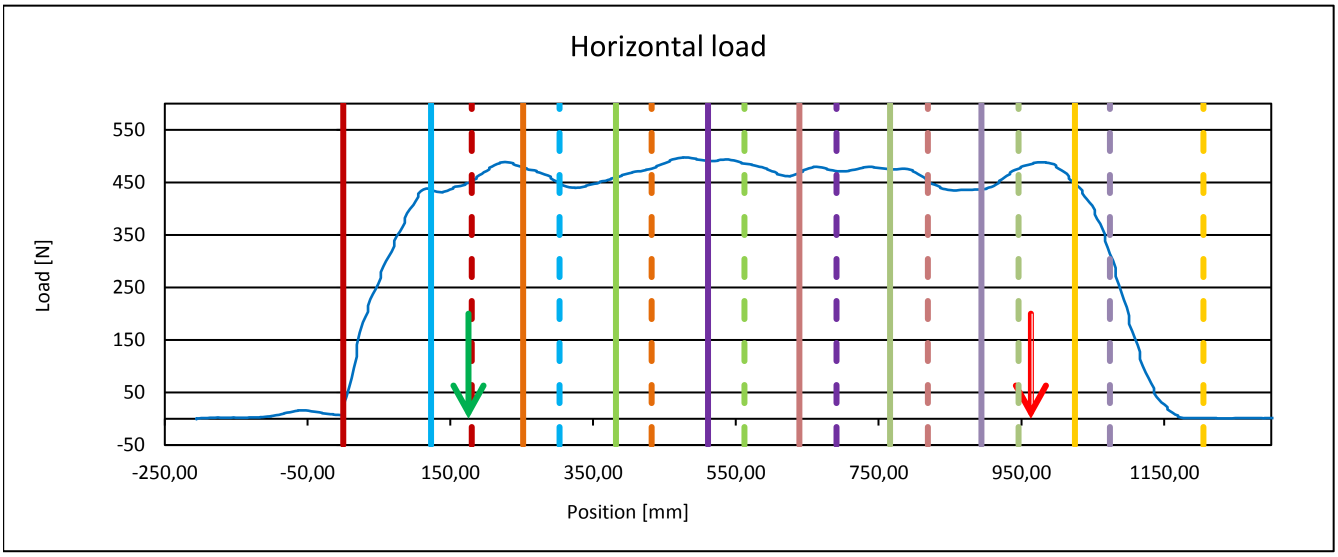
Averages in measuring length

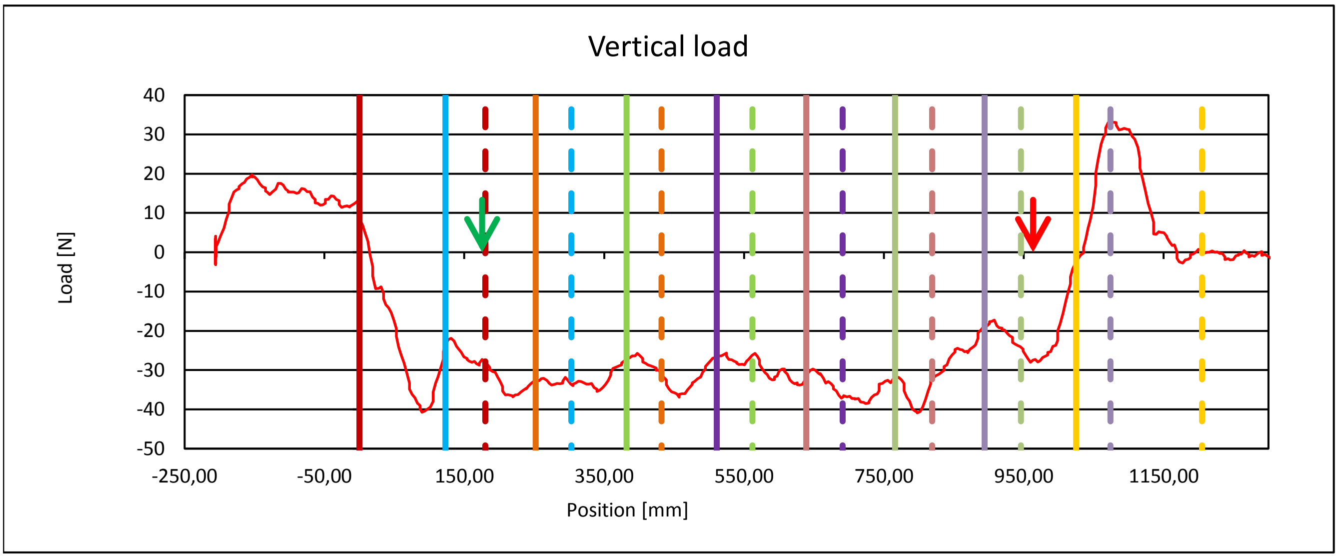
Start measuring length	175,4	mm
End measurement length	963,3	mm
Totaal length	787,9	mm
Average speed	30,7	mm/s
Average speed	110,5	m/h
Horizontal load cell	468,8	N
Total Vertical load	-30,8	N
Total force	469,8	N
Angle of total force	-3,8	Degree

Measured results

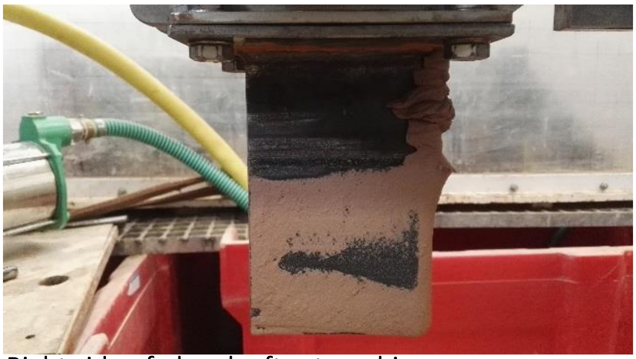









Left side of plough after trenching


Right side of plough after trenching


Frontview during trenching

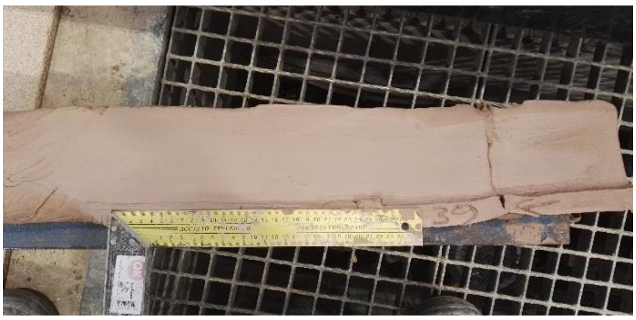

Sideview during trenching


Top of first section


Top of middle section


Top of last section

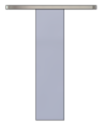

Cross section


Sides of the trench

TEST REPORT 40

General information

Test number:	40	Length of clay box:	1025 mm
Date of test:	15-12-2016	Water on top of clay:	No water mm
Time of test:	15:00	Depth of the plough:	94 mm
Test profile:	S	Set motor velocity:	-6 [-]
		Clay type:	Soft



Particular during test

Particulars of the clay block:

The clay sticks a lot to the plough at the end of the clay container. Clay was to soft to get a proper cross section picture

Particular events during the test:

Dry test

Material properties of the clay

Average shear strength*: 25,2 kPa
Average residual shear strength*: 16,2 kPa

**average of field vane test before trenching block 3 to 7*

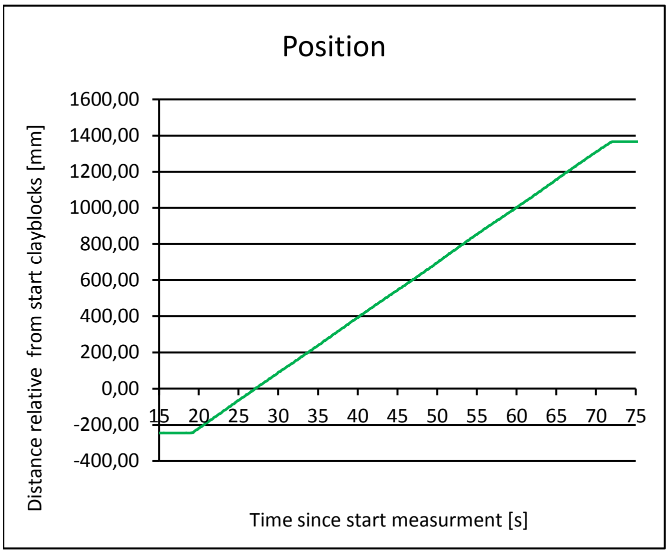
Field vane clay strength tests	**Block 1**	**Block 2**	**Block 3**	**Block 4**	
Shear strength test before trenching:	24	24	25	26	kPa
Residual strength test before trenching:	15	16	16	16	kPa
Shear strength test after trenching:	21	24	24	24	kPa

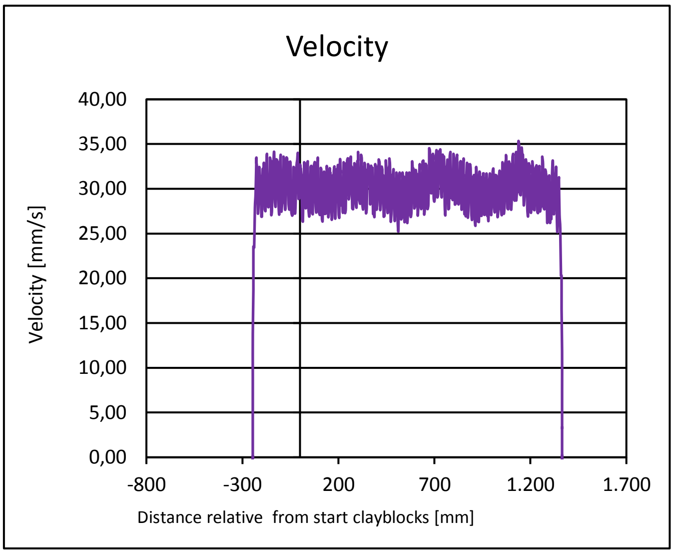
	Block 5	**Block 6**	**Block 7**	**Block 8**	
Shear strength test before trenching:	25	26	26	26	kPa
Residual strength test before trenching:	17	16	16	17	kPa
Shear strength test after trenching:	23	24	24	24	kPa

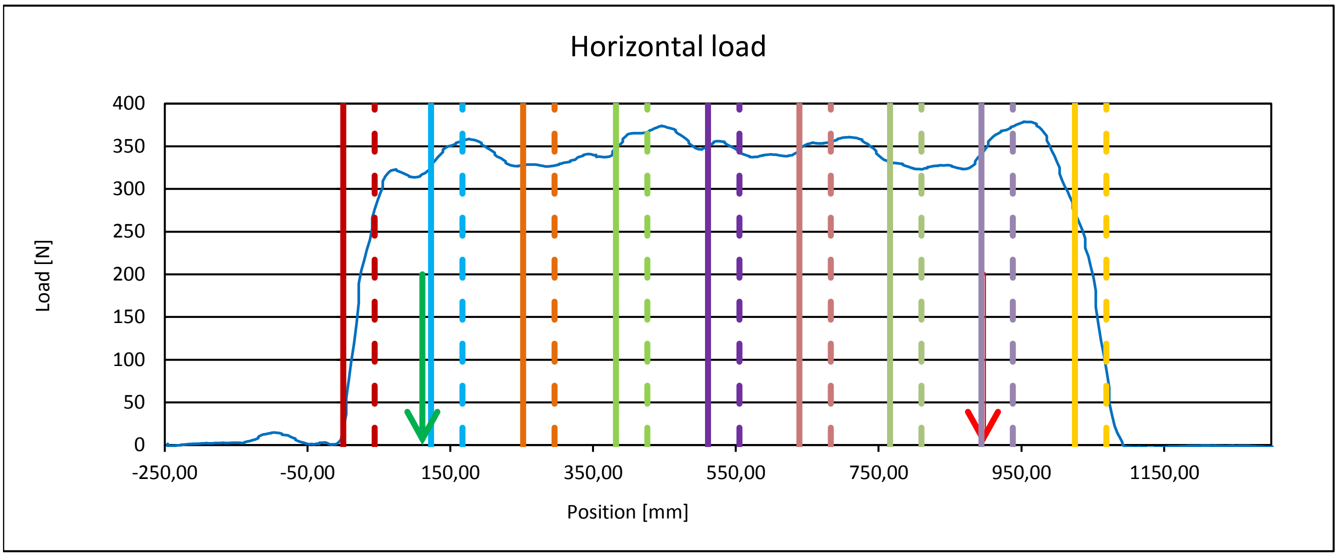
Averages in measuring length

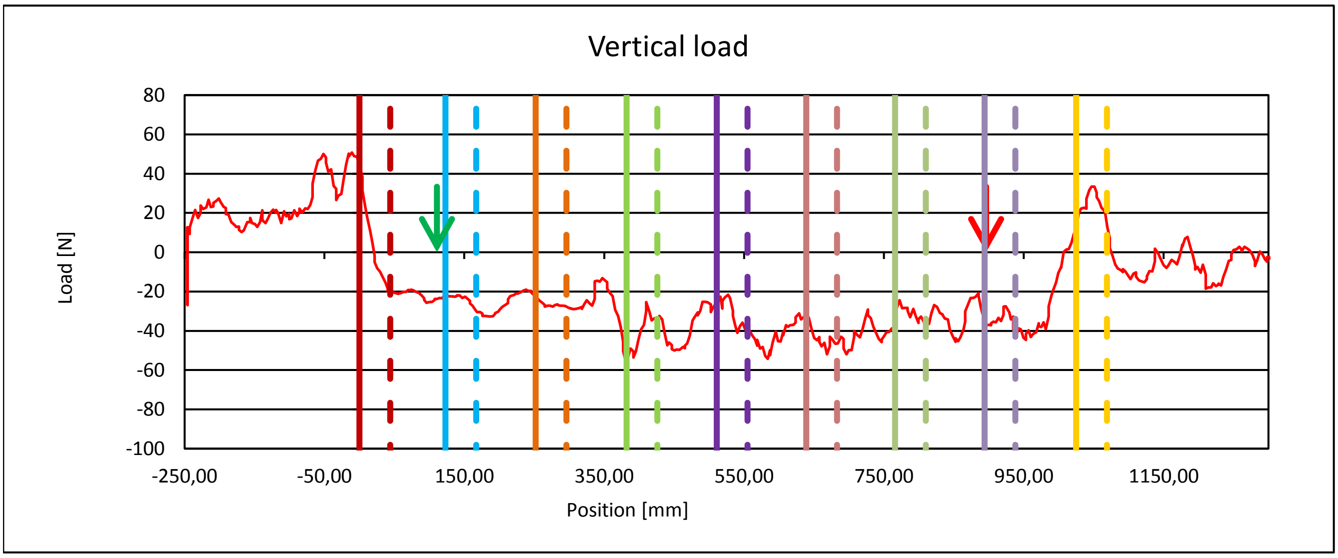
Start measuring length	110,8	mm
End measurement length	896,2	mm
Totaal length	785,4	mm
Average speed	30,6	mm/s
Average speed	110,2	m/h
Horizontal load cell	343,3	N
Total Vertical load	-33,6	N
Total force	344,9	N
Angle of total force	-5,6	Degree

Measured results









Left side of plough after trenching

Right side of plough after trenching

Frontview during trenching

Sideview during trenching

Top of first section

Top of middle section

Top of last section

Cross section

Sides of the trench

TEST REPORT 41

General information

Test number:	41	Length of clay box:	1015	mm
Date of test:	16-12-2016	Water on top of clay:	69	mm
Time of test:	14:00	Depth of the plough:	94	mm
Test profile:	L	Set motor velocity:	-24	[-]
		Clay type:	Hard	

Particular during test

Particulars of the clay block:

0

Particular events during the test:

Velocity of the plough 445 meters per hour

Material properties of the clay

	Before	After	
Average shear strength:	122,5	121,7	kPa
Average residual shear strength:	73,5	64,0	kPa

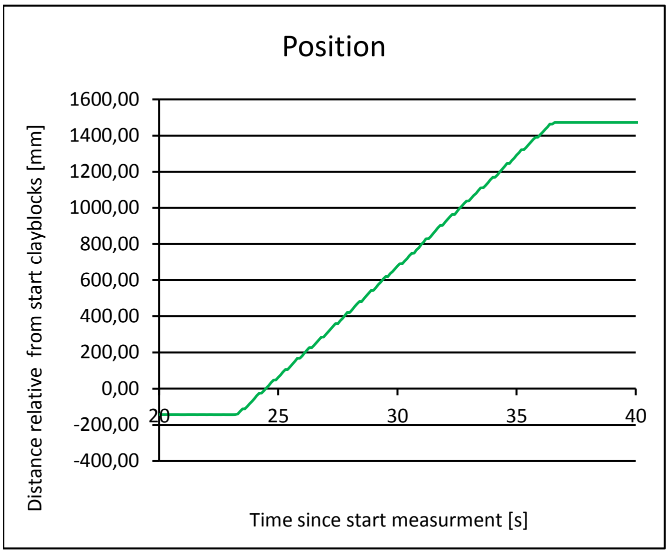
Field vane clay strength tests

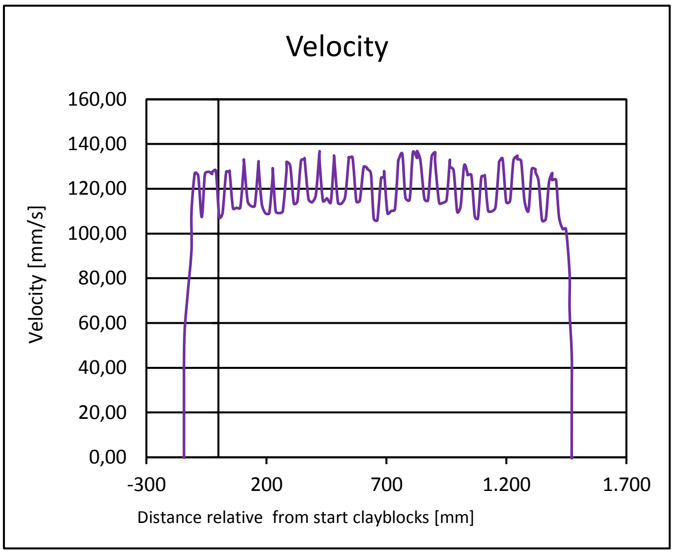
	Before		After	
	Shear	Residual	Shear	Residual
Left 1	129	60	132	74
Left 2	123	68	129	69
Left 3	No test	No test	128	54
Right 1	118	78	117	70
Right 2	120	88	108	53
Right 3	No test	No test	116	64

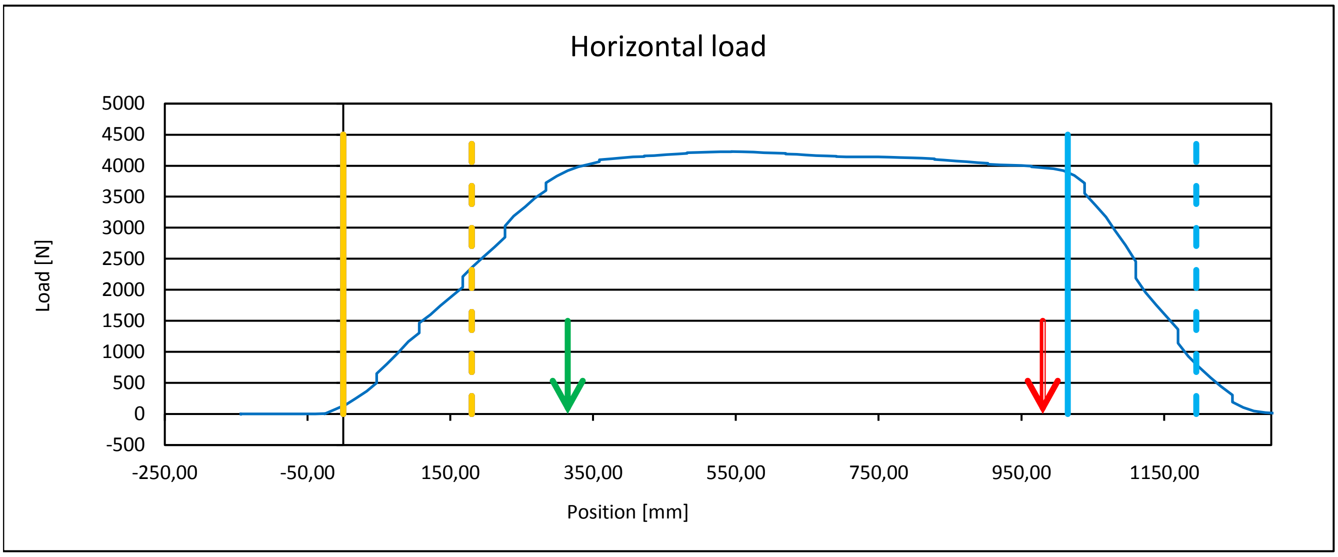
Averages in measuring length

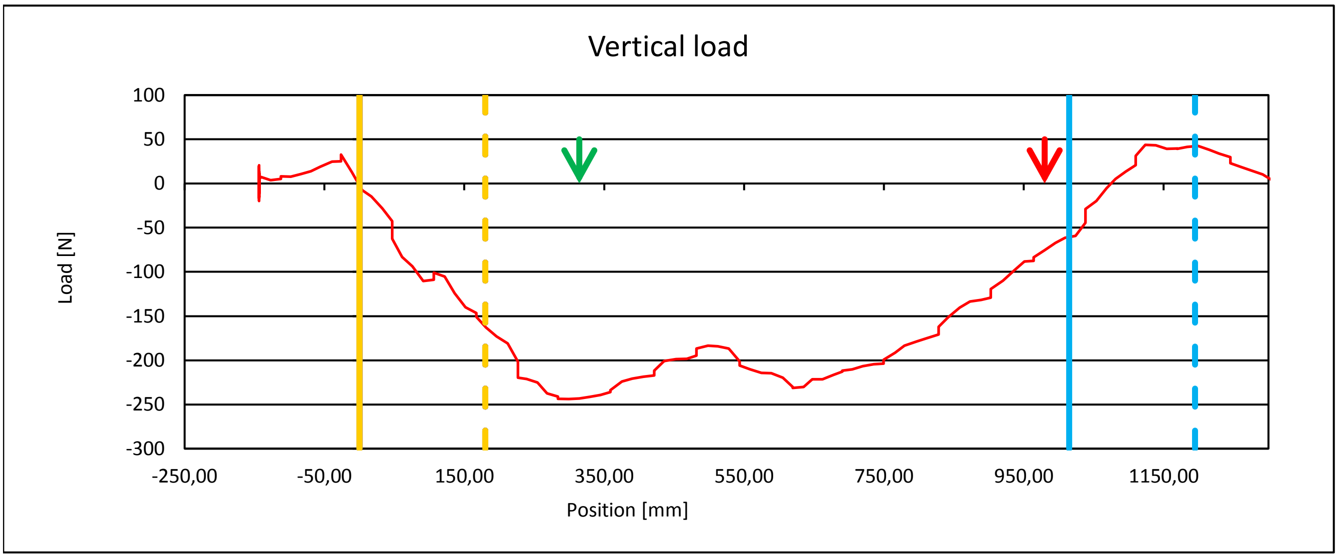
Start measuring length	314,4	mm
End measurement length	979,9	mm
Totaal length	665,5	mm
Average speed	123,7	mm/s
Average speed	445,4	m/h
Horizontal load cell	4123,1	N
Total Vertical load	-187,2	N
Total force	4127,3	N
Angle of total force	-2,6	Degree

Measured results










Left side of plough after trenching


Right side of plough after trenching


Frontview during trenching


Sideview during trenching


Top of first section


Top of middle section


Top of last section

Cross section

Sides of the trench