Water jetting for sheet piling in sandy soils

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Abstract

Pile jacking has many advantages over the traditional methods of piling including creating vastly less noise and vibration. Due to the frequent use of sheet piles in the construction industry, the efficient installation of sheet piles using pile jacking would save significant time and money within the industry, and is therefore of merit for research.

However, as pile jacking utilizes the reaction force from previously installed piles to install further piles, only a limited reaction force is available for pile penetration. One method to reduce the resistance of piles during installation is to utilize water jetting at the pile tip.

The benefits of water jetting have been seen in past research with several mechanisms being proposed for how these benefits accrue. However, it is unclear which of the mechanisms caused by water jetting is most significant, or how the mechanisms complement one another.

This project therefore aims to quantify how water jetting aids the installation of sheet piles in order to optimize the process and minimize the cost and water-use associated with the technique.

In order to investigate the mechanics of water jetting as an aid to press-in piling in sandy soils, controlled site testing was carried out in Kochi, Japan. Throughout testing, the variables controlled included: jet flowrate and nozzle diameter (and hence jet pressure), rate of installation, and rate of surging. The experimental work was followed by data analysis in Cambridge, which was complimented by a finite element model made using ABAQUS.

The data shows that plugging within the sheet pile causes a build-up of resistance at the base of the pile, preventing further penetration of the pile and causing the pile to 'stick', until enough water pressure has built up at the pile base to allow the plug to be destroyed. At this point, the pile appears to 'slip' into the soil, and the process repeats. The high water pressures are able to build up around the pile even in relatively permeable soils due to crushing of sand particles at the base of the pile forming an impermeable film.

The report illustrates that the beneficial effects of water jetting are caused by the high pressure nature of the jet rather than the saturation of the soil around the pile base. The rate of pile penetration is therefore heavily dependent on the jet pressure used for the installation, not the jet flowrate, as suggested in other literature.

It was also observed that high and low jet pressures induce two different mechanisms of pile installation. However, the jet pressure is only influential on the rate of penetration when the pile is deeper than 2 meters under the ground surface.

These conclusions have important implications for practise. As the process is pressure dependent, not flowrate dependent, the optimal conditions for pile jetting would utilise small diameter nozzles with only modest water flow rates. As water jetting is only influential deeper than 2 meters below the ground surface, during the initial installation a very low flowrate, or even no water jetting, could be utilised for optimisation of the water jetting process.

The recommendations will be provided to Giken Ltd. for use in future piling installations.

Contents

1. Introduction

1.1 Motivation

Pile jacking (press-in piling) inserts piles into the ground smoothly through the use of hydraulic rams. The negative shaft friction of piles already installed provides a reaction force during the piling process. Pile jacking has many advantages over the traditional methods of piling including creating vastly less noise and vibration. However, as the reaction force comes from previously installed piles, only a limited reaction force is available for pile penetration. In hard soils where the base resistance of the pile may be substantial, limited reaction force and machine capacity may make installation of piles problematic.

Sheet piles are frequently used in the construction industry as they can be extracted and reused, making them particularly suitable to temporary works. Sheet piles are usually less expensive than tubular piles, making them preferable for use. They are low displacement piles, therefore they create minimal heave of the ground surface during installation. Due to their frequent use, the efficient installation of sheet piles using pile jacking would save significant time and money within the industry, and is therefore of merit for research.

One method to reduce the resistance of piles during installation is to utilize water jetting at the pile tip. The benefits of water jetting have been seen in past research (Tsinker, 1988), with several mechanisms being proposed for how these benefits accrue. These mechanisms include reduction of the effective stresses around the tip of the pile leading to a reduction in base resistance, erosion of particles by the high pressure jet and transport away from the pile tip of fine particles formed by soil crushing (Summers, 1995).

Shepley (2013) carried out research into water jetting for piling in his PhD thesis 'Water injection to assist pile jacking'. Shepley's work was extensive and helped to explain many of the mechanisms taking place during water jetting. However, Shepley's work was based on centrifuge testing and used a tubular model pile. This report aims to draw conclusions on the benefits of water jetting for piling based on field testing using a sheet pile.

1.2 Project aims

This project arose from a long-standing relationship for collaborative research between the University of Cambridge and Giken Ltd.

The primary aim of the project was to investigate the mechanics of water-jetting as an aid to press-in piling in sandy soils using controlled site testing carried out in Kochi, Japan.

Although the main mechanisms by which water jetting is beneficial for piling have been researched previously by various means including scale modelling using centrifuges, it is unclear which of these mechanisms caused by water jetting is most significant in practice, or how the mechanisms complement one another. This project therefore aims to quantify how water jetting aids the installation of sheet piles in order to optimize the process and minimize the cost and water-use associated with the technique, utilising full-scale testing of instrumented sheet piles.

1.3 Report structure

The report begins with a literature review that discusses the merits of pile jacking and the process of water jetting. The methods for the experimental work are then explained, including a description of the installed piles, the sensors used, the piling and ground conditions, experimental accuracy and the challenges faced during experimental work. The experimental results are then analysed with discussion. The influence of the controlled variables are considered in turn, including the jet flowrate, the nozzle diameter (and hence the jet pressure), the rate of surging and the rate of installation. The mechanics of the 'stick-slip' mechanism are considered, and the high pressure and low pressure installation mechanisms compared. The results from the finite element analysis model are compared with the experimental results. Finally, the conclusions reached are discussed, recommendations are made for practise, and future work is explained.

2. Literature Review

2.1 Introduction

The following review will study literature related to the topic of water jetting as an aid to press-in piling. Firstly, the technique of press-in piling itself will be explored, before the influence of the surging rate and the rate of installation are considered. Literature relating to the water jetting technique will then be considered and finally, the effect of particle crushing at the pile base.

2.2 Pile jacking

Pile jacking (press-in piling) is a relatively new technique compared with the traditional methods of pile installation such as hammering and vibratory methods. Pile jacking was pioneered by Giken using machines such as the 'Silent Piler', photographed in **Fig. 1**. While traditional piling methods create large amounts of noise and vibration, making them unsuitable for use in urban environments (White et al, 2002), pile jacking conversely uses hydraulic rams to insert piles into the ground smoothly, using the negative shaft friction of piles already installed to provide a reaction force, eliminating the noise and vibration associated with traditional piling methods (White et al, 2000).

Fig. 1 Photograph of Giken's Silent Piler installing sheet piles (Giken Europe, 2013)

The machinery used by Giken for pile jacking requires significantly less head space than traditional piling techniques. Jacked piling is therefore more appropriate in applications where space is limited, for example the repair of bridge piers underneath operating bridge decks.

Another advantage of pile jacking is that the requirement for temporary works is smaller (Goh et al, 2004), reducing the impact of construction. Ishihara et al (2010) also argued that the quality control of the installed pile is better than that for a pile installed using traditional techniques because the jacked pile installation can be monitored with depth. The information gathered routinely during installation can then be used as a quality control check for the installed pile. The monotonic installation process may also lead to enhanced pile capacity owing to a reduced effect of friction-fatigue relative to driven piles, while retaining the pre-stressing effect common to displacement piles.

2.3 Surging

Surging is the process of applying an alternate downward and upward displacement to a pile, in order to reduce the penetration resistance (Delano, 2010; Burali d'Arezzo et al, 2013). As with hammered piles, the shaft friction is reduced by friction fatigue over multiple cycles. Surging can also increase excess pore pressures around the pile, reducing the effective stress and therefore the ground resistance. Cyclic loading involving stress reversal causes a degradation of shaft friction and base resistance due to particle crushing, volume changes due to shearing, and particle reorientation (Poulos, 1989). Surging may be symmetric, with no progress being made during surging cycles, or asymmetric with the down-stroke being greater than the up-stroke. Termination of the down-stroke due to force limits being breached typically limits the rate of penetration during surging.

2.4 Installation rate

A small amount of literature exists to describe the influence of the installation rate of piling on the actual rate of penetration, as this variable is specific to Giken and their machinery. However, Shepley (2013) writes that the installation rate is significant when considering the critical depth that piles can be installed to while carrying out water-jetting. He defines the critical depth as the pile depth at which the onset of loading occurs, following a period of injection-induced load elimination. Shepley identified two stages of pore flow, the first a spherical flow mechanism beneath the pile base and the second a return flow mechanism up the pile shaft to the ground surface. The critical depth is reached when the governing flow mechanism transforms from stage one to stage two. Shepley describes how the impact of water jetting is reduced for a reduced installation rate, due primarily to a decreased critical depth. This result can be compared with that found from the experimental work carried out for this report in *Section 4.4*. Shepley concluded that the installation process is linked to the removal of effective stress around the installing pile. The rate effect was suggested to be due to time dependent grain breakage, after discounting all other conceivable options.

Shepley (2013) also carried out analysis for paused installations, where the pile was periodically held at several depths during installation, whilst continual fluid injection was sustained. Shepley concluded that pausing the installation whilst continuing the water injection had no effect on pile installation. This conclusion contrasts with the conclusions made based on experimental data obtained for this report. Results and discussion of the results of the experimental work on paused installations are presented in *Section 4.10*.

2.5 Water jetting

Whilst the action of high energy water jets when cutting into brittle materials such as rock or concrete is well documented, the mechanisms governing water jetting in heterogeneous non-linear materials such as soil are still not well understood.

Water injection affects the ground around the pile by changing the effective stress state within the soil, by disturbing the ground structure immediately below the pile base and by washing fines through the surrounding soil matrix (Shepley, 2013). While all these mechanisms are helpful to pile penetration, the mechanism which dominates is unclear.

Tsinker (1988) wrote one of the first pieces about the topic of water jetting, and described a disturbed region, referred to as a ‘jet hole’. Later studies supported a region surrounding the pile where the pore pressures were increased from their in-situ values due to water jetting, confirming the filtration zone around Tsinker’s jet hole. A schematic of the jet hole is given in **Fig. 2**.

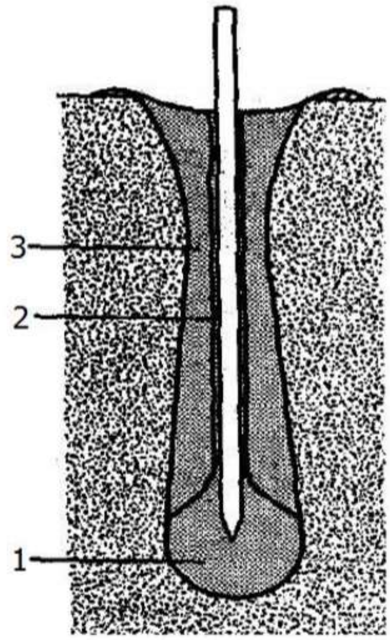

Fig. 2 Schematic showing Tsinker's 'jet hole' (Tsinker, 1988)

Most authors writing about the topic of water jetting have observed a region of rising up-flow immediately around the pile shaft, at the pile-soil interface. Fast flowing water transports particles to the ground surface. Observations made throughout the experiments carried out for this report agree with these theories and Tsinker's jet hole, and are discussed further in *Section 4.7*. Attempts have been made in the literature to correlate the particle movement with the jetting process, but they could not account for the load reduction. Zeilinger (2009) linked the up-flow at the pile-soil interface to the elimination of shaft friction during pile installation.

Because of uncertainties over the mechanisms of pile jetting, throughout the existing literature, there is little consensus as to which is the most important parameter in the water jetting process: whether it is the flow rate, the flow velocity, or the jet pressure.

Many studies in the literature considered ground disturbance and up-flow to be governed by erosion and transportation mechanisms. However, most of these studies, including Smith (2003), were based on observations of the ground surface, and few based on changes in the ground during installation. Few studies noted the effect of changing the pore pressure conditions around the pile. Monitored installations saw little change in the pore pressure distribution surrounding the pile, due to the preferential flow of water up the shaft, rather than radially.

Summers (1995) considered water jetting to have three aspects: fragmenting the impacting material, mobilizing the fragments and then removing them. This conclusion agrees with the results observed from the experimental work carried out for this report, as discussed in *Section 4.7*.

Carter (1996) carried out a full scale trial of water jetting and varied the nozzle size used. Throughout the experimental work, a flowrate of ~325 litres/min was used and a pressure of ~8 MPa. Carter found that the most effective nozzle diameter was 8 mm, directed downwards. However, he also found that a 6.8 mm diameter nozzle facing downwards, combined with two side nozzles of 3 mm diameter (total area 48 mm^2), created the same load reduction as the 8 mm diameter nozzle (area 50 mm^2). Therefore, Carter concluded that the effect of water jetting was determined by the fluid flow rate. However, there was little difference between most of the installations. The flow rate was nearly constant throughout the tests, resulting in a stable nozzle pressure. Therefore, there was little indication that flow rate was the determining factor on reducing pile resistance.

Lyons (1997) carried out experimental work on a scale model, using a nozzle size of 2 mm diameter. Lyons concluded that the flowrate was inversely proportional to the load required for pile installation, so therefore the effects of water jetting increase with increasing flow rate. The conclusions reached in this report agree and expand on Lyons' conclusion, through results obtained from full scale testing using several different sized nozzles.

Smith (2003) argued that pile advancement depends on sufficient material being eroded from the pile base. Pile refusal occurred once there was insufficient erosion of particles from below the pile base. Smith concluded therefore that a high flow rate is required throughout water jetting, to guarantee successful material erosion and hence successful pile installation. Smith also found that for a given flow rate, jetting was more effective in finer soils. Finer soils, with lower permeabilities, would generate larger excess pore pressures for the same flow rate, and increase reduction to the effective stress around the pile. Smith did not focus on this conclusion, although it agrees well with the work carried out for this report. However, all of Smith's observations were based on surface observations, with no consideration of the ground response below the pile base. Shepley (2013) considered the validity of Smith's conclusions to be limited, as the surface behavior will have been affected by the large flow rates and the small container used for the experimental work.

Denton (2004) continued the work of Smith, and confirmed that pile installation is dependent on flow rate. Denton wrote that the pump pressure was the most critical element for successful pile installation, and had to be above a minimum pressure. Large flow rates increased the pile installation rate but did not govern the process. He concluded therefore that pile jetting is reliant on erosion. Sufficient water must be below the pile to erode and transport material to the surface via a return flow. The minimum pressure was required to drive the water flow from the pile base to the ground surface.

Shepley's work (2013) used a scale model in the centrifuge. He concluded that a flow rate greater than 7000 litres/min would be required for successful pile installation. This is vastly greater than any flowrate recommended by industrial standards. However, this recommendation was based on the use of a 2 mm diameter nozzle in the centrifuge, which would be scaled to a 120 mm diameter nozzle for use in industry. This nozzle diameter is significantly larger than any used throughout the experimental testing conducted for this report. With a smaller diameter nozzle, Shepley might have concluded that lower flowrates would be acceptable for successful pile installation.

Shepley also emphasized the importance of the soil permeability in the water jetting process. Therefore, it is essential that a thorough site investigation is carried out before pile installation begins, in order to select the appropriate combination of flow rate, flow velocity and jet pressure to use.

Shepley concluded that injecting high pressure water reduces or eliminates effective stress around the pile. Low effective stress increases soil permeability, which increases the region affected by positive excess pore pressures. The bigger this region, the greater the potency of water injection, and pile loads can remain low.

Tsinker (1988) wrote that in sand, the water flow rate is more important than the jet velocity, whereas in gravel or clay, jet velocity is vital to loosen soil particles from around the pile. An effective jetting program is only successful if the jet velocity is sufficient to loosen soil and an appropriate flow rate of water is used to displace soil particles from below the pile base and carry them up the pile shaft to the ground surface.

There are some negative impacts of water jetting that must be considered, including particle uplift and the creation of difficult and hazardous site conditions due to the large volumes of water being pumped into the soil. Particle uplift can alter the ground composition and have negative environmental impacts. Moreover, the flow of water in the ground is a concern as it may affect the integrity of nearby structures. Adding water is less disruptive at lower flow rates, as the process is more controlled and causes little or no disturbance to the soil matrix, other than that required to install the displacement pile.

2.6 Particle crushing

Randolph et al (1994) proposed a 'rigid cone' region immediately below the pile base, in which highly crushed particles exist. This region was experimentally observed by White & Bolton (2004) as a semi-circular 'nose cone' region below the pile base, described as a highly compressed region of soil below the pile base in which significant particle breakage occurs, reducing the soil permeability in the zone. This region is shown in the schematic in **Fig. 3**.

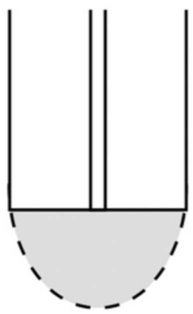

Fig. 3 The 'nose cone' region below the pile base (Shepley & Bolton, 2014)

Shepley & Bolton (2014) wrote that the crushed particles in this zone could reduce the attainable flow rate from water jetting as the jetted water has to pass through the rigid nose zone of crushed particles. Shepley & Bolton also recognized that another factor would decrease the permeability of the soil below the pile base. As the stress in the soil increases, the voids ratio would decrease, and this densification would also affect the permeability of the soil. However, this effect is small in comparison to the change in permeability caused by particle crushing.

Shepley & Bolton related the reduction in ground permeability to the decreased effectiveness of water jetting. This contradicts the results found in this report, which associate particle crushing and reduced ground permeability as being beneficial to the water jetting process. However, Shepley & Bolton considered a jet in the center of a solid circular-base pile, whilst the experimental work carried out for this report used a sheet pile, which will have led to different governing mechanisms in the ground immediately below the pile base. The impermeable film created by crushed particles and the effect that this has on the water jetting process is discussed in *Section 4.7*.

Yang et al (2010) wrote that the crushed material from the pile base is displaced radially as the pile advances, developing concentric zones around the pile shaft. This will create a film of crushed material around the pile shaft which may trap the high jet pore-pressures close to the pile, as observed during the experimental work carried out for this report, commented on in *Section 4.7*.

3. Methods

3.1 Introduction

The experimental work was carried out at the Niida test site in Kochi, Japan. The site is a coastal river outwash plain, located close to the coast as shown in **Fig. 4**. Testing was carried out over the summer of 2017 with 24 piles being installed under controlled conditions while monitoring driving conditions, earth pressures and water pressures acting on the pile and the water pressures in the surrounding soil.

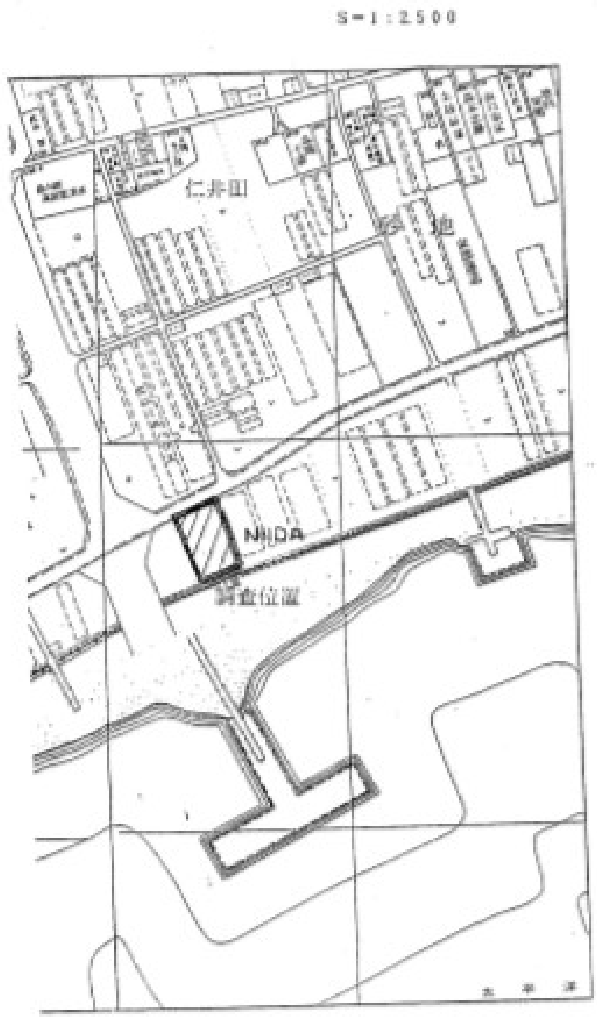

Fig. 4 Location of Niida test site (Carter & Gooch, 1995)

3.2 Pile installation

The Silent Piler, a machine developed by Giken in 1975, was used for the installation of all of the piles. The Silent Piler typically uses the shaft friction from piles already installed to create the jacking force to install a pile. However, in this experimental work, there was concern that piles installed in close proximity to the test pile might influence the data collected. Therefore, deadweight was used to create the reaction force, as shown in the photograph of the experimental setup in **Fig. 5**. This method is unusual for a Giken project and would not be used commercially.

Fig. 5 Photograph of the experimental setup used throughout the test (Giken, 2017)

U-shaped steel sheet piles of width 400 mm and length 10 m were installed at the test site. The cross-section of these piles is shown in **Fig. 6**.

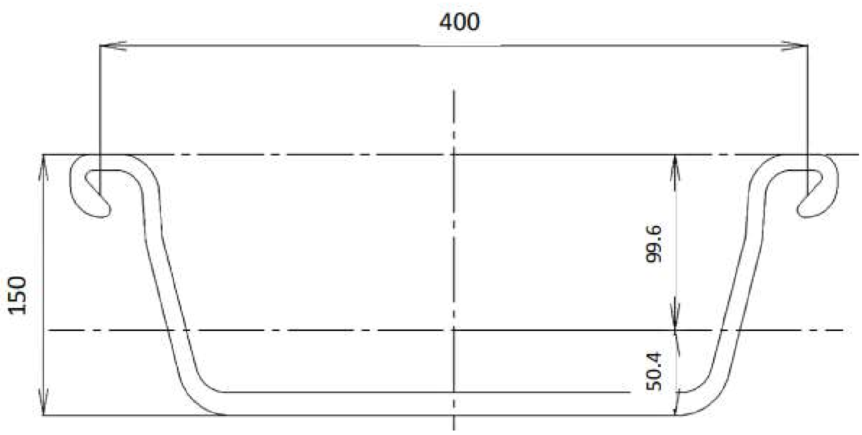

Fig. 6 Sheet pile section (dimensions in mm) (NSSMC, 2016)

In order to carry out the process of water jetting, a hose was attached to the pile with a single nozzle 70 mm above the base of the pile, as shown in **Fig. 7**. The hose was initially pinned and later welded to the pile, as described in *Section 3.7*. Upon completion of pile installation, the hose was detached by force and retracted from the pile.

Fig. 7 Photograph and schematic showing the location of the hose at the pile base relative to the sensors (Giken, 2017)

A plan view of the layout of the test is shown in **Fig. 8**.

Fig. 8 Layout of the piling work (Giken, 2017)

For each test the Silent Piler and the weights had to be positioned in the correct location. This was a time consuming process as the large weight of the equipment meant that a crane was required for any movement. The measurement piles remained in position for longer than the test piles as the measurement piles were used for several test piles at a time, whilst the test piles were extracted immediately after testing. The measurement piles took recordings of the water pressure in the surrounding soil, and the test piles took recordings of the forces along the shaft of the pile and the local water pressure values. When the piles were removed from the ground, they had to be cleaned and remarked, prepared for their next installation.

3.3 Sensors

Both the measurement piles and the test piles were equipped with water pressure sensors, earth pressure sensors and strain gauges. The sensors were located along the front and back of the pile, as shown in **Fig. 9**. The water pressure sensors were used to measure water pressure values close to the pile and also in the surrounding soil. The strain gauges were used to measure the shaft forces at different locations along the pile length. However, not all of the sensors were fully functioning. The earth pressure sensors did not work at all, and some of the strain gauges were also not functioning properly. However, it was not possible to fix the broken sensors, so the tests were carried out without these data recordings.

The sensors on the pile were manually connected to a data logger each morning on site via 25 meter cables. Measurements were taken from these sensors through the data logger, and also from the Silent Piler itself. The Silent Piler took measurements of installation force, installation depth and jet pressure. The measurement of jet pressure required calibration for each jet nozzle used. The calibration curves are provided in **Fig. 10**. The data loggers were housed under a tent and a waterproof casing to protect them from overheating due to high ambient temperatures and water damage due to rain.

As well as recording data using the data loggers, observations were recorded by hand. Observations included water rising to the surface/being drawn down from the surface in the piling hole, the depth of plugging and any exceptional noise/vibration created during the piling process.

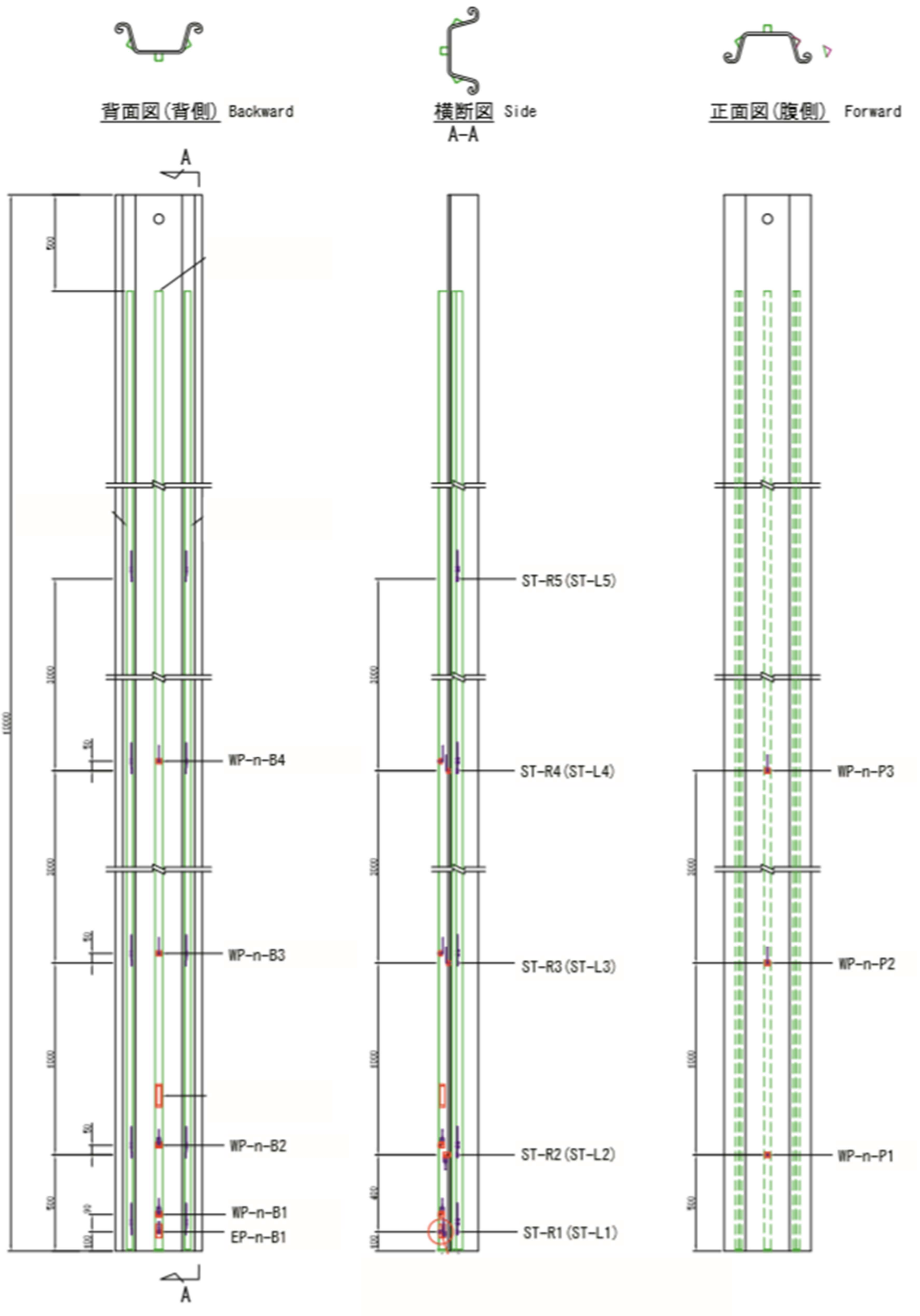

Fig. 9 Layout of water pressure sensors, earth pressure sensors and strain gauges along the pile length (Giken, 2017)

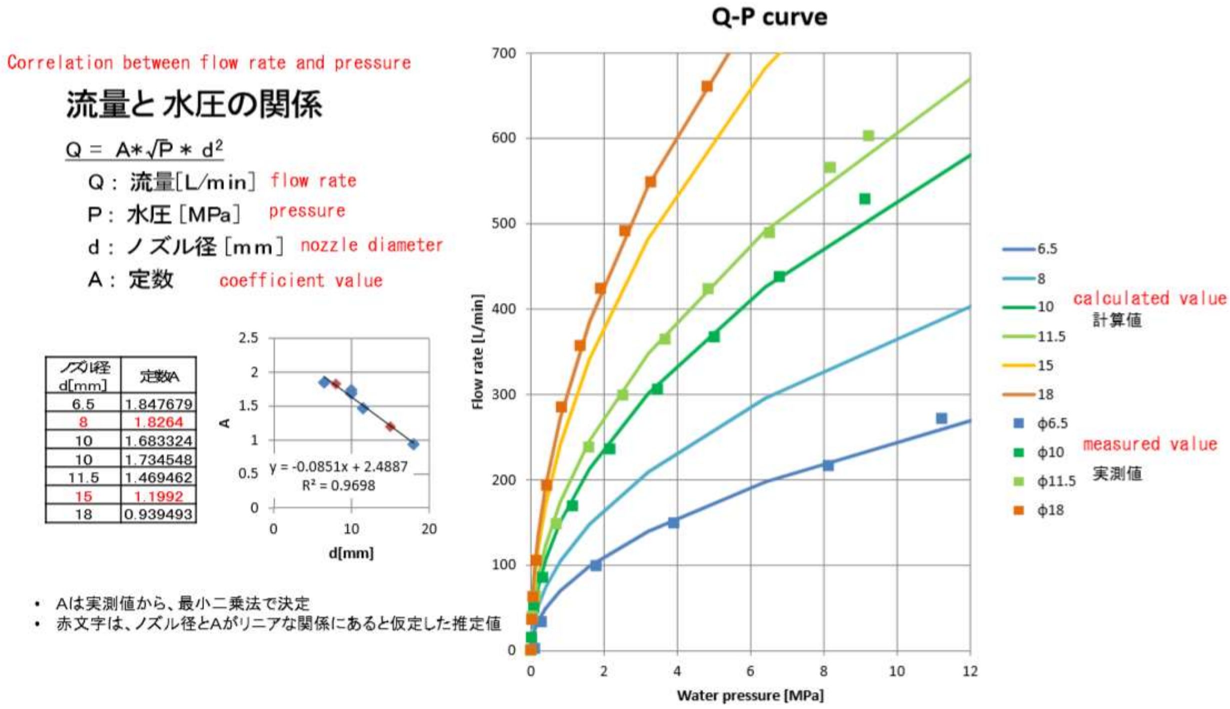

Fig. 10 Calibration curves relating pressure to flow rate for each nozzle (Giken, 2017)

3.4 Piling conditions

Over the course of 5 weeks, 24 piles were installed to varying depths. A single Silent Piler was used to install all piles. Even with the aid of water jetting, some piles were unable to be installed under the specific conditions chosen as insufficient machine capacity was available to reach the desired penetration depth with certain jetting parameters. Although all tests aimed to penetrate 8 meters into the soil, many tests were terminated before this point was reached as no further progress was being made.

Information of piling conditions is provided in **Table 1**. During the tests several factors were varied: installation rate, nozzle diameter and flowrate (and consequently jet pressure), and surging mode. Surging reduces the penetration resistance by applying alternate downward and upward displacements to a pile, as described in *Section 2.3*. The downward and upward displacements are shown in **Table 1**, where 200-100 mm means 200 mm downward displacement and 100 mm upward displacement. The installation stroke is defined as the downward displacement of the surging stroke, and the extraction stroke is defined as the upward displacement of the surging stroke.

No.19 was a control test with no water jetting. Pile rejection took place at 2.5 m depth, indicating the necessity for water jetting in sandy soils.

	Installation rate	*Nozzle diameter*	*Flowrate*	*Jet pressure*	*Surging*
	mm/s	mm	l/min	MPa	mm
No.5	58	15.0	600	6.0	200-100
No.7	104	15.0	600	6.0	200-100
No.8	104	15.0	300	1.1	200-100
No.9	196	15.0	300	1.1	200-100
No.9-2	104	15.0	300	1.1	200-100
No.10	58	15.0	300	1.1	200-100
No.11	104	15.0	300	1.1	200-50
No.12	104	18.0	360	1.3	200-100
No.13	104	11.5	240	1.2	200-100
No.14	104	18.0	600	4.5	200-100
No.15	104	15.0	300	1.1	200-100
No.16	104	15.0	600	6.0	200-100
No.17	104	8.0	300	6.0	200-100
No.18	104	8.0	300	6.0	200-100
No.19	104	-	-	-	200-100
No.19-3	104	8.0	240	4.0	200-100
No.20	104	10.0	420	6.5	200-100
No.21	104	10.0	300	2.9	200-100
No.22	104	8.0	360	10.0	200-100
No.23	104	6.5	300	11.0	200-100
No.24	104	10.0	600	9.7	200-100

Table 1. Piling conditions for tests

3.5 Ground conditions

The ground conditions on the Niida test site were investigated in 1995 through SPT testing in three boreholes. The locations of these boreholes are shown in **Fig. 11** with the data obtained from the boreholes shown in **Fig. 12**. It can be seen that the site consists of a surface sand layer approximately 4 m thick, underlain by sandy gravel. The soil layers slope gently from North to South and the water table is at approximately 7.5 m depth. The sandy layer within which much of the installed piles were located has an SPT value increasing approximately linearly from 10 at 1 m depth to approximately 50 at the water table. Press-in piling without an auxiliary method is inapplicable to ground conditions with an SPT value greater than 25 (International Press-in Association, 2016), hence water jetting is used for this ground condition.

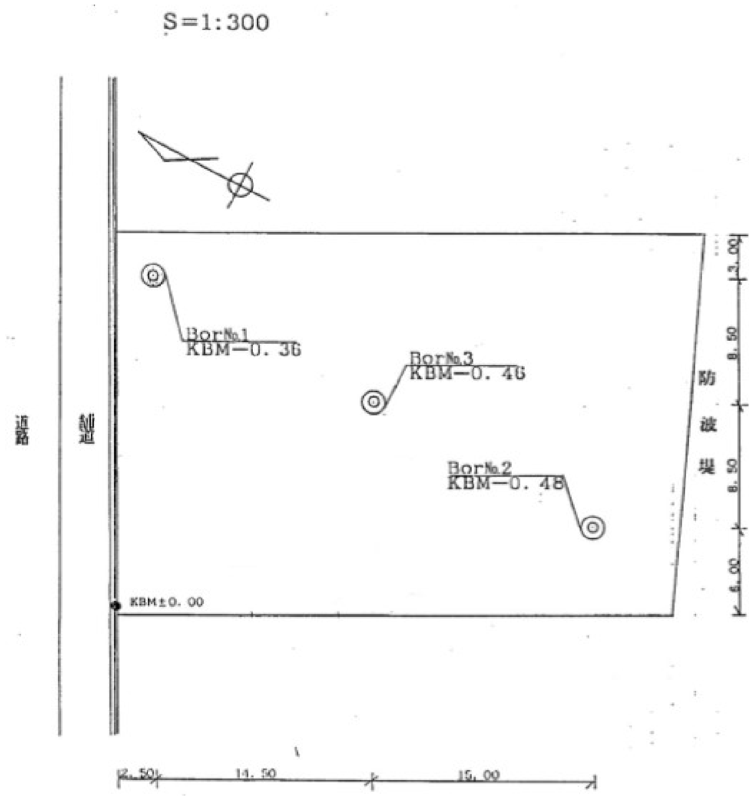

Fig. 11 Borehole locations at Niida site (Carter & Gooch, 1995)

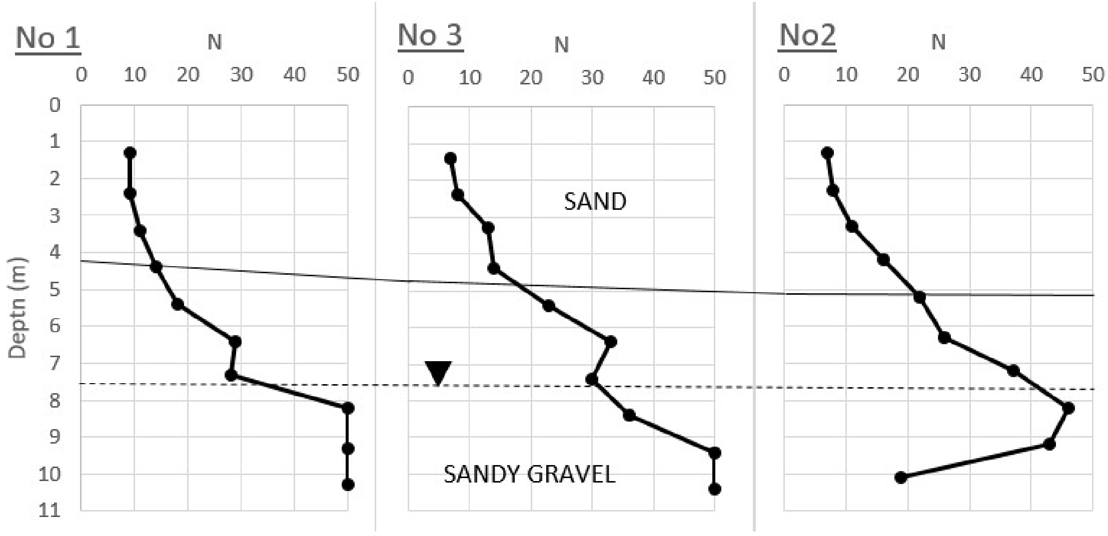

Fig. 12 Borehole data for Niida test site

3.6 Experimental accuracy

Overall, the experimental accuracy throughout the testing was high. All of the data was collected automatically by the sensors and data logger to a high level of precision. However, there was noise present in many of the readings.

Repeats were carried out in different locations, and showed a good level of reliability, as demonstrated in **Fig. 13**.

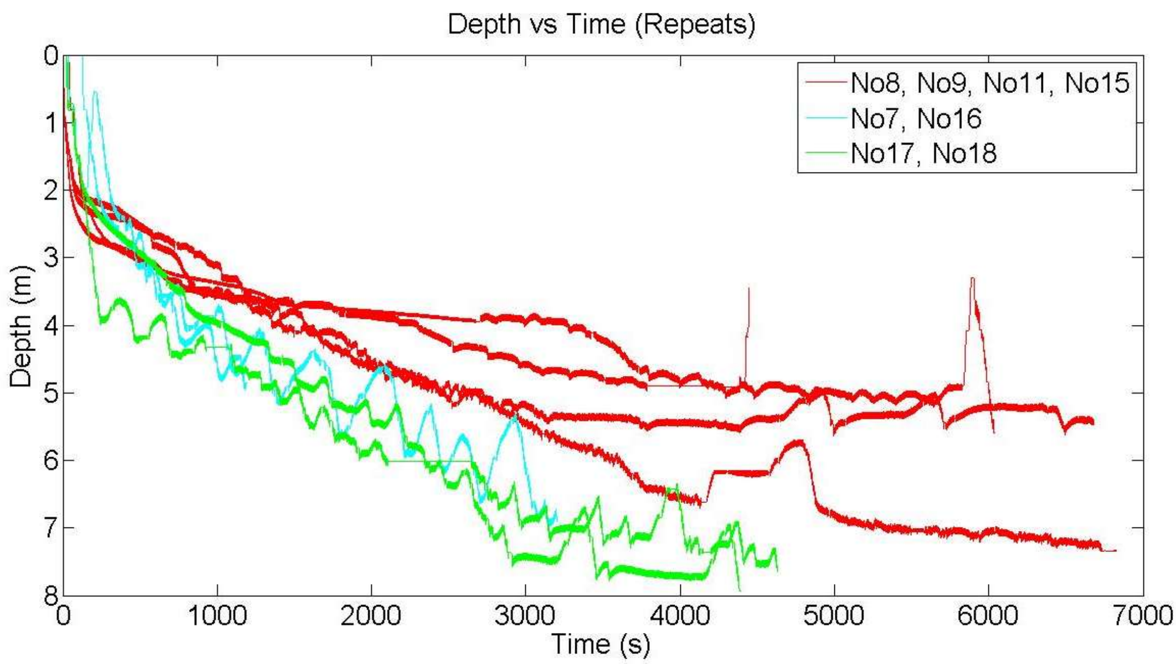

Fig. 13 Plot showing the installation rate of repeats in different locations

It was noted during analysis of the experimental data that strain was measured by the strain gauges when the piles were outside of the ground. This was assumed to be a thermal strain and was subtracted from all of the strain data.

A time shift between the data logger and the piler data also had to be manually accounted for, which may have led to inaccuracies in the results. The time shift was not constant, but varied during pile installation implying an error in the sample rate on one of the systems, which led to inaccuracies in some of the plots. Although this time shift was accounted for in Matlab, some inaccuracies are still likely to be seen.

Occasionally, as the piler was adjusted during pile installation, the pile was seen to slip downwards. This led to inaccuracies in measuring the pile displacement into the ground as this was calculated based on piler movements. To account for this error, the depth of the pile was recorded manually at regular intervals.

The depth of plugging during pile installation was difficult to measure due to the geometry of the piler and the inaccessibility of the piling hole. The plug depth was measured manually using a tape measure, leading to an inaccurate measurement.

3.7 Challenges

One of the first challenges faced was that under high water pressures, the hose became detached from the pile owing to the thrust of the jet. This problem was overcome by welding the hose to the pile instead of pinning it. This process was more time consuming before installation, but it prevented the hose becoming detached during pile installation, saving time overall.

Another issue faced was that some pile damage was attained due to the high forces experienced by the pile during installation. There was concern that this damage might affect the function of the sensors, although a small amount of testing proved that this was not the case, and basic welding could repair the damage.

The main problem during pile installation was pile rejection, as discussed in *Section 3.4*. Regardless of the test conditions used, some piles could not be installed to their target depths. Attempts were made to install them over several hours, which meant that a vast amount of water was pumped out of the jet, causing the water tank to run empty. When the water tank was empty, piling for the day had to be stopped. This was a large inconvenience and slowed down the progress of the testing.

4. Results & Discussion

4.1 Introduction

During the piling operation the piler attempts to follow the surging mode shown in **Table 1**. There is, however a secondary control in that if the manually-set limitation of jacking force (300 kN) is reached during the installation stroke, the installation stroke is terminated and the extraction stroke commences. This limit of jacking force is much smaller than the capacity of the machine. Factors that are influential in determining the limitation values are the available reaction force, the stability of the machine and avoidance of damage to the piles.

This secondary control means that we must differentiate between the rate of installation and the rate of penetration. The rate of installation is the intended increase in depth for each cycle of surging. The rate of penetration is the actual increase in depth for each cycle of surging. These rates differ due to the jacking force limitation that terminates the installation stroke before the intended displacement has been reached. This results in a decreased rate of penetration, or even partial pile withdrawal, when hard ground conditions are encountered.

The variables controlled throughout testing included: jet flowrate and nozzle diameter (and hence jet pressure), rate of installation, and rate of surging, as described in *Section 3.4*. The influence of each variable, along with the influence of the test location on the rate of penetration will be considered in the following sections. This is followed by discussion of the 'stick-slip' mechanism and the impermeable film formed around the pile base. The high pressure installation mechanism will then be contrasted with the low pressure installation mechanism, before explanation of the shaft force and water pressure variation during pile installation. Finally, the finite element model created will be discussed.

4.2 Influence of jet pressure vs. jet flowrate

Fig. 14 shows the progress of pile penetration with time, grouping the tests according to the jet flowrate used, all using a 15 mm diameter nozzle. This plot appears to show that the rate of penetration increases with a larger flowrate. This agrees with the conclusions of Lyons

(1997) as discussed in *Section 2.5*, who carried out tests with varying flowrates and a single nozzle diameter.

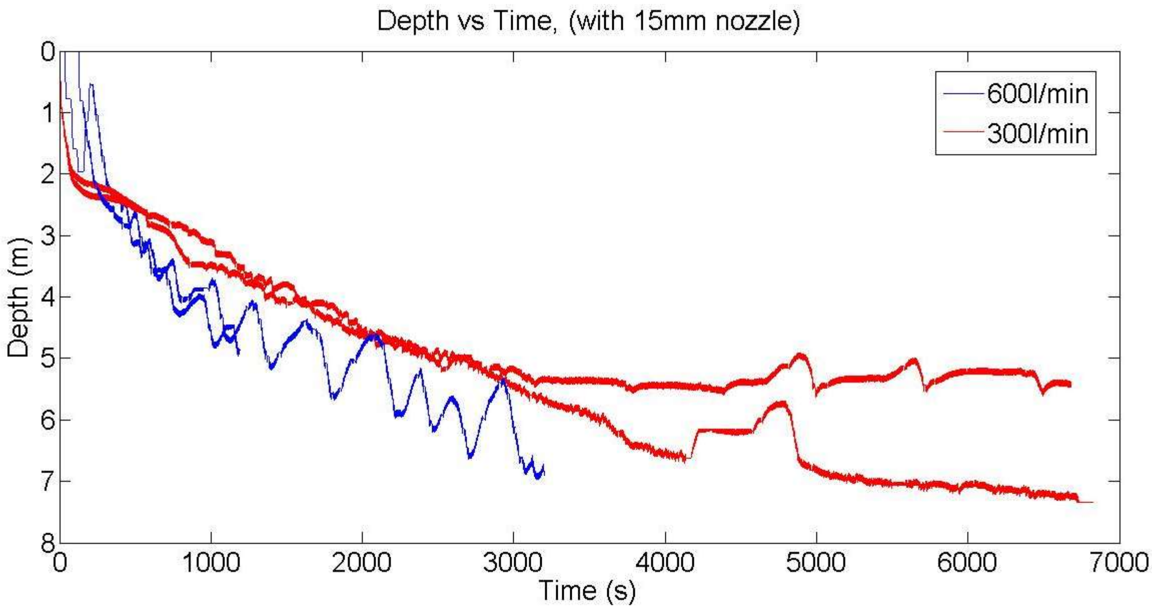

Fig. 14 Rate of penetration increasing with jet flowrate

However, **Fig. 15** shows that the rate of penetration increases with decreasing nozzle diameter, for a constant flowrate. This is a result that has not previously been explored in the literature, and leads to the explanation that the rate of penetration is in fact dependent on jet pressure, rather than jet flowrate.

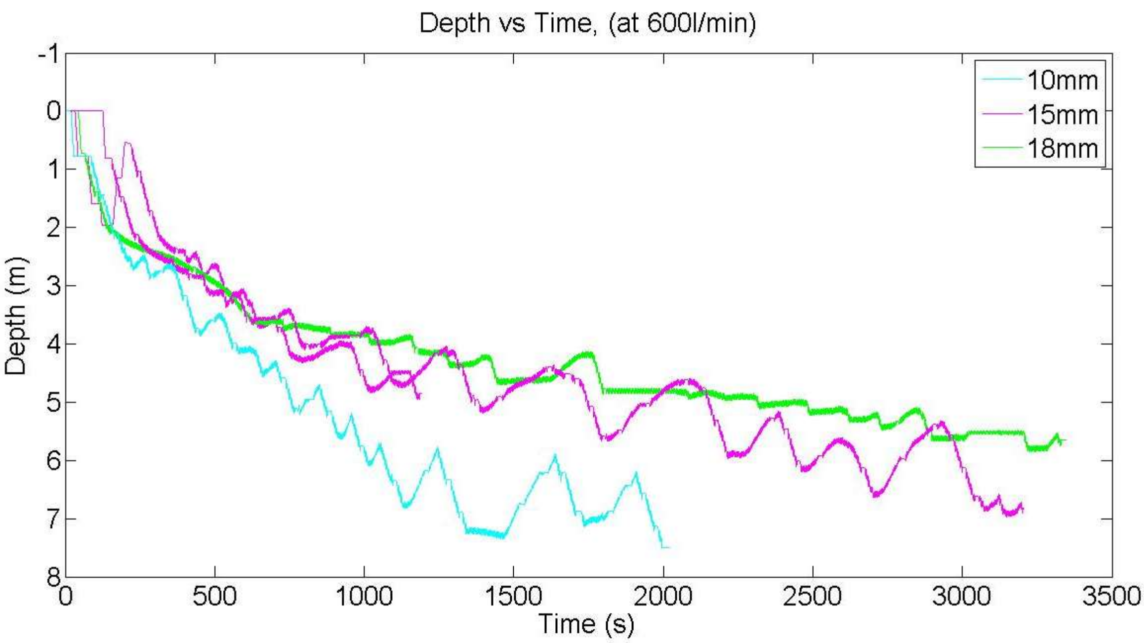

Fig. 15 Rate of penetration increasing with decreasing nozzle diameter

Fig. 16 shows the progress of pile penetration with time, grouping the tests according to the jet pressure used. It can be seen that while the piles are installed rapidly to around 2 m depth, beyond this point the penetration slows and becomes a function of jet pressure. Analysis of the data obtained from the 24 piles installed illustrates that the rate of penetration is highly dependent on the jet pressure (which can be achieved with several combinations of nozzle size and flowrate) as shown in **Fig. 16**, but only weakly affected by the jet flowrate itself. This is a significant result as it shows that water jetting is aiding pile installation due to the high pressure nature of the jet, rather than due to the seepage flow around the pile base. This result is explored further in *Section 4.7*.

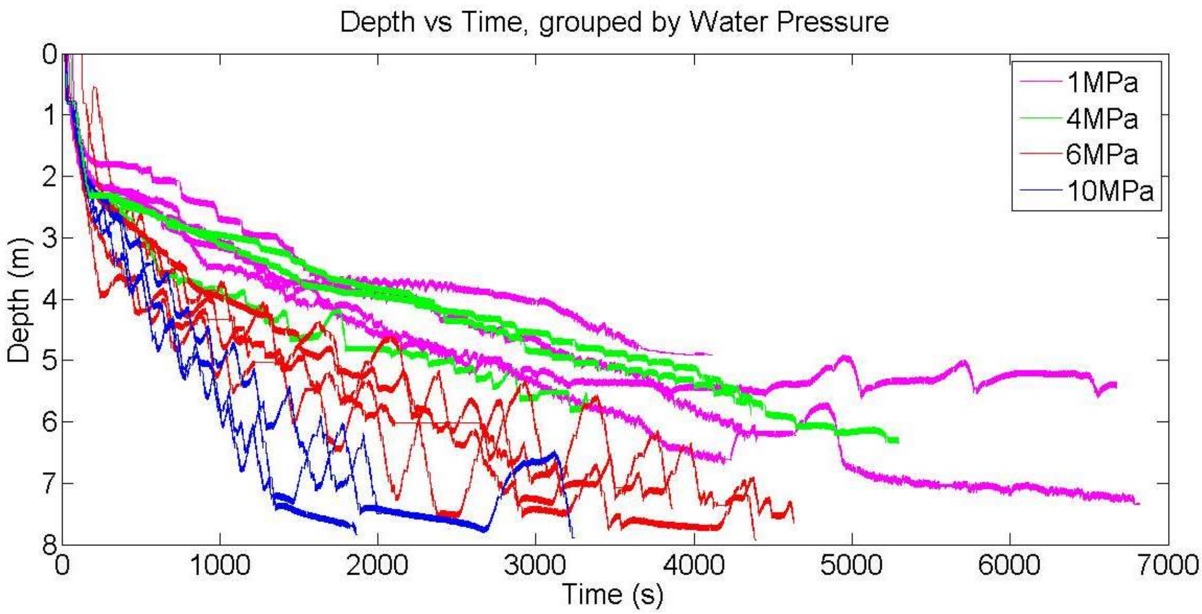

Fig. 16 Penetration rates of tests, grouped by jet pressure

Fig. 16 also shows that there are two different installation mechanisms, one for higher pressures (more than 6MPa) and one for lower pressures (less than 6MPa). The installation mechanism for higher pressures, while more rapid than that for lower pressures, is cyclic and includes periods of withdrawal from the ground as well as installation. The installation mechanism for lower jet pressures, while less efficient, is much smoother throughout the installation. This result is explored further in *Section 4.8*.

Due to the vast amount of data collected, it is difficult to gain an understanding unless a simplified method is found for analysing the data. Therefore, the plot shown in **Fig. 17a** was created. This plot shows that the pile penetration velocity decreases with installed pile depth, as expected due to the increased pile resistance. The plot also shows that a higher jet pressure leads to an increased penetration velocity. Initially pile penetration velocity is high regardless of the jet pressure used, as after 1 m of installation, all tests have an average velocity between 60 mm/s and 70 mm/s. **Fig. 17b** shows that as the piles reach greater depths, the velocity of penetration is significantly larger for tests with higher jet pressures. After 2 m of installation, the average velocity for tests at 1 MPa is half of that for tests at 10 MPa. After installing 7 m, the tests at 10 MPa are installed at a velocity nearly six times the velocity of the 1 MPa tests.

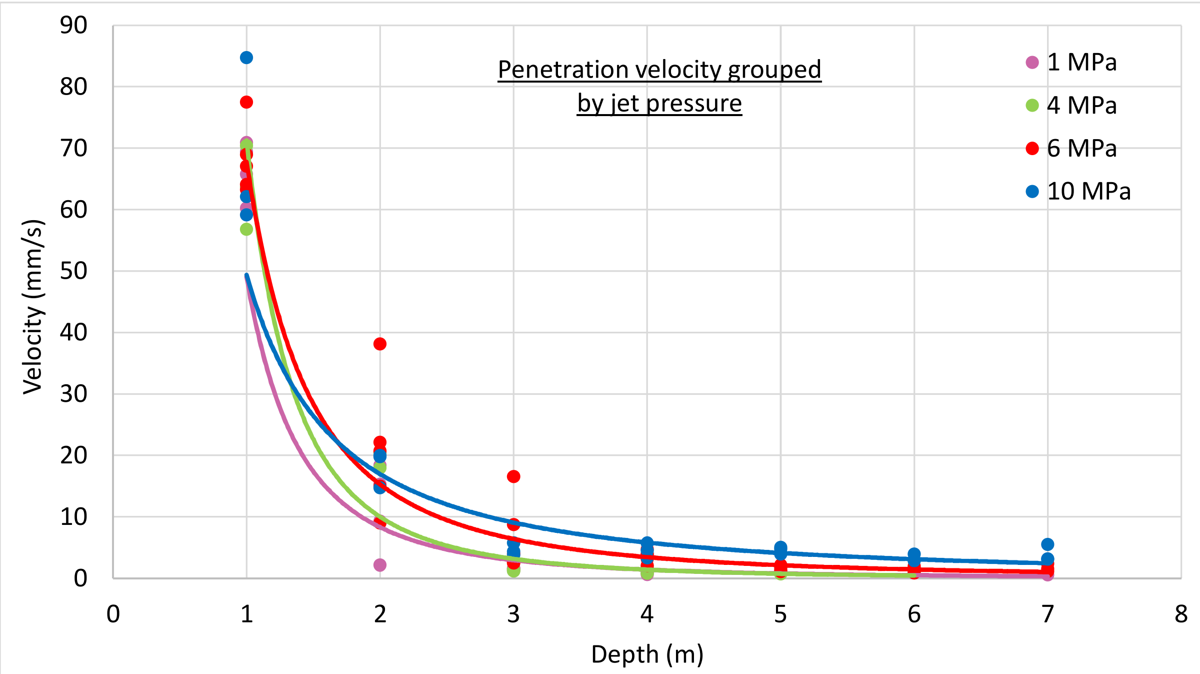

Fig. 17a Rate of penetration attained in each incremental meter of depth for various tests

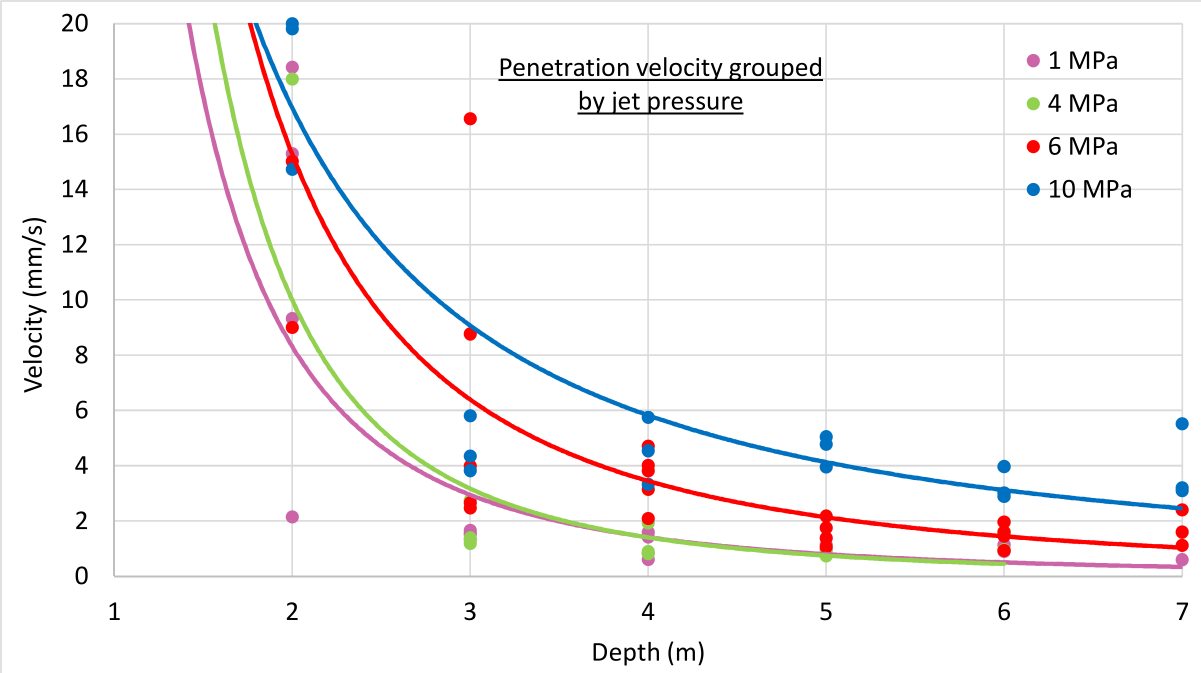

Fig. 17b Rate of penetration attained in each incremental meter of depth at a higher level of zoom

This important result highlights that it is the jet pressure that is important to the water jetting process, not the flowrate. Therefore, a low flowrate and a small nozzle can be combined to create high pressure, rather than a high flowrate and a large nozzle, as Shepley (2013) suggested. This result enables cost and water to be saved and the optimum conditions for water jetting to be approached.

4.3 Influence of surging

The plot in **Fig. 18** demonstrates the effect of surging on the installation of the sheet piles by comparing 200-100 mm and 200-50 mm surging. However, from this plot, it is clear that the change in surging mode has no influence on the rate of penetration of the piles. This is likely to be because the rate of penetration of the piles is controlled by the 300 kN limiting force rather than the maximum displacement permitted by the surging rate, as discussed in *Section 4.1*. Only two tests of the 24 were carried out using 200-50 mm surging, so this data will simply not be included in any further analysis.

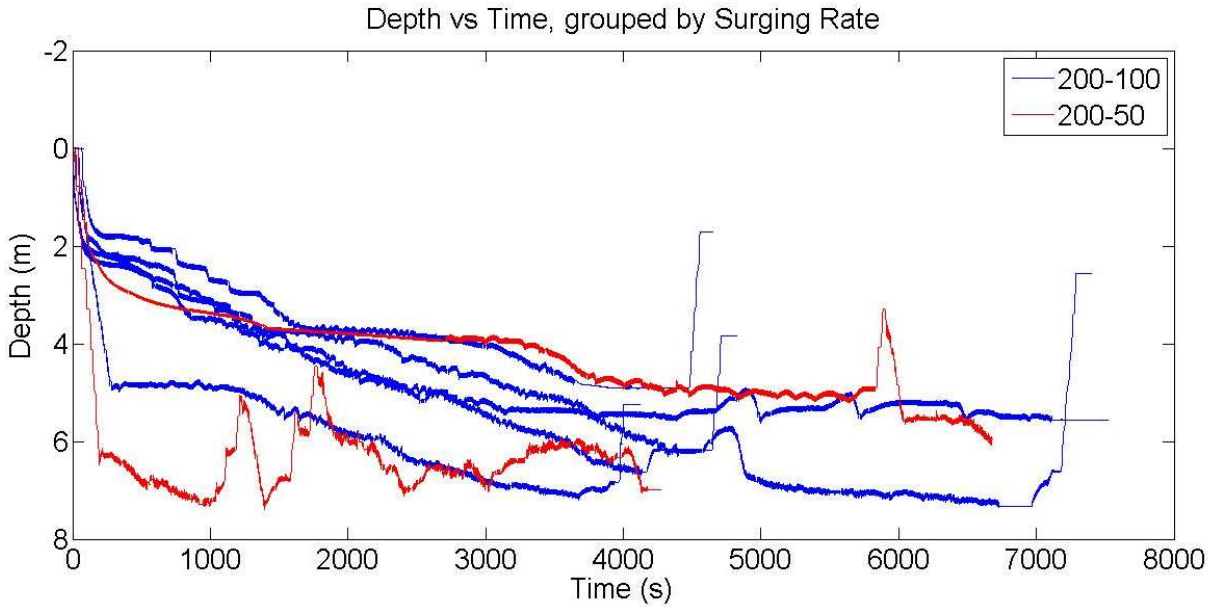

Fig. 18 Penetration rates of various tests, grouped by surging rate

4.4 Influence of rate of installation

Fig. 19a and **Fig. 19b** show the effect that the rate of installation has on the rate of penetration of the sheet piles. As expected, initially, the fastest rate of installation leads to the fastest rate of penetration. This result is shown in **Fig. 19a**. However, as shown in **Fig. 19b**, as the tests continue, the 104 mm/s rate of installation tests are installed more quickly than the 196 mm/s rate of installation test.

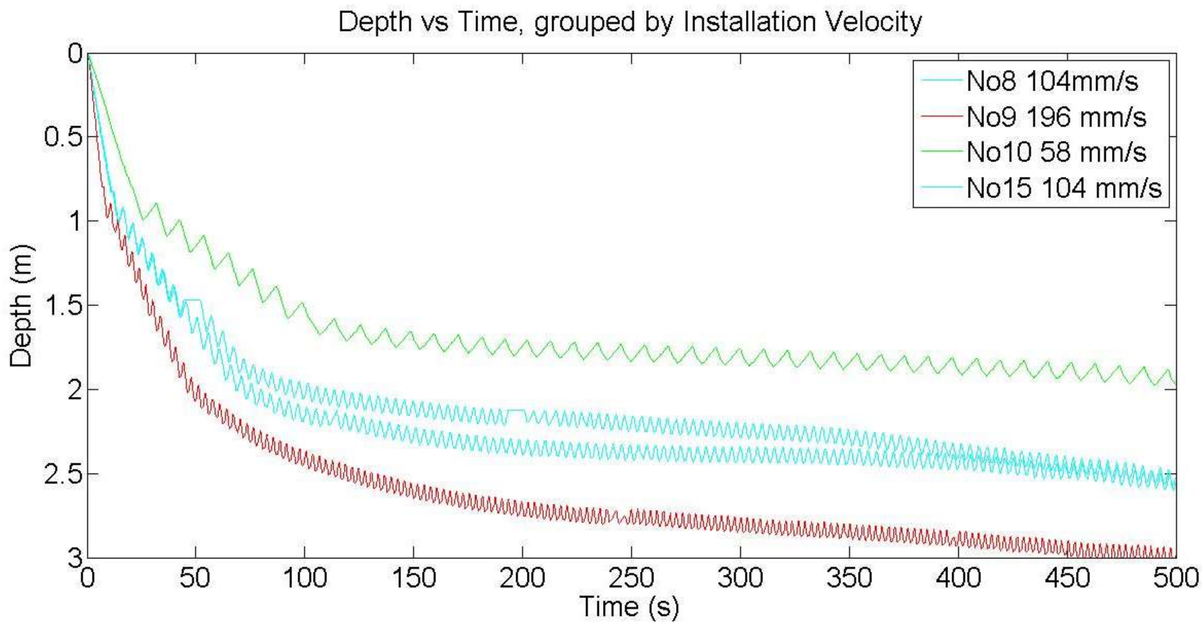

Fig. 19a Initial penetration rate for varying rates of installation

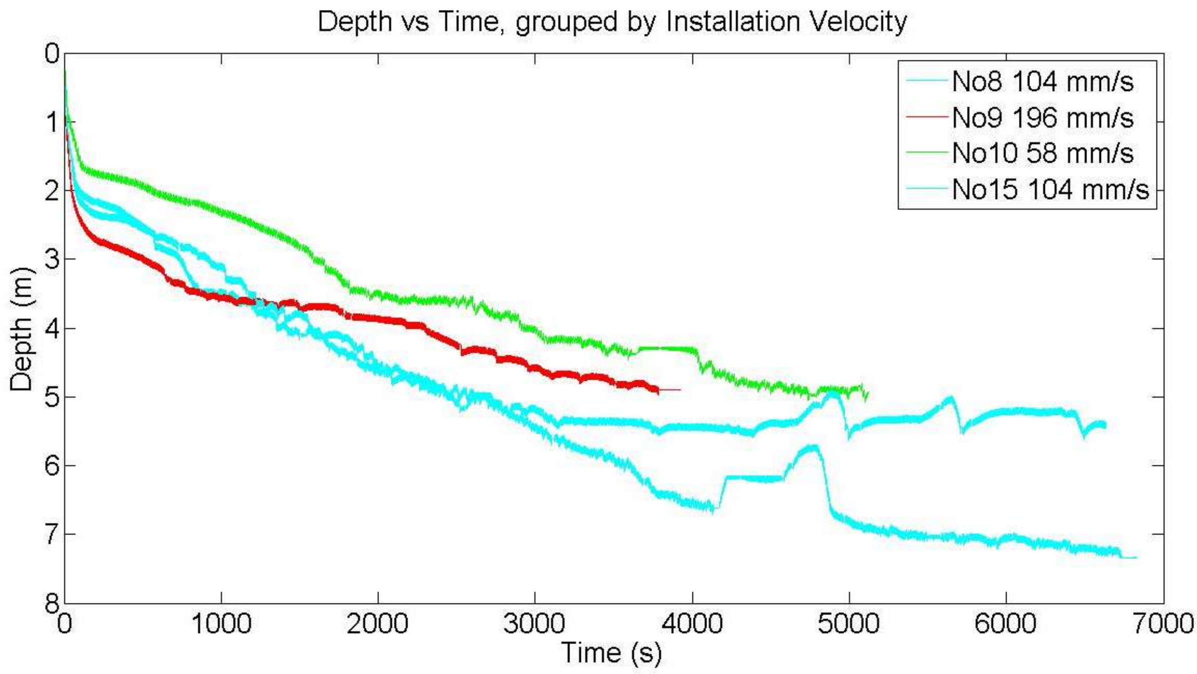

Fig. 19b Overall penetration rate for varying rates of installation

This result is seen because the 196 mm/s rate of installation test moves the pile more quickly through the soil than the 104 mm/s rate of installation tests, and therefore more suction is created in the former test. This is essentially a move further towards undrained behavior in a dilatant material and hence exhibits an increase in soil strength. The suction hinders the penetration rate of the piles by creating resistive forces to installation, so the 104 mm/s tests are installed more quickly than the 196 mm/s test.

In the case of the faster rate of installation, the water jetted into the soil has no time to move through the soil, and therefore the soil near to the pile base is forced to dilate. This means that the resistance to piling is high for the 196 mm/s rate of installation test. However, for the 104 mm/s tests, the jetted water has sufficient time to flow out of the area immediately below the pile base, causing less dilation of the soil, and therefore less resistance to installation. Additionally, in the 104 mm/s rate of installation tests, the jetted water has longer to accumulate below the pile base before the installation force is applied. Therefore, the soil below the pile base is made softer, so when the installation force is applied, the pile progresses further into the soil. In the 196 mm/s rate of installation test, less time for the jetted water to accumulate below the pile base leads to harder soil, and therefore more resistance to pile penetration. For these reasons, the 104 mm/s rate of installation tests had the highest rate of penetration.

During test No.9-2, the rate of installation was changed after 3000 seconds, as shown in **Fig. 20**. Before 3000 seconds, the rate of installation was 104 mm/s, and after 3000 seconds the rate of installation was changed to 196 mm/s. The rate of penetration changes accordingly with the change of installation rate, slowing significantly when the rate of installation increases. Before 3000 seconds, the rate of penetration is approximately 1 mm/s, and afterwards it decreases to approximately half of its previous value, at 0.5 mm/s. This relationship between the rate of installation and the rate of penetration agrees with that found in **Fig. 19b**.

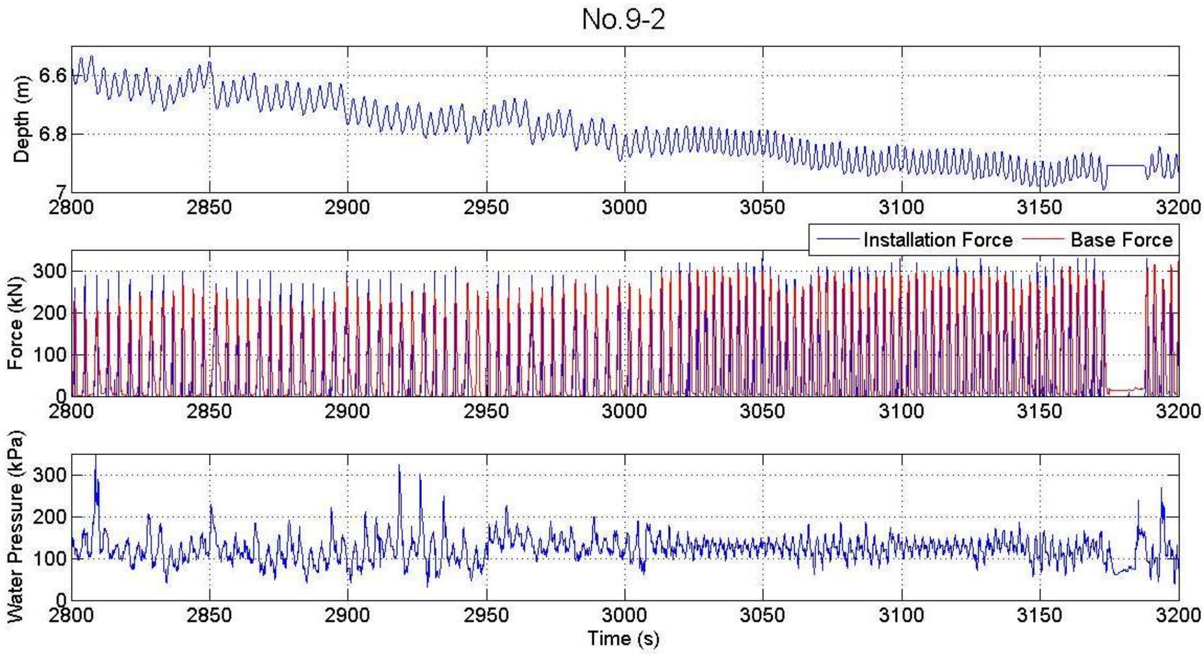

Fig. 20 Plot showing the change in rate of installation during test No.9-2

4.5 Influence of location

The locations of the individual tests were deemed uninfluential. It was hypothesised that there may have been localised soil deposits across the site that were leading to the differing behaviour observed in various tests. However, no clear pattern was seen from the data. The CPT data implies a slight slope of the soil layers across the site, however this is not significant enough or shallow enough to impact on the data. A plot of test repeats is shown in **Fig. 13**, and does not show enough variation between repeated tests to warrant further investigation.

4.6 'Stick-slip' mechanism

Due to the vast amount of data collected, it was chosen to analyse individual tests at a close level before generalising the results to all tests. Most of the analysis in this section was carried out for test No.21 but has been found to be applicable across all of the tests carried out.

During pile installation, it was observed that piling made no progress for prolonged periods before sudden, rapid movement. This will be referred to as the 'stick-slip' mechanism. An example of this mechanism is shown in **Fig. 21**. The pile can be seen to suddenly progress almost 200 mm in depth in the short period between 4125 and 4130 seconds. This 'stick-slip' mechanism has been observed in all tests.

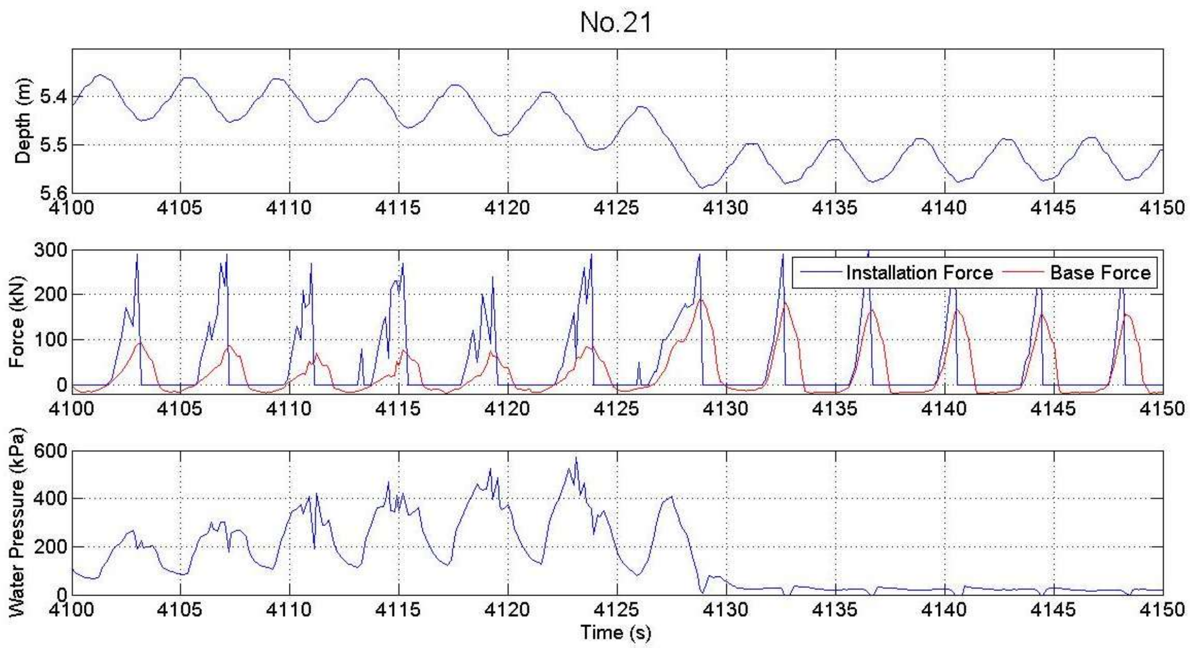

Fig. 21 An example of the 'stick-slip' mechanism

In tests No.18 and No.21 it was observed that before the pile slipped in the soil, instead of the installation force peaking once as expected, double peaks were observed. This observation can be seen in **Fig. 21**. These double peaks in the force measurement can be explained by the movement of the pile, as it is about to slip further into the soil.

4.7 Impermeable film

It can be seen that during the stick-slip process there is a substantial increase in the pore-pressures measured around the pile base prior to slipping. In test No.21, the water pressures surrounding the pile increase by nearly twelve times from 50 kPa to 600 kPa, as shown in **Fig. 21**. The high pore-pressures could not be sustained close to the pile for the available water flow rates unless a substantial decrease in the local permeability around the pile had occurred, as the native sand is highly permeable. This decrease in permeability could be achieved by crushing of the sandy soil by the repeated surging of the sharp edges of the sheet pile to form a silty filter layer around the pile. The water jet then moves the silt particles to create the impermeable film surrounding the pile base, trapping jet water against the pile shaft and allowing the water pressure values to build. A schematic of this process is shown in **Fig. 22**. Due to the water pressure build up around the pile base, a flow of water from the pile base towards the ground surface will be created, thus reducing the friction on the pile shaft.

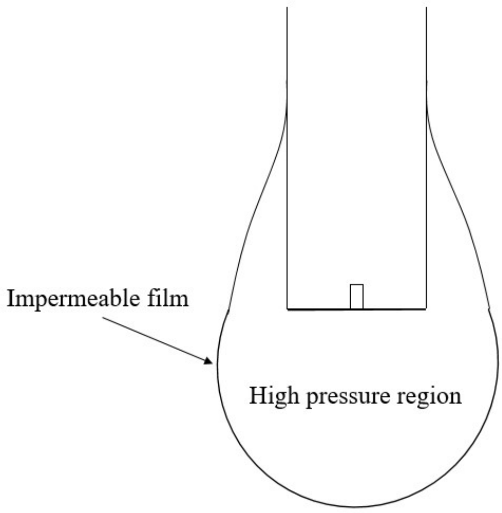

Fig. 22 Impermeable film and high pressure region around the pile base

The increased pore pressures around the pile reduce the base capacity of the pile and the friction acting on the lower section of the pile shaft, resulting in a transfer of load further up the pile shaft owing to the constant maximum head load applied. When insufficient shaft capacity is available to balance the applied head load, the pile slips into the soil. Once the pile slips, the water pressures drop off to almost zero very rapidly as the water jet moves into a layer of uncrushed material, allowing pore-pressures to rapidly dissipate until the crushing process repeats. This process in which water is seen to disappear from the ground surface with an associated increase in pile resistance is often referred to as 'water binding' (Stevens, 2015).

It was noted in *Section 4.2* that water jetting is aiding pile installation due to the high pressure nature of the jet. Shepley (2013) suggested based on centrifuge test data in saturated sands that water jetting aided installation due to fluidization of soil around the pile base. This would suggest that the flowrate of the water jet was important, rather than the jet pressure. Most of the piling discussed in this paper took place above the water-table in partially saturated soil. Although it seems that water flow rate might be important in this case as it can cause saturation of the soil surrounding the pile base and hence ease pile installation when water jetting, the observed data indicates that this effect has a minimal impact on the ease of pile installation. Potentially, saturation of the soil is unimportant as the soil is able to drain very quickly due to its sandy gravel composition. Moreover, only a very local zone around the pile base is saturated and therefore the impact of soil saturation on the effective stresses at the pile base is likely to be small, these being dependent on the integral of soil density down from the soil surface.

The image in **Fig. 23** shows the pile base after extraction. The pile is very clean and polished, implying abrasion by fine particles, namely the sand that has been crushed into silt when the impermeable film is formed. If the uncrushed sand particles were responsible for the abrasion, it would be expected to see a scratched pile surface rather than a polished one. Moreover, due to the high permeability of the sandy gravel, it would be implausible to see such high water pressures around the pile base were this impermeable film not formed.

Fig. 23 Image taken during site testing showing a clean and polished pile on extraction of test No.21 (Giken, 2017)

Fig. 24 shows another image taken on site during test No.12. This image shows particles suspended in water rising from the borehole formed during pile installation. As the particles are suspended, they are likely to be silt sized particles, despite the pile being installed in a sandy gravel, providing further evidence of the crushing of sand particles at the base of the pile. The water injected during water jetting is then able to carry these fine particles to the ground surface.

Fig. 24 Image taken during site testing showing silt particles suspended in water rising from the piling borehole (Giken, 2017)

It is hypothesized that without water jetting, the combined effects of shaft friction and base resistance on a plugged sheet pile exceed the piler capacity, preventing pile penetration. Plugging within the pan of the sheet pile causes the large values of base force measured.

However during water jetting, as the sand particles crush, the soil permeability falls allowing high water pressures to be trapped against the sheet pile. The high pressures both reduce friction on the outside of the sheet pile and prevent plugging within the pan. Destruction of the plug decreases the base resistance and allows the pile to make progress into the soil. This behaviour is what is leading to the 'sticking', and then 'slipping' of the pile.

4.8 High pressure vs. low pressure installation

In *Section 4.2* the difference between the two installation mechanisms for high pressure and low pressure jetting was highlighted. The installation mechanism for high pressure jetting is rapid, cyclic and included periods of withdrawal from the ground, whilst the installation mechanism for low pressure jetting is less efficient but smoother throughout the installation process. A plot of a high pressure installation mechanism is shown in **Fig. 25** for test No.22, showing the installation force, base force, and water pressure variation near the pile base throughout pile installation. This can be contrasted with the plot of a low pressure installation mechanism shown in **Fig. 26** for test No.21.

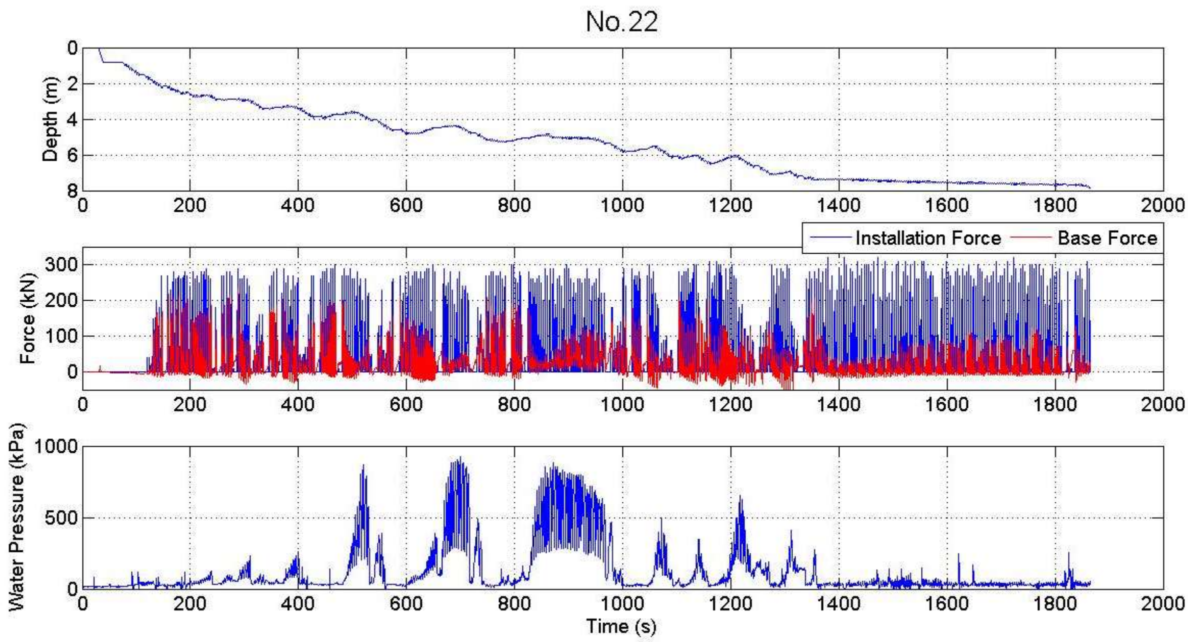

Fig. 25 An example of a high pressure installation mechanism in test No.22

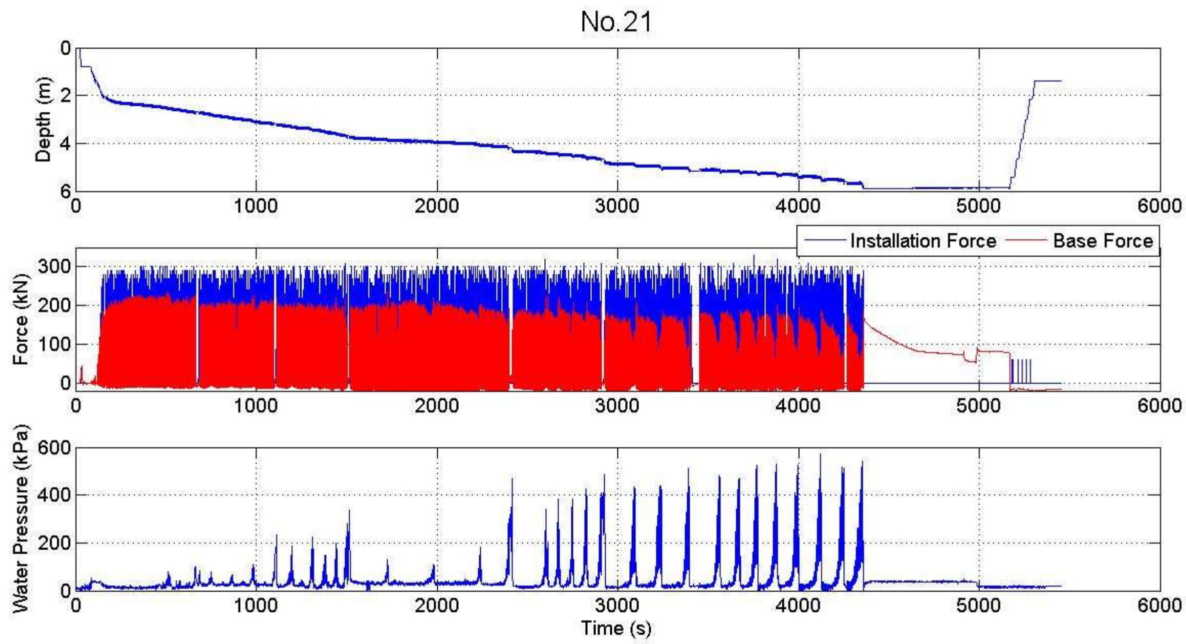

Fig. 26 An example of a low pressure installation mechanism in test No.21

The larger water pressure values that build up at the base of the pile in the high pressure mechanism take longer to increase than those in the low pressure mechanism. Whilst the high pressure mechanism appears to be more cyclic at the macro level, when a closer look is taken, as shown in **Fig. 27**, pile penetration is more continuous throughout the pile installation. This contrasts with the low pressure mechanism, which looks continuous at the macro level, but when looked at closer, as in **Fig. 28**, the process is highly cyclic at a small scale. The high pressure mechanism leads to a prolonged and deeper slip, as shown in **Fig. 27**. The slip process takes 200 seconds and slips through over 1 metre of depth. This can be compared to the low pressure mechanism, shown in **Fig. 21**, where the slip takes less than 5 seconds and only slips through 0.2 metres. **Fig. 27** shows that the high pressure mechanism can also lead to brief periods of pile withdrawal during the overall slip phase.

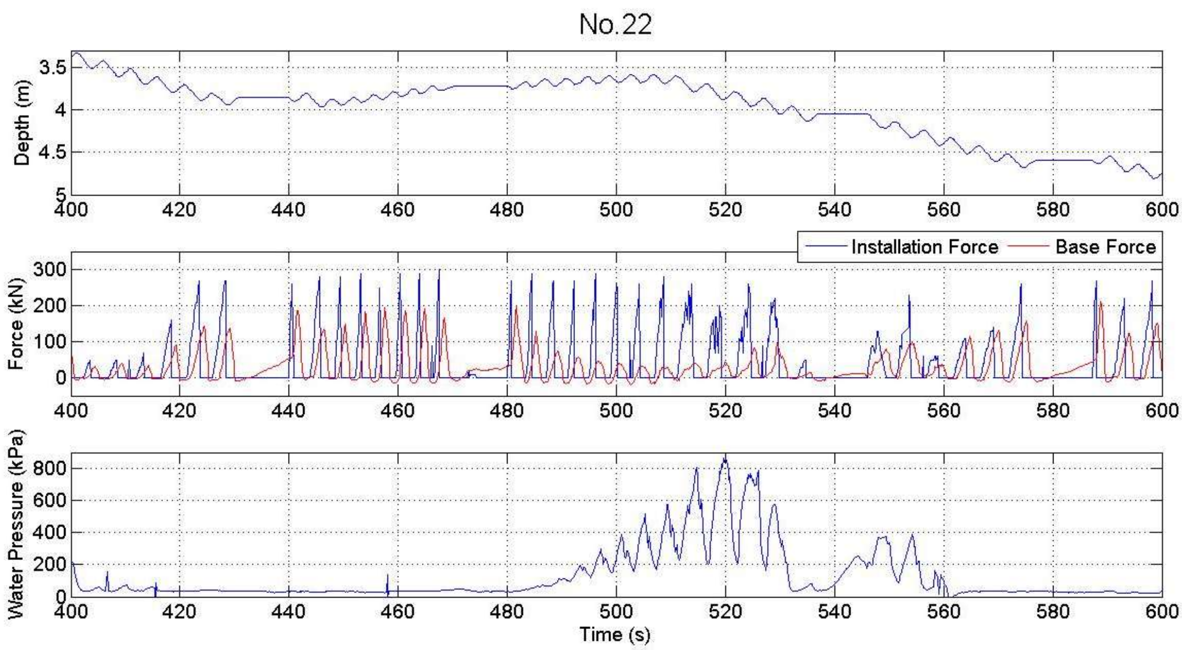

Fig. 27 A high pressure installation mechanism 'slip' in test No.22

In the high pressure installation mechanism, the base force is lower throughout installation than in the low pressure installation mechanism. This is anticipated, as the high jet pressure is able to maintain an open cavity underneath the pile base, by moving particles away from the zone immediately underneath the base of the pile. As the base resistance is lower, the amount of crushing of the sand particles is lower, because the particles experience a lower effective stress. As there is less crushing, the effect of the impermeable film and the corresponding decrease in permeability in the zone underneath the pile base is smaller.

Additionally, any particles that are crushed are more easily washed away by the high pressure jet. For these reasons, the pile installation is gradual rather than cyclic, as there is less of a cyclic build-up of water pressures underneath the pile base. The base resistance that is measured is likely to be a reaction force from the zone of high water pressures directly underneath the pile base, as explained in *Section 4.10*. The majority of the resistance faced by the pile in the high pressure installation mechanism is shaft friction. The water pressure values in the high pressure mechanism reach higher values than those in the lower pressure mechanism, due to the nature of the water jetting, even though the effect of the impermeable film is less significant in this mechanism.

In the low pressure installation mechanism, the lower jet pressures have more difficulty disturbing the soil at the base of the pile. Therefore, the base resistance experienced throughout installation is more significant. This means that there is more crushing of the soil below the pile base, leading to the impermeable film being formed. Once formed, the film too is less easily disturbed as the jet pressure is lower. The presence of the impermeable film allows the build-up of water pressure underneath the pile base, leading to the cyclic 'stick-slip' mechanism observed, and the cyclic behaviour of pile installation.

4.9 Shaft force variation

Fig. 28 shows the variations in shaft force along the length of the pile before the pile 'slip' takes place for test No.21. It can be seen that the shaft force recorded at 0.5 m above the base of the pile (the base force plus shaft force in the bottom 0.5 m of the pile) decreases as the water pressure builds up. Conversely, the forces recorded at 1.5 m and 4.5 m above the pile base increase during the water pressure build up, as the total load must be equal to that applied by the piler. This shows that prior to the slip, the resistance to pile movement is being transferred from resistance at the base of the pile to resistance up the shaft of the pile. Once the base resistance has been eliminated, the pile is able to make progress into the soil.

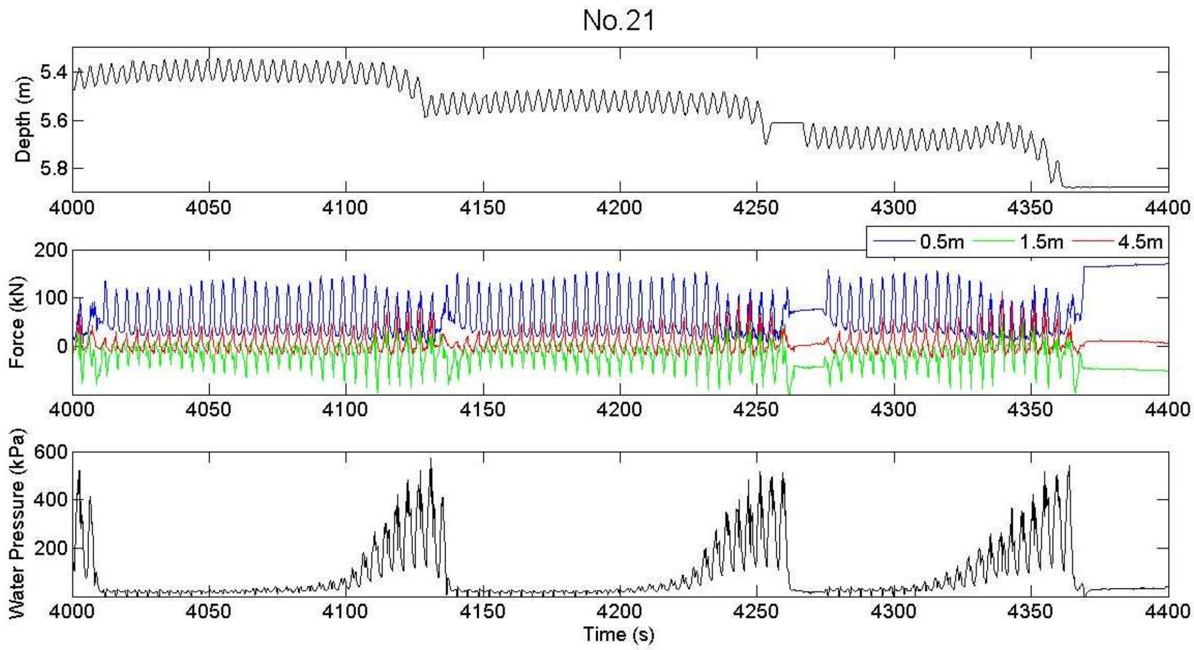

Fig. 28 Water pressure build-up and shaft force variation during the stick-slip mechanism in No.21

4.10 Water pressure variation

At the end of some tests, water jetting was continued whilst the pile remained stationary. Examples of this process can be seen in **Fig. 29** and **Fig. 30** for tests No.15 and No.16 respectively. During test No.15, jetting was carried out at 1 MPa for 10 minutes whilst the pile was stationary. At 7825 seconds, the pile was then installed into the soil, whilst the water jet was still at 1 MPa. The 200 mm stroke was easily achieved in full, as shown in **Fig. 29**. However, once this initial stroke was complete, the pile experienced rejection from the ground. During test No.16, jetting was carried out at 9 MPa for 10 minutes whilst the pile was stationary. At 6415 seconds, the water jet was turned off, before installing the pile into the soil at 6425 seconds. Similarly as to test No.15, the 200 mm stroke was easily achieved, as shown in **Fig. 30**, before also experiencing rejection.

Fig. 30 highlights another important result, as at 6415 seconds when the water jet is turned off, the base resistance at the pile base is seen to also fall significantly. This result implies that when water is jetted at a high pressure, a significant component of the base resistance is due to water pressure acting on the base of the pile. Therefore, when the pile is being surged, and water is being jetted at a high pressure, the base force seen is likely to be due to the water pressure, and the resistance to piling from effective stresses in the soil is coming wholly from the shaft resistance, not the base resistance. When the pile is stationary, the water pressure acting on the pile base is balanced by the negative shaft friction along the pile length. If the pile is considered to be plugged, it has an approximate area of 400 mm x 150 mm, and at a jet pressure of 10 MPa, this gives a force due to the water pressure of 600 kN. If dispersion of some of the jetted water through the soil is accounted for, giving an upthrust on the plug which must also be carried by the pile, this force can be considered fully responsible for the 200 kN maximum base resistance measured in test No.22.

From these limited tests, it is clear that water jetting without surging of the pile does aid pile installation, contrary to the conclusion that Shepley (2013) made. However, it is unclear how much jetting is required in order to achieve the full intended installation stroke. Perhaps a much smaller volume of water jetted into the soil would saturate the local area around the pile base, allowing successful penetration. This is an area of research that could be further developed, as discussed in *Section 5.3*.

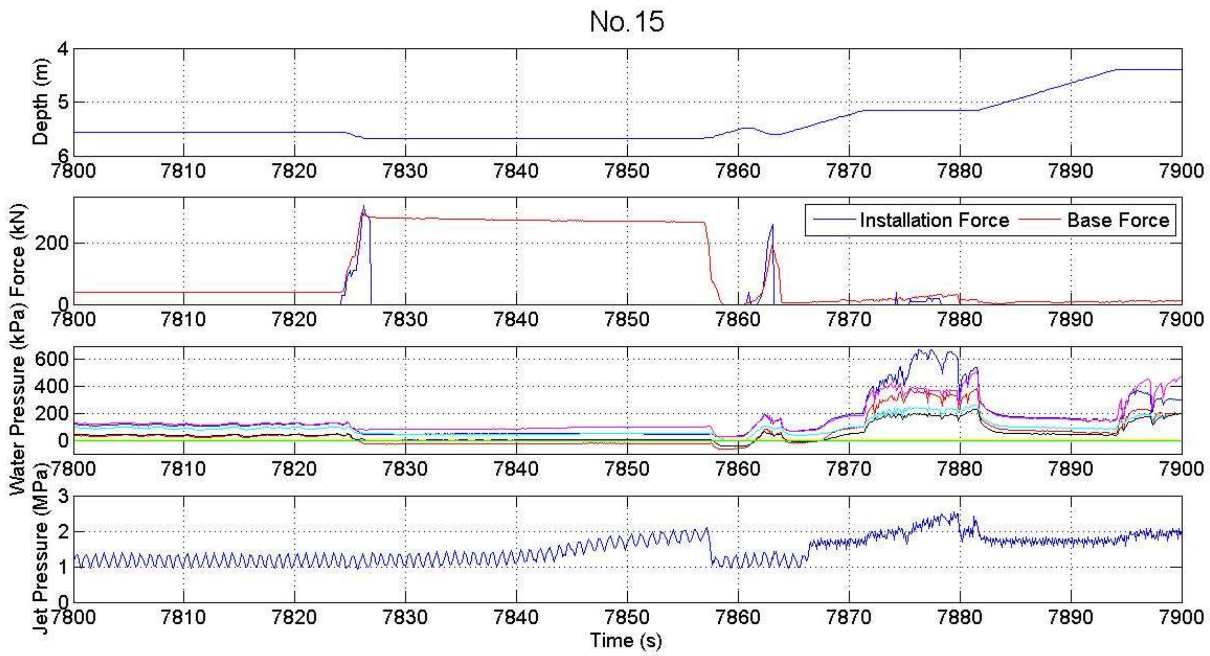

Fig. 29 Jetting without surging for test No.15

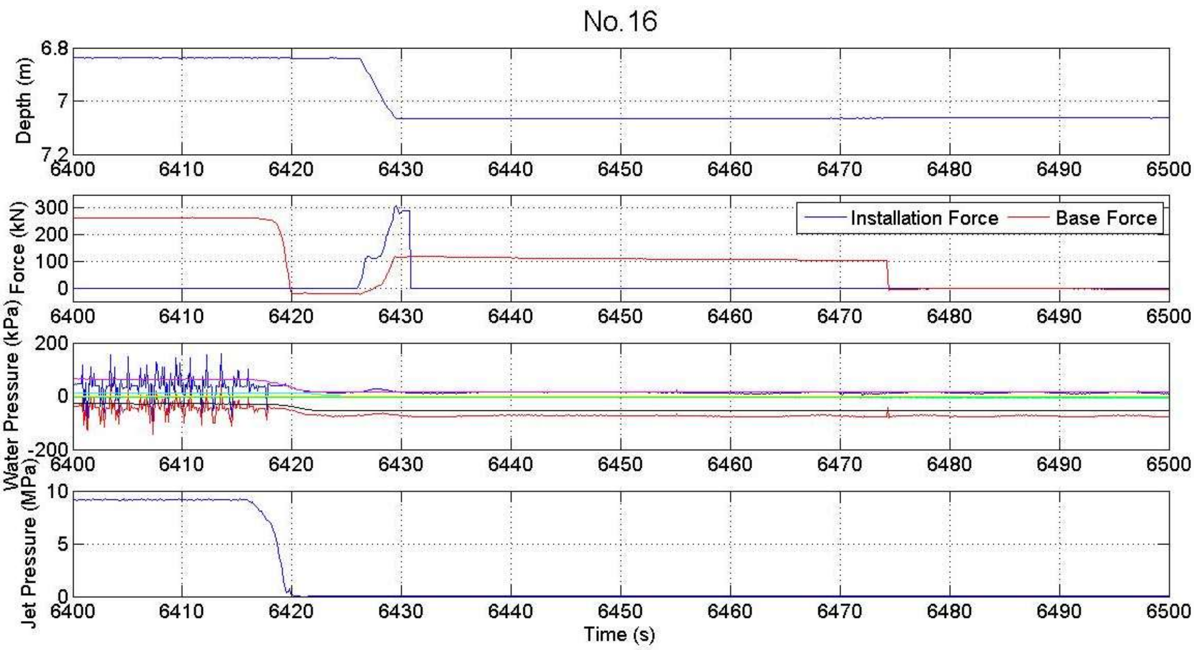

Fig. 30 Jetting without surging for test No.16

4.11 Finite element analysis

Fig. 31 shows a slice through a 3D finite element analysis model that was made using ABAQUS. The model was created to investigate the fluid pressure variation within the soil under different test conditions. The model draws an analogy between heat conduction and fluid flow in soils, by modelling the problem of water jetting as a thermal problem. This analogy is valid as both processes are governed by the same form of differential equation. In the model, water pressure is analogous to temperature. A constant temperature source is applied at the node 70 mm above the pile base, to resemble the flow from the jet. The contours show the temperature distribution within the soil block which can be extrapolated to represent the water pressure distribution within the soil block.

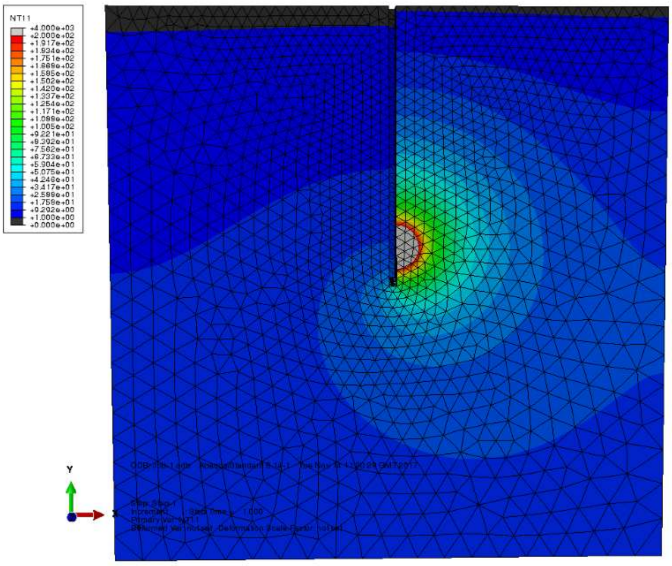

Fig. 31 Image exported from ABAQUS showing the water pressure distribution around the pile base within the soil block

From this model, it can be seen that when the water pressure at the jet nozzle is 4 MPa, the water pressure at the pile base is 80 kPa and the water pressure at the edge of the soil block (0.5 m distance from the nozzle jet) is 10 kPa. These pressures are very low, as expected. It was intended to measure the water pressure values in the soil surrounding the pile on site, however due to the rapid radial decline of pressures, this was very difficult to do in reality. The closest measurement that it was possible to take was at a distance of 1 m from the pile (as shown in **Fig. 8**), due to the pile and machinery geometry. Moreover, the water pressure values in the area surrounding the pile were not expected to vary significantly because the majority of the piling took place above the water table. In order to vary the water pressure values, the entire region of soil would have to be saturated first, requiring vast volumes of water to be jetted into the soil. Therefore, the results produced by the finite element analysis are very useful as they complete a gap in the experimental work, and are more sensitive to small variations in water pressure than the water pressure sensors used in the field.

This model doesn't model the inertia of the water jet, nor does it indicate the direction of the water flowing out of the jet. The exclusion of these factors is likely to give water pressures lower than the true values. The model also assumes a constant soil permeability throughout the soil. This may be an incorrect assumption due to crushing of the soil particles at the base of the pile.

The crushing of soil particles at the base of the pile creates a region of higher permeability soil directly beneath the pile base. The high permeability region allows the build-up of large values of water pressure in this region, before the values decrease significantly over a short distance away from the pile base, into the uncrushed region of soil. This phenomenon was observed in the experimental work but is not reflected in the ABAQUS model due to the constant soil permeability used. If a variable soil permeability was used in the ABAQUS model, it would be expected to see higher water pressures at the pile base and an even more rapid decline in water pressures with distance away from the pile base.

The water pressures found from the ABAQUS model can be compared to the measured water pressure values. The numerical analysis was conducted for a jet pressure of 4 MPa, as was test No.19-3 (**Table 1**). In No.19-3, the water pressure sensor closest to the base of the pile measured values up to 400 kPa. This is five times larger than the water pressure at the pile base found in the numerical analysis. This result agrees with the predictions in the previous paragraphs, based on the assumptions made in the model. The measured water pressures are also highly variable, which is not reflected in the ABAQUS model.

5. Conclusions

5.1 Concluding remarks

This project comprised of experimental work carried out with Giken Ltd. in Kochi, Japan, followed by extended data analysis and finite element analysis. The project aimed to investigate the soil mechanisms that allow water jetting to aid sheet pile jacking, and to find the optimum conditions for the water jetting.

Throughout testing, the variables controlled included: jet flowrate and nozzle diameter (and hence jet pressure), rate of installation, and rate of surging. The most important variable was the jet pressure, whilst the rate of surging was concluded to be uninfluential. The rate of installation influences the rate of penetration of the pile, with 104 mm/s being the optimum installation rate.

The report has illustrated that the beneficial effects of water jetting are caused by the high pressure nature of the jet rather than the saturation of the soil around the pile base. The rate of pile penetration is therefore heavily dependent on the jet pressure used for the installation, not the jet flowrate, as suggested in other literature (Shepley (2013); Lyons (1997); Smith (2003)). It was also observed that high and low jet pressures induce two different mechanisms of pile installation. However, the jet pressure is only influential on the rate of penetration when the pile is deeper than 2 meters under the ground surface. These conclusions have important implications for practise, as discussed in *Section 5.2*.

The surging of the sharp edges of the sheet pile cause crushing of the sand particles around the pile base, which form an impermeable layer around the pile base. This layer traps jetted water, leading to a region of high water pressure below the pile base and around the pile shaft, reducing base resistance, shaft friction and pile plugging. Prior to slipping, the shaft friction near the base of the pile decreases and is transferred to shaft friction further up the pile. Only once the shaft friction near the base of the pile has decreased significantly enough, can the pile make progress into the soil, with the pile becoming unplugged. As the pile progresses into the soil, the crushed material forms a film around the pile shaft allowing high water pressures to be retained close to the pile shaft, reducing the shaft capacity. Once the pile has slipped into the soil it has entered an uncrushed region in which the water pressures can drain quickly away. The base resistance is thus high until crushing has once again occurred.

For two pile installations, jetting water whilst the pile was stationary was tested. In these cases, jetting for a prolonged period did allow the pile to penetrate into the soil, although it is questioned whether the amount of water jetted to permit this penetration was excessive and unnecessary.

5.2 Implications for practice

It has been demonstrated from the data presented that water jetting can have a substantial effect on the ease of pile installation in dense sandy soils. In order to achieve optimum penetration in these types of soils, the jet pressure appears to be the most important parameter, to create a high pressure region around the pile base. It is thus proposed that the optimal conditions for pile jetting would utilize small diameter nozzles with only modest water flow rates.

As noted in *Section 5.1*, the jet pressure is only influential after the first 2 metres of penetration into the soil. Therefore, during the initial installation, a very low flowrate, or even no water jetting, could be utilised in order to optimise the water jetting process.

Another suggestion for practise is to use an alternative surging rate, of 200-10 mm. This is recommended to avoid pile withdrawal when attempting to penetrate through hard ground. During a 200-100 mm surging cycle, if the ground is difficult to penetrate, the installation stroke might only gain 20 mm due to the maximum force limitation, whilst the extraction stroke completes the full 100 mm. After a few surging cycles, this results in pile withdrawal. Therefore, the 200-10 mm rate of surging is suggested, in order to prevent pile withdrawal in difficult ground conditions.

The final recommendation is to use a more dispersed nozzle in order to reduce plugging within the sheet pile. Carter (1996) carried out some research into this area but the results are not highly reliable. Jetting in several directions might be more efficient at reducing the amount of plugging and hence increase the rate of pile penetration.

These recommendations will be provided to Giken Ltd. for use in future piling installations.

5.3 Future work

One potential area of future work is into the process of water jetting whilst the pile is stationary, before attempting further penetration. Tests such as these were carried out in the work described above, but not to a significant enough extent to be able to draw conclusions from them. The pressure of the water jetted, the time permitted for stationary jetting, and whether the jet is left on or turned off during attempted pile penetration are all variables that could be controlled. From these tests, it could be concluded whether jetting whilst stationary is more or less efficient than jetting whilst surging the pile, and whether this depends on other piling conditions, for example the jet pressure.

In the work completed, after stationary jetting, the control of a maximum pile displacement of 200 mm was still applied. However, this limited the usefulness of the results obtained. In order to learn more from the data, this control should be relaxed and the pile displacement after jetting should be plotted against the time for jetting, or the volume of water jetted into the soil. The maximum secant gradient of this plot should be found, which would determine the optimum rate of jetting and pile installation. Depending on the relationship between pile displacement and time for jetting found, the most efficient method of pile installation could be identified, whether this is continuous installation (the red curve in **Fig. 32**) or a particular combination of rate of installation and pausing for jetting (the blue curve in **Fig. 32**).

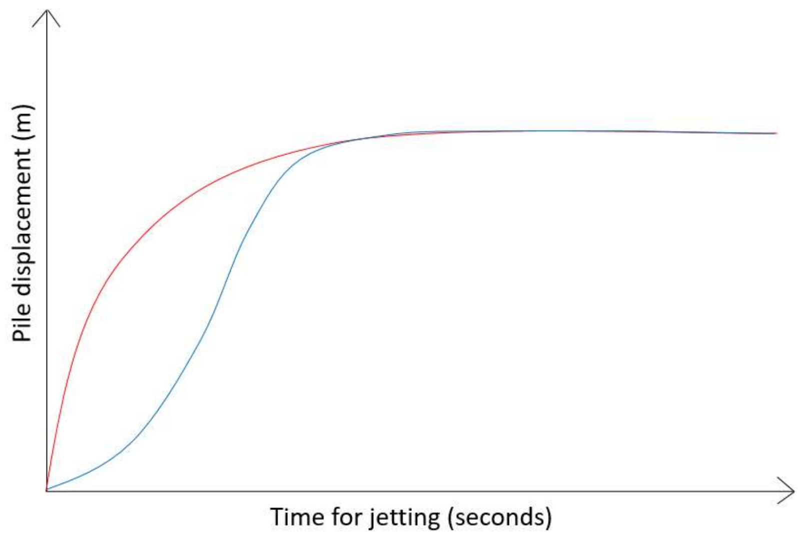

Fig. 32 Example of plot showing the optimal jetting pause time

Another potential area of future work is further research into the differences between the high pressure and low pressure installation mechanisms identified in *Section 4.8*. This report has clearly identified that there are two separate mechanisms, although the mechanics explaining the two different mechanisms could be further investigated. Further tests should be carried out to identify at which pressure the mechanism changes and to identify the optimum pressure at which to jet water.

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7. Appendix: Risk Assessment

The initial risk assessment did not highlight any major hazards as all of the work carried out in Cambridge has been computer-based. Therefore, the main hazards were thought to be RSI, back pain and eye strain. The initial risk assessment reflected the hazards actually encountered well, as no hazards outside the identified scope were experienced. This initial risk assessment can therefore be considered as accurate and effective.

However, the initial risk assessment submitted did not account for any of the hazards encountered during the field work carried out in Kochi, Japan, as it was submitted after the field work was completed.

There were significantly more hazards encountered during the field work than there were during the computer analysis phase of the project. For this reason, the initial risk assessment should have been carried out much earlier, to account for projects in which the experimental work was carried out before the start of the academic year.

However, whilst the field work was ongoing, some health and safety (H&S) observations were recorded. A H&S meeting was carried out each morning before site work commenced, detailing the specific hazards for the day and how to conduct oneself in order to prevent injury. However, the rules laid out were not strictly adhered to, and hazards were present across the site.

Due to the nature of the test equipment, long, mobile cables were laid across the site, presenting a trip hazard. Mobile phones were frequently used on the site and acted as a distraction, preventing workers giving their full attention to the equipment that they were controlling. The methods used to waterproof the equipment were crude, which could have led to equipment damage and failure.

However, the standard of uniform was exceptional across the site and throughout the entire time spent working on site in Japan. All workers ensured that they were wearing the correct gloves for the specific job that they were doing, and helmets were always worn.