Water Jetting for Sheet Piling

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ABSTRACT

This project arose from 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. The experimental work was followed by analysis of the data collected, and the data analysis was complimented by a finite element model made using ABAQUS. The main findings of the research are that the rate of pile installation is heavily dependent on the jet pressure used, and that high and low jet pressures induce two different mechanisms.

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.

Key words: *Press-in, water-jetting, particle crushing, water pressure, stick-slip*

1. Outline of the project

1.1. Place

This project 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. 1**. 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.

1.2. Background and objectives of the project

As press-in piling utilizes the reaction force from previously installed piles to install further piles, only a limited reaction force is available for pile penetration. In hard soils where the base resistance of the pile may be

Fig. 1 Location of Niida test site (Carter & Gooch, 1995)

substantial, limited reaction force and machine capacity may make installation of piles problematic. 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). It is unclear, however, which of these mechanisms 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.

2. Structural type and piling method

2.1. Ground condition

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. 2** with the data obtained from the boreholes being shown in **Fig. 3**. 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.

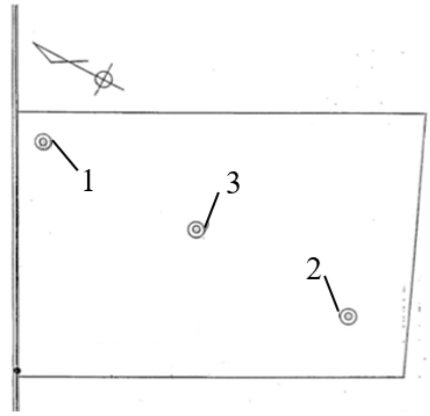

Fig. 2 Borehole locations at Niida site (Carter & Gooch, 1995)

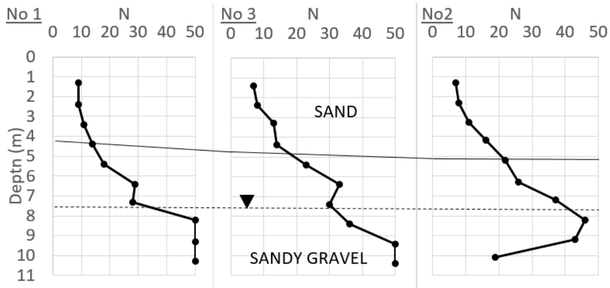

Fig. 3 Borehole data for Niida test site

2.2. Structural type

U-shaped 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. 4**.

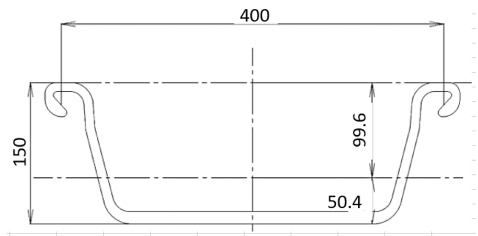

Fig. 4 Sheet pile section (dimensions in mm) (NSSMC, 2016)

3. Press-in piling

3.1. Layout

A plan view of the layout of the test is shown in **Fig. 5**. No. 18, No. 11, No. 6 and No.3 were "measurement piles" whilst all other piles were "test piles". The distance of test piles from measurement piles was varied in order to obtain water pressure readings in the soil surrounding the test piles. Water pressure sensors were located on the front and back of all piles at intervals along the pile length. The water pressure measurements and complications associated with them are discussed in *Section 5*.

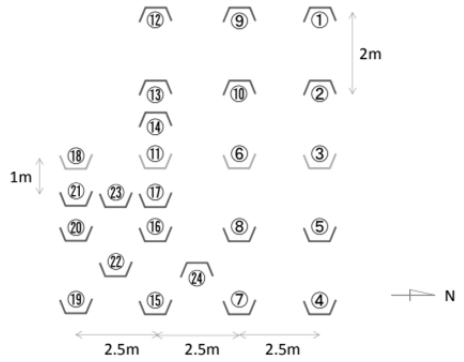

Fig. 5 Layout of the piling work

3.2. 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 press-in 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 is the process of applying a downward displacement and an upward displacement to a pile alternatively, in order to reduce the penetration resistance (Delano, 2010; Burali d'Arezzo et al, 2013). 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.

Table 1. Press-in conditions for tests

	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

4. Analysis of piling data

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 limitation of jacking force is much smaller than the capacity of the machine. Influential factors in determining the limitation values are the 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.

Fig. 6 shows the progress of pile installation with time. It can be seen that while the piles are installed rapidly to around 2 m depth, beyond this point the installation slows and becomes a function of jet pressure. Analysis of the data obtained from the 24 piles installed illustrates that the installation rate is highly dependent on the jet pressure (which can be achieved with several combinations of nozzle size and flowrate) as shown in **Fig. 6**, but only weakly affected by the 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 6*.

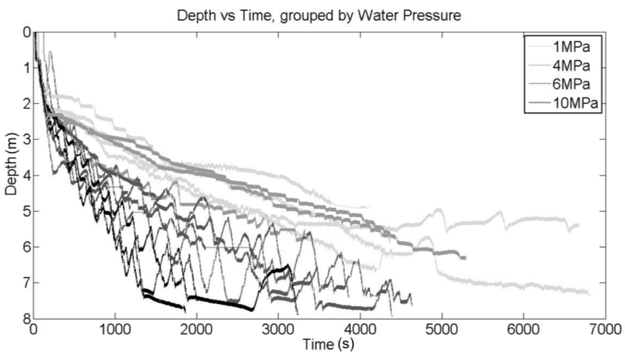

Fig. 6 Installation rates of tests, grouped by jet pressure

Fig. 6 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.

Due to the vast amount of data collected, it is difficult to gain an understanding unless a simplified method is found for analyzing the data. Therefore, the plot shown in **Fig. 7a** was created. This plot shows that the pile installation velocity decreases with installed pile depth, as expected due to the increased pile resistance. This plot also shows that a higher jet pressure leads to an increased installation velocity. Initially pile installation velocity is high regardless of the jet pressure used, after 1 m of installation, all tests having an average velocity between 60 mm/s and 70 mm/s. **Fig. 7b** shows that as the piles reach greater depths, the velocity of installation 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.

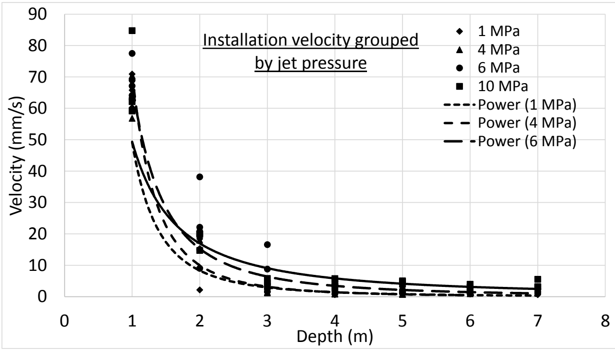

Fig. 7a Installation velocity attained in each incremental meter of depth for various tests

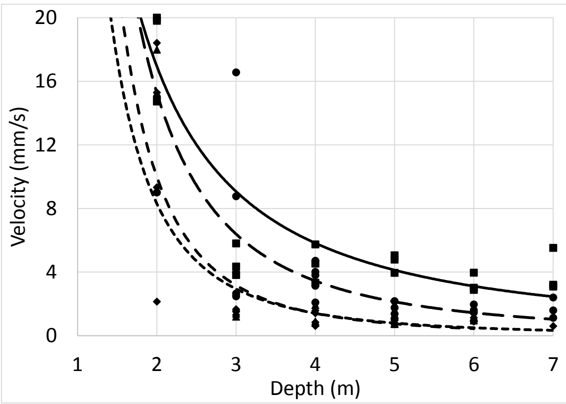

Fig. 7b Installation velocity attained in each incremental meter of depth at a higher level of zoom

Scatter is seen in **Fig. 7a** and **Fig. 7b** due to uncontrollable site factors and variability originating from the manual operation of the Silent Piler.

This important result highlights that it is the jet pressure that is important, 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. This result enables cost and water to be saved and the optimum conditions for water jetting to be approached.

5. Finite element analysis

Fig. 8 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 sheet pile is modelled as an impermeable object within the permeable soil block. The contours show the temperature distribution within the soil block which can be extrapolated to represent the water pressure distribution within the soil block due to the process of water jetting.

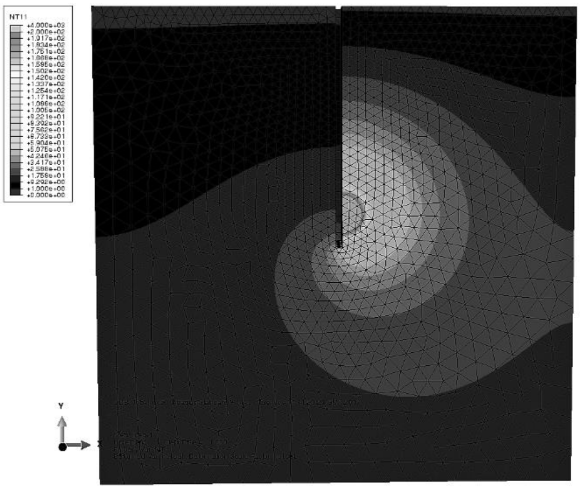

Fig. 8 Image exported from ABAQUS showing the water pressure distribution around the pile base within the soil block

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. 5**, due to the pile and machinery geometry. Therefore, the results produced by the finite element analysis are very useful as they complete a gap in the experimental work.

This model does not 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 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 paragraph, based on the assumptions made in the model. The measured water pressures are also highly variable, which is not reflected in the ABAQUS model.

6. 'Stick-slip' mechanism

During pile installation, it was observed that the 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. 9**. The pile can be seen to suddenly gain almost 200 mm in depth in the short period between 4125 and 4130 seconds. This 'stick-slip' mechanism has been observed in all tests.

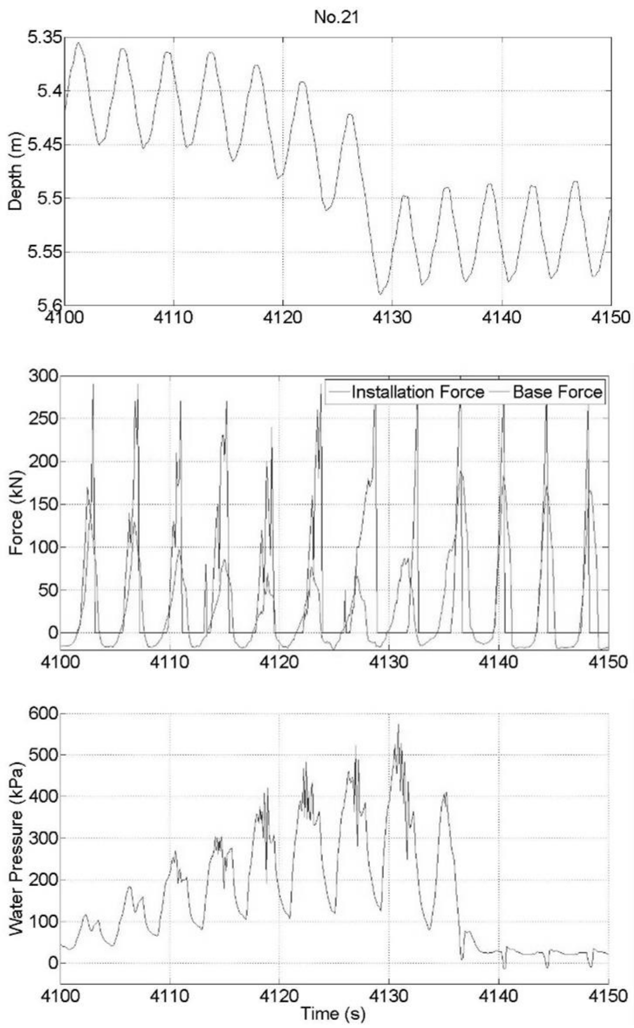

Fig. 9 An example of the 'stick-slip' mechanism

It can be seen that during this stick-slip process there is a substantial increase in the pore-pressures measured at 70 mm above the pile base prior to slipping. In test No.21, the water pressures surrounding the pile base increase by nearly twelve times from 50 kPa to 600 kPa. 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. This 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. 10**. 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.

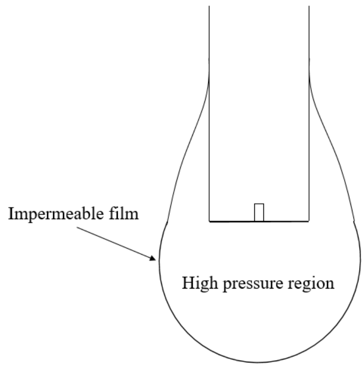

Fig. 10 Impermeable film and high pressure region around the pile base

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* 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. 11** 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. 11 Image taken during site testing showing a clean and polished pile on extraction of test No.21

Fig. 12 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. 12 Image taken during site testing showing silt particles suspended in water rising from the piling borehole

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 when 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 behavior is what is leading to the ‘sticking’, and then ‘slipping’ of the pile.

Fig. 13 shows the variations in shaft force up 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.

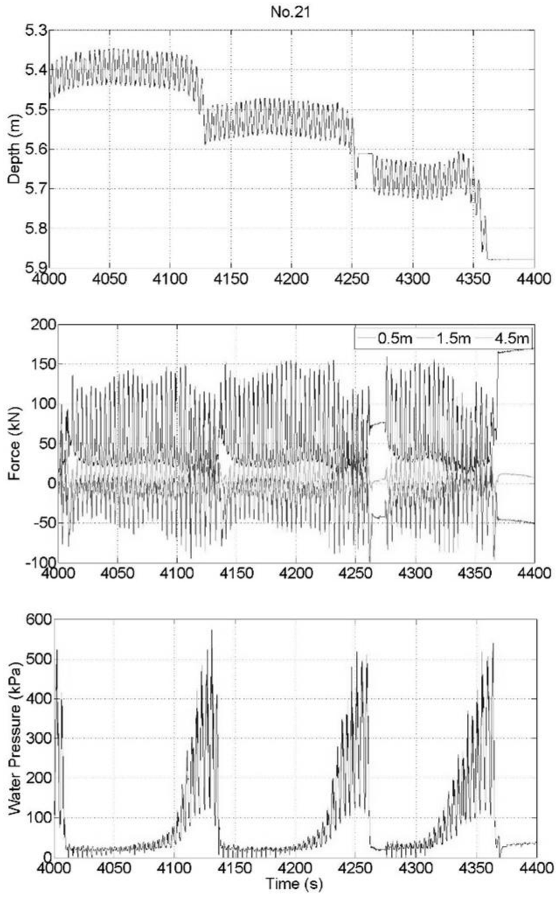

Fig. 13 Water pressure build-up and shaft force variation during the stick-slip mechanism in No.21

7. Implications for Practice

It has been demonstrated from the data presented here 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.

8. Concluding remarks

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

The paper 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 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, allowing jet pressures to be trapped, reducing shaft friction and pile plugging.

It is proposed that the 'stick-slip' mechanism is occurring due to plugging within the sheet pile, causing the pile to 'stick'. The pile is only able to 'slip' when the water pressure at the base of the pile has increased to a significant level and destroys the plug, reducing the resistance at the base of the pile and allowing pile installation. This process is repeated throughout the installation of the piles.

9. Acknowledgements

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