Water injection aided pile jacking centrifuge experiments in sand

Essais en centrifugeuse d'installation de pieux vérinés dans le sable avec injection d'eau

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ABSTRACT: Jacked piles have several advantages over conventional piling techniques; namely the low noise and vibration output from the process. However they are often difficult to install in hard ground conditions. A supplementary water injection technique can be used to reduce installation loads. Water is injected from the pile toe at high pressure and flow rates into the ground, achieving large reductions in installation loads. In this research, water injection aided pile jacking was modelled on a geotechnical centrifuge. A dense, fine sand was used and multiple pile installations were completed in order to investigate the effect water injection has on installation loads. To complete the modelling, a high water pressure supply for use on the centrifuge was developed and systems to maintain centrifuge balance were implemented. This paper also identifies and validates a method for calculating pressures of interest based on the limited measurement locations available.

RÉSUMÉ : L'installation des pieux vérinés présente plusieurs avantages comparativement aux techniques de pieux conventionnelles, en particulier cette méthode est peu bruyante et génère de faibles vibrations. Cette technique est par contre difficile dans les sols denses et compacts. L'injection d'eau supplémentaire permet de réduire les charges d'installation. L'eau est injectée au niveau de la base des pieux dans le sol sous forte pression et à haut débit, ce qui permet une réduction importante des charges d'installation. Dans cette étude, l'installation des pieux vérinés assistée par injection d'eau a été modélisé dans une centrifugeuse géotechnique. Un sable dense et fin a été utilisé et de nombreuses installations de pieux ont été réalisées pour évaluer l'effet de l'injection d'eau sur les charges d'installation. Pour compléter la modélisation, une nouvelle alimentation d'eau sous haute pression pour utilisation en centrifuge a été développée et un système de maintien de l'équilibre de la centrifuge a été implémenté. Cette recherche identifie et valide également une méthode de calcul des pressions d'intérêt basée sur des localisations de mesure limitées sur le terrain.

KEYWORDS: jacked pile, centrifuge, sand, water jetting, water injection

1 INTRODUCTION

Jacked, or silent, piling is an increasingly important method for pile installation. Construction projects in urban or sensitive areas desire a low-impact means of installing pile walls or piled foundations. This is due to their low disruptive nature – producing little noise and few ground vibrations (White et al. 2000). In addition, they often require fewer enabling works due to the smaller machinery (Goh et al. 2004).

However, jacked piles are restricted by the maximum deliverable installation force. Often this is limited by the available kentledge for counterweight systems. In the case of the jacked piling system produced by Giken Seisakusho Ltd., a Japanese piling contractor, reaction force is provided by the previously installed piles in the pile wall. Three or four piles are used in tension to provide the installation load for the subsequent pile. In this case the load limit is set by the capability of the machine, not necessarily the available reaction force. In all cases, if the piling load approaches the load limit of the machine, the installation rate may fall to an uneconomical level or even pile refusal.

To reduce or prevent these situations, a supplementary installation technique can be used. The aim of any such technique is to maintain the advantages of the installation, with low noise and vibration levels, but also reduce the installation load so that piles can be jacked into hard ground. Many techniques exist to achieve this, such as surging, pre-augering and gyropiling. However, the use of a supplementary water injection during the pile installation to reduce the installation forces is of particular interest for this study.

Modelling of the water injection technique has been completed using the Turner Beam Centrifuge at University of Cambridge. A high pressure water supply was developed for use on the centrifuge in order to replicate the high water pressures and flow rates experienced in the field. This paper will outline the current use of the technique, in addition to the centrifuge modelling completed.

2 DEVELOPMENT OF WATER INJECTION

Water jetting has been in common use for decades, mainly for offshore pile installation (Tsinker 1988). The offshore setting provides a large water source and no nearby structures that may be affected or damaged. Typical flow rates for this early technique exceeded 1500 litres per minute in all soil types. In addition, water jetting was found to be disruptive to the soil fabric around the installed pile. The ground was liquefied so that the pile could be installed under self weight. This resulted in global particle rearrangement where large particles sank to the bottom of the pile installation.

The technique has since been improved to allow its more widespread use. Required flow rates were reduced to below 1000 litres per minute following a review from Tomlinson and Woodward (2008).

If the water jetting technique is used in conjunction with another pile installation method – pile jacking with supplementary water injection, then the flow rates can be reduced further. There is no longer a reliance solely on the water flow to install the pile. Instead the pile is jacked and the water injection is used to reduce the required installation loads. Flow rates for this method reduce to less than 300 litres per minute, and depend on the size and type of pile being installed.

The aim of water injection is to aid pile installation with minimal impact to the surrounding ground. Water injection should only be required during periods of high pile installation loads. During these phases, high water injection rates would be required to reduce the installation loads. Once the installation loads are sufficiently reduced, the flow rate can be reduced unless pile loads begin to increase again.

Despite the variety of full scale testing completed, there is still uncertainty over the water injection technique. The main unknown is the governing mechanism. Some options have been suggested, most recently the scour system outlined by Schneider et al. (2008), however further research is required to investigate the technique further.

3 CENTRIFUGE MODELLING

Initially, the aim of the centrifuge testing was to find an effect on the pile installation load when using the water injection system.

3.1 *Model construction*

A body of fine sand was prepared to a relative density of 80 % in a centrifuge container, 850 mm in diameter, to a depth of 320 mm. This was saturated from the base with de-aired water.

The sand was prepared so that it possessed a low permeability by mixing fine Fraction E silica sand with a commercially available builders sand. To ensure continuity between tests, the sand was repeatedly sampled and the particle size distribution (PSD) was found for different batches using the Single Particle Optical Sizing (SPOS) technique. Figure 1 shows the particle size distribution of the mixed sand compared with the Fraction E and builders sand components.

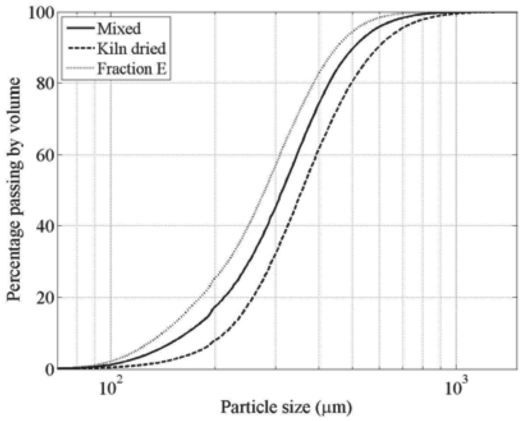

Figure 1. PSD comparison of the mixed sand for testing with standard sand types, Fraction E and a builders sand.

3.2 *Model pile*

A bespoke instrumented model pile was constructed for the testing program. A stainless steel tube of 12 mm outside diameter was used, with a water delivery pipe running through the centre. Stainless steel was chosen due to its strength, hardness and resistance to corrosion – preventing buckling during testing or surface abrasion over multiple installations. This ensured consistency over all the installations. A photograph of the pile is shown in Figure 2.

Strain gauges were used to monitor the axial load at the pile toe and the pile head. Two full Wheatstone bridges were used at each location.

The water delivery pipe was a 2.5 mm internal diameter plastic pipe. This terminated at a detachable nozzle at the pile toe which could be easily changed between tests. Different nozzles were used throughout the test program. Nozzles using only a central orifice will be assessed in this paper. These were modelled on small orifice plates, with a nozzle diameter of 0.5, 1.0, 2.5 and 3.0 mm.

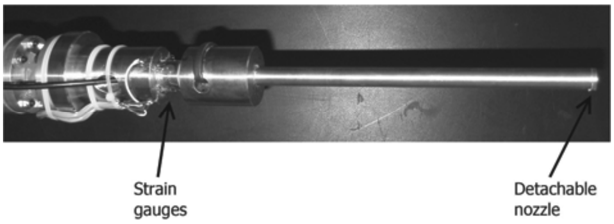

Figure 2. Photograph of the model pile as used, with nozzle attached at the toe and visible strain gauges at the pile head.

3.3 *Water injection system*

In order to model the water injection technique, a new system was required to provide high pressure water to the pile at a relatively high flow rate. Previous centrifuge testing of water jetting used low flow rates and pressures, due to the chosen pumping system.

Typical pumping systems for use one board a centrifuge package are based on a syringe pump. Such systems are commonly used for modelling excavations, where fluid is drained from a region to simulate ground volume loss, or for simulating pile jetting, such as the jetted spudcan experiments of Gaudin et al. (2011). Syringe pumps are limited by the actuator used to drive the piston. The actuator provides a high degree of control over the flow, but also restricts its use to low flow rate and low pressures. In addition, syringe pumps typically have a small volume capacity, meaning it is difficult to maintain high flow rates for a long period of time.

To avoid this issue during testing, the new system developed derived water pressure from the radial acceleration down the centrifuge arm. Water was provided to the slip rings at typical mains pressure (around 200 kPa) and then fed to the package through a pipe running down the beam. Moving through the gravitational field gives an increase in pressure according to:

$$P_{package} = P_{slip\ rings} + 0.5\rho\omega^2\left(r^2_{package} - r^2_{slip\ ring}\right) \quad (1)$$

where P is the pressure at the package and slip rings measured in Pascal, ω is the angular velocity of the centrifuge in rad/s and r is the radius from the centre of the beam of the package and slip rings in metres.

This procedure developed peak pressures at the model of 1.2 MPa and sustainable flow rates of up to 3.5 litres per minute. Water pressure and flow rate were monitored at the centrifuge model, a short distance from the pile toe. This location was chosen for the simplicity of mounting a pressure transducer and a turbine flow meter in the water delivery system. In addition, a solenoid valve was used to allow or terminate flow to the pile.

Pressure at the pile toe could be calculated following the centrifuge test using pipe flow theory as laid out by Goforth et al. (1991). Loss factors can be confirmed by comparing calculated values with data taken during a flow test – where the pile toe is suspended above the sand surface and water is passed through the system. The calculations can then be extended to allow for different toe positions in the acceleration field and the toe pressure at all pile depths can be found.

Flow rate control was achieved using a manually operated flow tap before the slip rings. This controlled the water flow delivered to the centrifuge. Any changes were made by hand during the centrifuge flight. The on board instrumentation is monitored to ensure that a consistent and appropriate flow was being delivered to the pile. The position of this control tap governed the peak flow rate and was unchanged throughout a single installation.

3.4 Maintaining balance

The centrifuge at Cambridge is balanced using a fixed mass counterweight. This is cumbersome to change during a test week and cannot be changed mid-flight. Therefore the mass of the experimental package had to remain constant throughout the centrifuge test, despite adding water to the package at very high flow rates.

A passive standpipe system was designed in order to drain excess water out of the experimental package into the centrifuge chamber. The standpipe was positioned within the sand body near the edge of the container – remote from any pile locations. A set of holes at the base of the standpipe linked the water level in the standpipe to the water table in the sand body.

Holes at the top of the standpipe allowed water to drain out of the package through a set of drainage pipes. If the water level exceeded the design water level at any point, water would exit the package by draining through these top holes.

To monitor the success of the standpipe, pore pressure transducers were used. A series of these were positioned in the sand body to monitor the pore pressures around an advancing pile installation. Additionally, these transducers provided knowledge of the water table position in the model. A further transducer was placed at the base of the standpipe to check that the drainage system was functioning.

3.5 Testing program

All centrifuge tests to be presented in this paper were completed at an acceleration of 60g. According to length scaling, this modelled a 720 mm diameter, close-ended tubular pile installed to a depth of 11.4 m. For the purpose of future discussion, all future units will be at the model scale.

A soil stabilisation loop was completed before the first installation in order to prevent excessive change of the sand body between the first and subsequent flights. Following this, multiple pile installations were completed in a single flight using the centre's 2D actuator (Haigh et al. 2010). Piles in a single flight were spaced at 140 mm ($12D_p$), but final pile spacing was close to 70 mm ($6D_p$). A typical pile layout is shown in Figure 3.

The nozzle at the pile toe was changed between flights to investigate the importance of the nozzle layout. The nozzles restricted the peak achievable flow rate, in addition to attracting further pressure losses at the pile toe.

4 RESULTS

The discussion of results will be split into sections to discuss the success of the water injection system and pile installation information.

4.1 Water injection system

The novel water injection system proved to be successful. The feeder pressure from the mains water supply provided a relatively steady pressure of 200 kPa during testing. The flow rate to the beam was controlled using the manual control tap; a variety of flow rates were possible using this simple control.

Multiple flow rates were essential in order to calibrate the loss factors in the pipe between the measurement point and the pile toe. Increased confidence in the calculation could be achieved if more unique flow rates were tested. Figure 4 shows a plot of the data points used to find the loss factors for four different nozzle sizes.

On comparing these flow test results, the effect of changing the nozzle becomes immediately apparent. As predicted, the smallest nozzle attracts the largest pressure losses; denoted by the steeper gradient lines of best fit in the figure. This is a similar result as monitoring the pressure loss from small orifice plates blocking flow through a pipe and highlights how the loss factors are dominated by the nozzle used.

With the larger nozzle sizes, larger flow rates were achievable with smaller losses. There is little to no difference between the 2.5 mm and the 3.0 mm diameter nozzles due to their similar size to the feeder pipe. The 2.5 mm nozzle acts as a continuation of the feeder pipe, and the 3.0mm nozzle effectively reduces the sharpness of the pipe exit; both have little effect on the pressure loss.

4.2 Maintaining balance

The standpipe system maintained the balance of the centrifuge. As shown in Fig 5, the pressure of the standpipe remains constant throughout the flight plotted. The two dotted lines for the standpipe PPT represent brief periods where the instrument failed during the test.

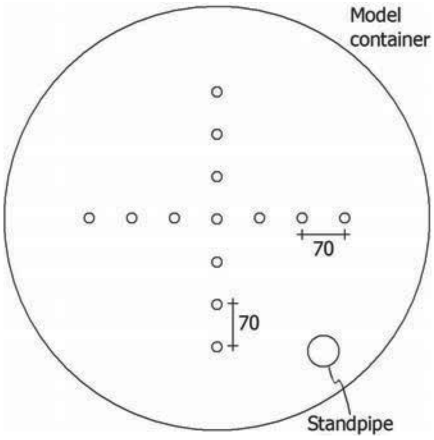

Figure 3. Typical pile layout in a single test week. At least four flights are completed at 140 mm pile spacing in each flight.

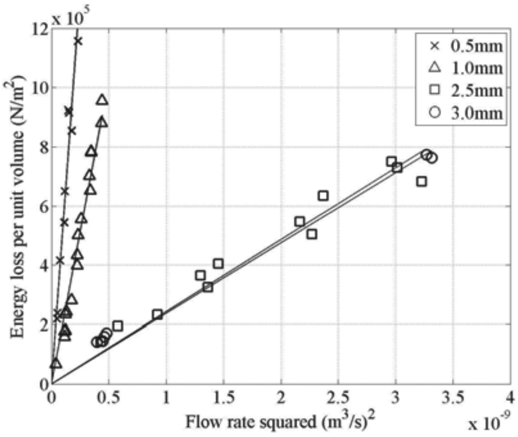

Figure 4. Energy loss per unit volume of water passing between the pressure line and the termination nozzle. All lines of best fit shown have a correlation R^2 value greater than 0.94. The smallest diameter nozzle attracted the largest loss, as expected. The 2.5 mm and 3.0 mm nozzles attracted the same loss due to their relative size to the feeder pipe.

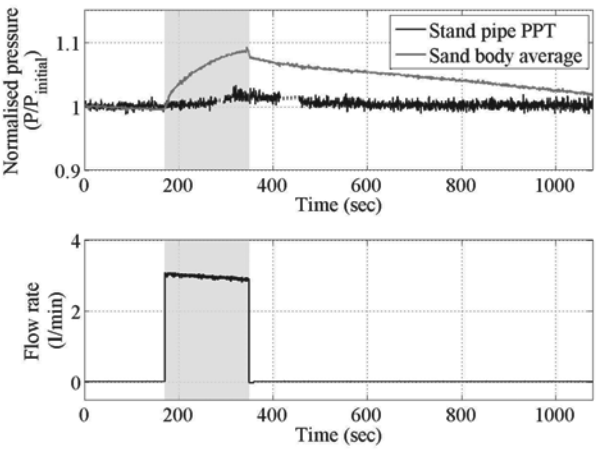

Figure 5. Illustration of a water injection event and subsequent model drainage. Water is added to the model at around 3 litres per minute for nearly 200 seconds (highlighted by the shaded region). This causes the sand body to fill with water, represented by the increase in the normalised pressure. Meanwhile, the stand pipe water level remains constant and the pressure unchanged. (A dotted line represents a brief period where the instrument failed.)

During an injection event, a small difference is evident in the system. This is indicated by the increase in the sand body water pressure during the injection phase. A small pressure difference between the sand body and the standpipe arises, driving water flow into the standpipe. Any additional water in the standpipe drains away through the drainage holes at the top of the standpipe.

The base pressure of the standpipe remains constant throughout the process, showing that the standpipe maintains a constant water height, as designed. With time, the pressure difference between the standpipe and the sand body reduces. This will slow the rate of drainage through the standpipe, until the pressures become equal and no excess water is present in the model after a time greater than 1100 seconds.

4.3 *Installation load results*

Multiple centrifuge tests were completed on identical sand bodies. The sand bodies were tested for their continuity via a control installation, without water injection. This was effectively a penetration test and gave a reference to compare the water injection aided installations to. There was good agreement between the different control installations over the multiple sand bodies used.

Figure 6 shows some installation data. The pile head loads for three installations are shown – a control installation and two water injection installations, one using a 1.0 mm diameter nozzle and the other a 3.0 mm diameter nozzle. In addition, the model flow rate is plotted, to show the link between the delivered flow rate and reduction in load when compared to the control installation.

Initially, load is generated in all installations as all piles are installed to a depth of $2D_p$ without the aid of water injection. At this depth, the water supply to the pile is activated and the load reduces to zero. The flow rate is allowed to stabilise at this level as the pile installation continues.

The difference between the two nozzles is apparent, with the smaller nozzle allowing a smaller peak flow rate to be pushed through the pile. Despite a significant flow rate of 1.3 litres per minute, there is little reduction in the pile load. The maximum load reduction is experienced at the shallower depths, where the load can be reduced to zero. Load reduction then diminishes with depth as the pressure at the pile toe becomes closer to the hydrostatic pressure in the sand body.

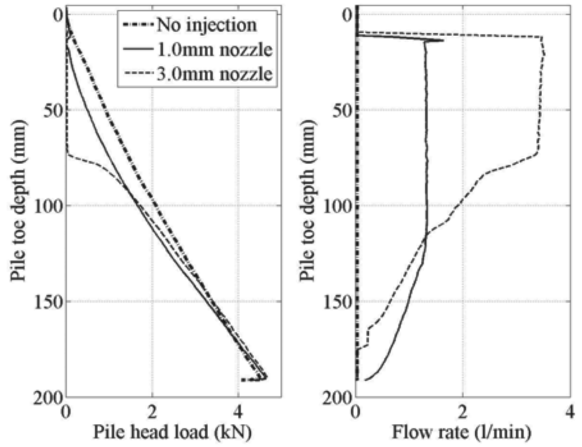

Figure 6. Comparison of effects of nozzles. Diameters 1.0 and 3.0 mm nozzles are compared with the no injection installation. The flow rate delivered to the pile is displayed for all installations in the right plot.

5 CONCLUSION

A water injection system has been successfully developed and tested on the centrifuge at University of Cambridge. Peak pressures of 1.2MPa and peak flow rates of 3.5 litres per minute were delivered to the model pile. The system has been tested to find the energy loss in the pipe line, with the aim of calculating the toe pressure during an installation.

To maintain centrifuge balance during high flow rate events, a standpipe system was developed and its performance closely monitored. This proved successful for the duration of testing.

In addition, the system has been used to complete multiple installations of water injection aided jacked piles. Different nozzles were tested during the experimental program to investigate their different effects. Whilst the effect of injection reduces with depth, it was discovered that the larger nozzles were the most effective at reducing installation loads.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

Gaudin C., Bienen B. and Cassidy M.J., 2011. Investigation of the potential of bottom water jetting to ease spudcan extraction in soft clay. *Geotechnique*, 61(12) 1043-1054.

Goh T., Shiomi T., Yamamoto M., Ikeda T. and Motoyama M. 2004. A solution for road construction. In *6th Malaysian road conference*, Kuala Lumpur.

Goforth G.F., Townsend F.C. and Bloomquist D. 1991. Saturated and unsaturated fluid flow in a centrifuge. In *Centrifuge in soil mechanics*, 497-502, Ko and McLean.

Haigh S.K., Houghton N.E., Lam S.Y., Li Z. and Wallbridge P.J. 2010. Development of a 2D servo-actuator for novel centrifuge modelling. In *7th international conference on physical modelling in geotechnics*, 239-244, Zurich.

Schneider J.A., Lehane B.M. and Gaudin C. 2008. Centrifuge examination of pile jetting in sand. In *2nd IPA workshop*, 17-24 New Orleans.

Tomlinson M. and Woodward J. 2008. *Pile design and construction*. Taylor & Francis, London

Tsinker G.P. 1988. Pile jetting. *Journal of geotechnical engineering* 114(3), 326-334.

White D.J., Sidhu H.K., Finlay, T.C.R., Bolton M.D. and Nagayama T. 2000. The influence of plugging on driveability. In *8th international conference of the deep foundations institute*, 299-310. New York.