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Centrifuge testing of a silent piling concept using the push-in method

C. Davidson, Y.U. Sharif, M.J. Brown, S. Robinson
University of Dundee, Dundee, United Kingdom, csdavidson@dundee.ac.uk

B. Cerfontaine
University of Southampton, Southampton, United Kingdom

M. Ottolini, W. Sonnema
Heerema Marine Contractors, Leiden, Netherlands

M. Huisman
bp, Utrecht, Netherlands(bp did not participate in this research)

ABSTRACT: Regulations and concern regarding noise and air pollution during offshore foundation installation operations has led to increased interest in the development of alternative foundation solutions. An extensive series of centrifuge testing has been conducted at the University of Dundee, in partnership with Heerema Marine Contractors, to develop a silent piling concept using push-in-piles. This approach uses a cluster of four smaller diameter open-ended piles to replace a single larger diameter pile. Instead of using an impact hammer to install the piles, which generates high levels of noise and requires costly and potentially polluting noise mitigation measures (e.g., bubble curtains), each pile is pushed into the soil in turn using a sequence of strokes while the others provide the necessary reaction force. This paper details the development of the novel centrifuge testing equipment, including the implementation of digital sensors for continuous measurement of the internal soil plug, and results of the testing programme which demonstrate the installation requirements of the pile groups in sandy soil.

1 INTRODUCTION

The noise emitted into the environment by the numerous offshore construction activities has been recognised as being harmful to marine life (Bailey et al., 2010). Regulations and guidance define noise emission limits and require efforts to mitigate noise levels (Müller and Zerbs, 2013, Danish Energy Agency, 2022). Measures to reduce the noise from operations like pile driving include bubble curtains, real-time efficiency controls with underwater monitoring or large physical barriers. Such efforts may be costly and, in the case of bubble curtains, require fossil-fuel powered equipment adding to CO_2 emissions of the project (Cerfontaine et al., 2021).

Impact free push-in or jacked piling methods do not generate significant levels of noise and are an attractive alternative to hammered piles. To provide the large reaction forces necessary for the push-in method, a group of four smaller diameter piles has been proposed as a replacement for a single larger pile. Conceptually, the piles are jacked individually in a sequence with three of the four piles providing the reaction force required to push one pile at a time. Cerfontaine et al. (2021) reported on discrete element modelling of this method and gives further information on the concept. This paper is intended to detail the actuator, control system, and sensor technologies used in the centrifuge modelling.

2 CENTRIFUGE TESTING METHODOLGY

Replication of field scale stresses were deemed important in studying the performance of the push-in-pile concept, ensuring interactions between piles in the group and the soil were modelled correctly. Centrifuge modelling techniques were employed for these investigations. This section details development of the actuator, associated control and data acquisition (DAQ) systems and testing methods.

2.1 Actuator design and development

A custom-built actuator was designed and fabricated by Heerema Marine Contractors (HMC) for use in the University of Dundee (UoD) centrifuge. The actuator or "rig", pictured in Figure 1 mounted to the model container on the centrifuge, consists of four independent vertical axes driven by four servomotors situated at each corner of the rig such that the four piles are arranged in a square configuration at the centre of the rig. This is illustrated in the horizontal cross-section through the actuator shown in Figure 2.

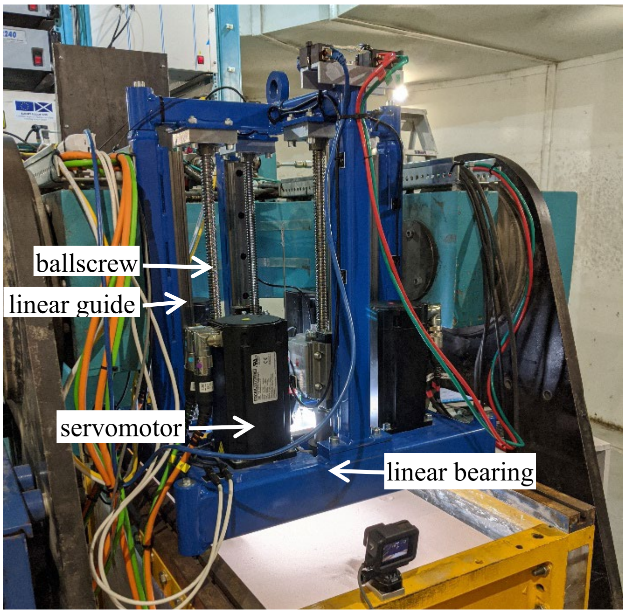

Figure 1. Four-axis push-in-pile actuator mounted on model container and installed on the UoD centrifuge.

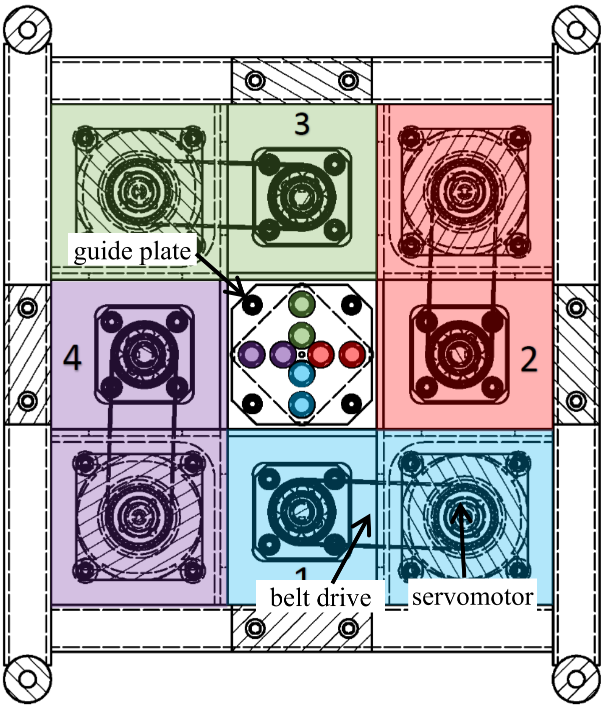

Figure 2. Cross-section through base of actuator showing axis and pile configuration and numbering. Note multiple potential spacings of the pile group in central guide plate.

A belt drive with a 1:1 gear ratio linked each Kollmorgen AKM54H-ANCNC-00 servomotor to a ball screw rod, to which a linear bearing was attached via a ball screw nut. In turn, this was mounted to a linear guide rail which provided a rigid and smooth axis for the bearing. The working limit of each axis was 10kN for compressive and tensile loading. A pinned connection between the pile cap and two plates was used to mount the piles to the drive system. This allowed for different pile group spacings by moving the pins between predefined holes in the mounting plates (Figure 3). Finally, the piles passed through a guide plate with different centre-to-centre hole spacings, of either 1.5 or 4 times the pile diameter (D), mounted in the base of the actuator (Figure 2 and 3). Bronze bushes minimised friction between the guide plate and piles.

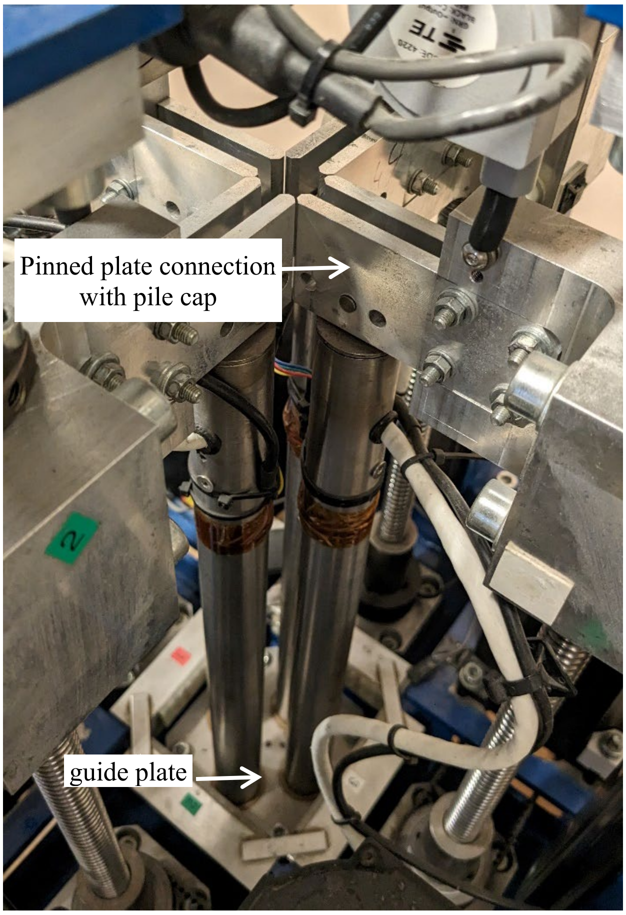

Figure 3. Instrumented piles passing through guide plate at 1.5D spacing.

Four Kollmorgen AKD-P00606-NBCC-E000 servo drives provided power and feedback for the servomotors. The drives interfaced into the control system via the Kollmorgen Ethercat protocol.

The control and data acquisition system was founded on a National Instruments CompactRIO

9047 real-time controller mounted in the central cabinet of the centrifuge. NI9202 and NI9264 C-series modules provided the data acquisition and voltage supply capabilities respectively. LabVIEW 2018.1 software was used for actuator control and the reading and logging of the measured data at 250Hz. The cRIO was programmed in hybrid mode to utilise both FPGA and scan engine capabilities.

2.2 Instrumentation

The principle aim of the test programme was to ascertain the installation loading requirements of the pile group, potential refusal depths of the push-in sequence, measure the axial load capacity of the group and in continuously monitor the development and behaviour of any internal pile plugging.

Figure 3 shows the pairs of HBM XY71-3/350 strain gauges on each pile with their Kapton tape protection, configured in a full Wheatstone bridge arrangement. This approach provided a robust and sensitive solution to measuring the individual axial force on each pile head, with compensation for any bending or temperature effects. All strain gauges were powered with a 9V supply, with equal length cables, minimising any resistance imbalance within each strain gauge sensor and between the four piles.

To calculate the force acting on the pile from the output voltages measured from the strain gauges, the properties in Table 1 were assumed/measured and applied to equation 1. A full load-based calibration of the strain gauges up to the theoretical axial capacity of the piles was not conducted due to the possibility of damaging the piles during the process. However, a relatively low axial load of 1kN was applied to one of the piles with an Instron 5985 Universal Testing Machine to confirm the accuracy of the output from equation 1 (Hoffmann, 1989) with the selected parameters in Table 1.

*Table 1. Properties required for calculating force from strain gauge output voltage. *Assumed parameter value.*

Parameter	Value
Gauge factor (GF)	2.06
Pile inner diameter	28.0mm
Pile outer diameter	30.6mm
Pile cross-sectional area (A)	119.6mm2
Young's Modulus* (E)	205 000N/mm2
Poisson's Ratio* (μ)	0.3
Supply Voltage (Vs)	9V

$$F = \left(V_o - V_{ref}\right)\frac{2}{V_s}\frac{1}{GF(1+\mu)}EA \qquad (1)$$

Where F is the measured axial force (N), V_o is the output voltage from the strain gauges, V_{ref} is the reference voltage at zero load, V_s is the supply voltage, GF the gauge factor of the strain gauge, μ the Poisson's ratio of steel, E the Young's Modulus of steel, A is the cross-sectional area of the pile.

Displacement of the piles was measured individually using analogue Micro-Epsilon WDS-750-P60 draw wire transducers (DWT) with a 750 mm range mounted to the top of the actuator using a 3D printed attachment. These four DWTs directly measured the displacement of the pile at the pile head connection to the actuator.

Continuous measurement of the height of soil inside each pile was essential to correctly interpret and understand the observed behaviour of the pile group. Several methods and technologies were investigated and trialled during the testing to develop a robust and accurate measurement method. Firstly, a 150mm stroke linear voltage displacement transducer (LVDT) (Burster 8709) was installed inside one of the piles to try and continuously measure the plug height during the test. A plastic pad was added to the LVDT tip to reduce the pressure, but even with this, the presence of the LVDT resting on the sand surface appeared to influence the plug formation and tests with the LVDT instrumented pile were limited.

Infrared (Sharp GP2Y0E02A) and ultrasonic (Maxbotix MB1043 HRLV-EZ4 similar to Garcia Galindo et al. (2018) distance measurement sensors were also unsuccessfully trialled. These analogue voltage output sensors, secured in the piles with a 3D printed holder, both gave inconsistent readings when tested with the piles embedded in sand. This was attributed to reflections from the internal surface of the pile and the varying reflectivity of the sand surface.

After further research, digital laser-based time-of-flight sensor technology was trialled and found to reliably measure the height of sand inside the pile with millimetre resolution. VL53L1X sensors made by ST Microelectronics mounted on a Pololu development board were sourced and developed for measuring the plug length. The VL53L1X sensor measures the time-of-flight of pulses of a 940nm class 1 laser (eye safe) to measure distances independently of ambient lighting and surface characteristics of the target. The sensor has a configurable region of interest on the detector which can be used to reduce the field of view. These features of the sensor were ideal for use in the relatively small diameter piles to measure the distance to the sand surface with no ambient lighting. The measured values were checked by moving a sand coated plug inside the pile by a known distance.

The VL53L1X sensor uses I^2C digital communication protocols. An Arduino Uno R3 micro-controller, mounted on the push-in rig, was used to interface between the sensors and the centrifuge on-board CompactRIO (cRIO) DAQ. The code to operate and read the sensors was written using Arduino software with the serial output from the Arduino read by the cRIO via a USB connection. Figure 4 shows the plug measurement system.

Digital communication of the type used in the VL53L1X sensors is designed to work over short distances (e.g., across a printed circuit board). This meant a booster was required to transmit the signals over the ~4m distance between the sensors and the CompactRIO. An Adafruit LTC4311 I_2C extender was installed next to the VL53L1X sensor to boost the signal from the sensor to the Arduino.

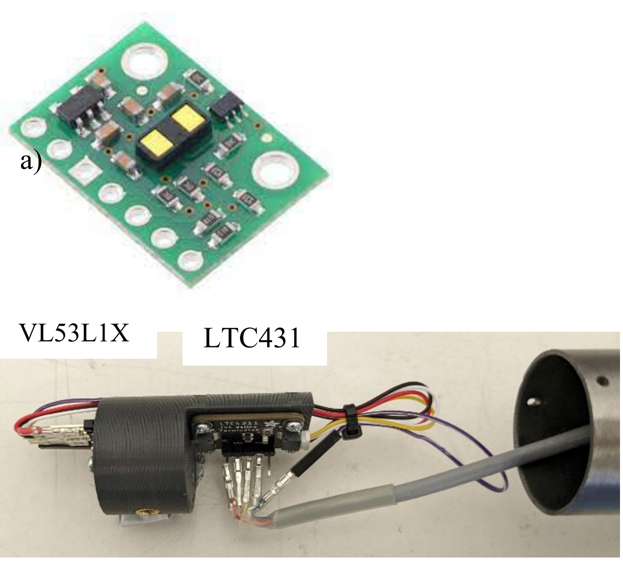

Figure 4. a) VL531X time-of-flight distance sensor. b) distance sensor (VL53L1X) and signal booster (LTC4311) mounted ready to install inside the model pile.

2.3 Sand properties and preparation

Table 2. HST95 sand properties (Lauder, 2010, Al-Defae et al., 2013).

Property	Value
Effective particle size, D_{10} (mm)	0.09
Average particle size, D_{50} (mm)	0.14
Critical state friction angle, ϕ'_{crit} (°)	32
Angle of dilation* at $D_r = 60\%$, ψ (°)	11.2
Peak friction angle* at $D_r = 60\%$, ϕ'_{pk} (°)	41
Maximum dry density, ρ_{max} (kN/m^3)	17.58
Minimum dry density, ρ_{min} (kN/m^3)	14.59

**Inferred from best-fit relationship from direct shear tests at effective stresses of 50-200kPa and critical state friction angle at 60% relative density (Al-Defae et al., 2013).*

Dry HST95 sand with properties shown in Table 2 (Lauder, 2010, Al-Defae et al., 2013, Jeffrey et al., 2016) was used in all tests. The sand beds were prepared using the air-pluviation method with a slot pluviator to a relative density of 72% at a depth of 460mm into a model container 500mm wide, 800mm long and 550mm deep. A single test was performed in the centre of each box.

2.4 Model piles and scaling laws

The 540mm long steel model piles with outer and internal diameters of 30.6 and 28mm were spaced at 1.5 times their diameter for the test reported.

Dry sand testing is significantly faster, more cost effective and has been demonstrated to provide the same results as saturated tests under drained conditions (Li et al., 2010). All tests were conducted at an acceleration level of 37.1g at 125mm below the dry sand surface which provided an equivalent saturated scaling factor of 1/50. The prototype dimensions of the model pile were therefore 1.53m *OD*, 1.4m ID. A target penetration depth of 250mm or 12.5m was dictated by the available stroke length of the instrumented piles installed in the actuator.

2.5 Push-in-pile installation sequencing

The push-in-pile concept utilises the axial resistance from three of the four piles in the group to provide a portion of the reaction force for the remaining pile to be pushed, or jacked, into the soil. Additional reaction load is provided by the weight of the driving tool. By pushing each pile in turn through a prescribed sequence, the pile group can advance into the soil. The sequence in which the piles were pushed is illustrated in Figure 5 in terms of the force acting on each pile with time through the whole installation cycle. Five distinct phases of loading made up each installation cycle which was designed to install the pile group by 0.5m. The phased installation started after an initial penetration, or stabbing, of the piles to a combined compressive load on the pile group equal to the assumed tool-weight of 20MN.

Phase 1 of the installation sequence saw Pile 1 installed by a prescribed displacement-controlled distance of 0.5m. During this period, the measured load from Pile 1 was subtracted from the tool weight and the resulting load divided by three. Using individual PID feedback control, this load was then applied to Piles 2, 3 and 4 using a velocity-controlled motion. In this way, the behaviour of the prototype tool is realistically simulated, and the piles behave in the correct manner. This method of loading and control is then applied to Piles 3, 2 and 4. The piles were installed in this sequence to minimize the effect of increased soil stress from the installation of the previous pile affecting the pile being installed.

The final phase of the installation cycle is to return the load on each of the four piles to one quarter of the tool weight, again by using the velocity-controlled force feedback system.

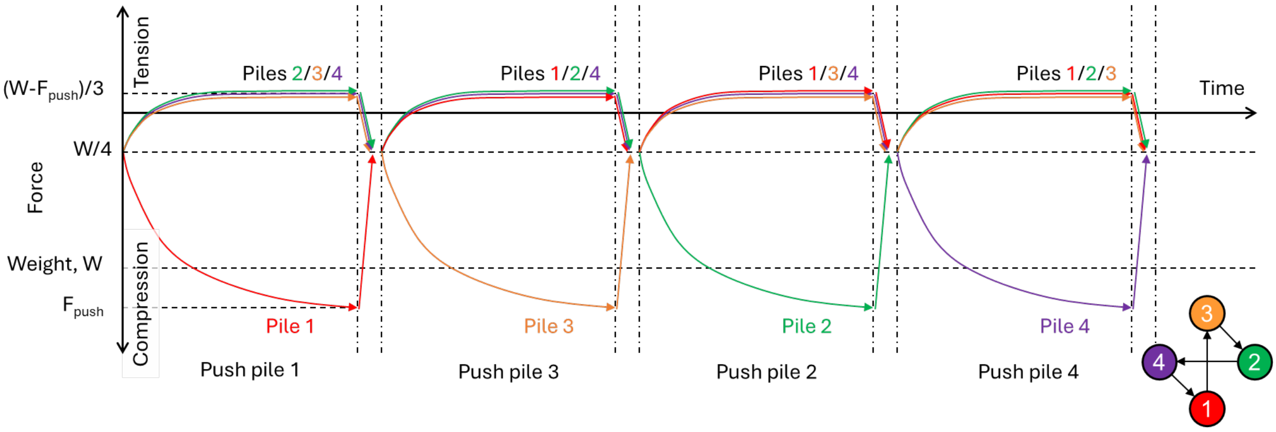

Figure 5. Force-time behaviour of piles during a push-in installation cycle.

3 RESULTS AND DISCUSSION

Data from the installation of the pile group spaced at 1.5D in dense sand are presented at prototype scale and demonstrate the performance of the testing system and the push-in-pile concept. Figure 6 shows the installation force from surface to the target depth of 12m for each pile separately and for the group/cluster. Note that tensile loads are positive and compressive loads are negative in this figure. The data shows the push-in-pile concept can install the-pile group to the target depth in dense sand. Implementation of this method would provide a silent pile installation technique, overcoming regulations on noise emissions and reducing costs by omitting costly mitigations.

The pile group was initially penetrated to a depth of 2.93m under displacement control where the load on the group was approximately equal to the 20MN tool weight. Following this, the push-in installation cycles were commenced. The total load of the group was, on average, maintained at the 20MN tool weight. While the pile being pushed in was experiencing a compressive load, the other three piles were loaded with the relevant reaction force. Until the eighth cycle, the reaction loads were still a net compressive force; in that situation, the installation resistance of the penetrating pile is less than the superimposed weight. However, after the eighth cycle, the reaction forces moved into net tensile loading to a maximum of 6.3MN at the final cycle where the pile being pushed in experienced compressive loading of almost -39MN.

The length of the sand column inside the piles, as measured from the pile tip, was measured continuously during the installation of the piles (Figure 7). For reference, the unity line shown represents the condition in which no plugging of the sand occurred, i.e., the pile would be considered as coring.

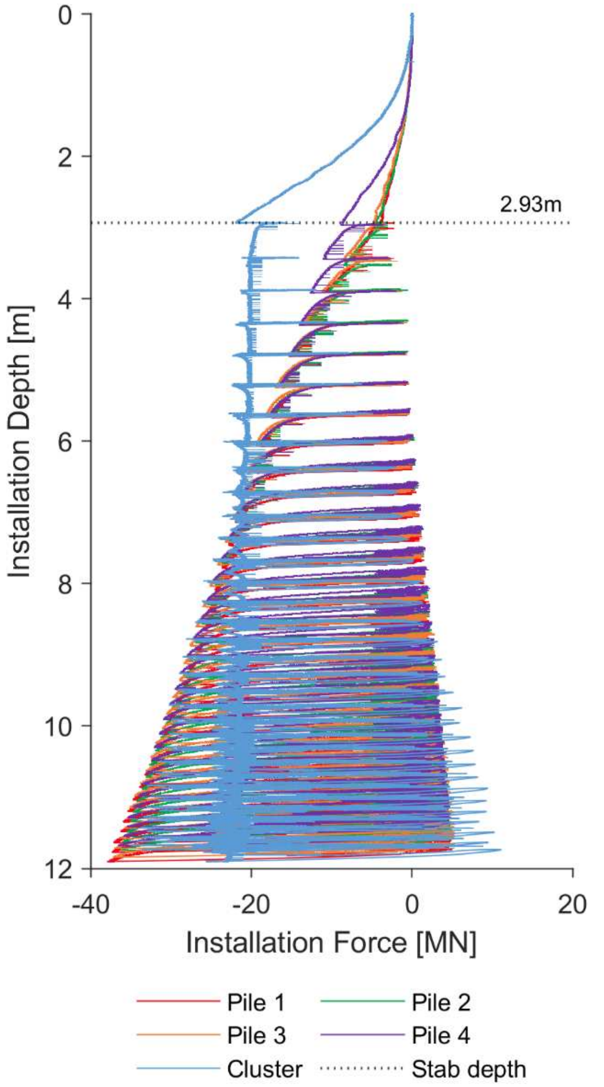

Figure 6. Installation force versus depth of pile group. Note compressive loads have negative values.

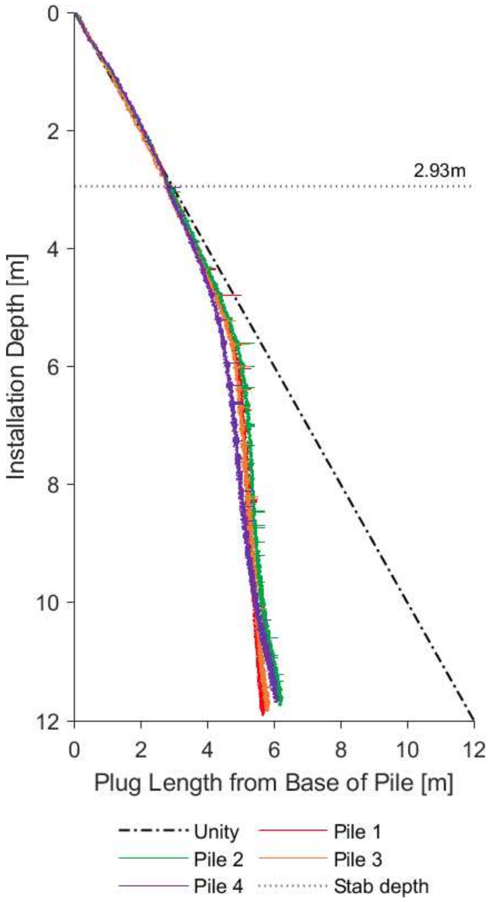

Figure 7. Plug length (height from pile tip) data.

Figure 7 demonstrates that this condition occurred during the stabbing phase to 2.9m. During the push-in sequence, the height of sand inside all piles does not increase in line with the pile depths, and they begin to plug. From 5.5m depth there is a distinct change in gradient of the plug length versus depth data in Figure 7 for all piles. From this point to the final depth of 12m, the plug lengths of all piles only increase by 1m for piles 2 and 4 and 0.5m for piles 1 and 4.

Further centrifuge testing is being done to investigate mitigation measures suitable in a field setting to control the formation of soil plugs. Preventing the plug formation entirely is not considered beneficial to the push-in process. The additional stress generated in the soil from pushing a plugged versus a coring pile is likely to create greater shaft resistance on the piles which are providing the reaction force to the pile being pushed in. Consequentially, the performance of the system and the overall depth of penetration may be improved.

4 CONCLUSIONS

The installation of a pile group using the push-in method can provide a silent alternative to hammer driven piles, reducing the environmental impact, associated risks, operational effort, and cost of offshore foundation operations.

Centrifuge testing investigating the performance of the push-in concept required design, development, and fabrication of a custom actuator. The four-axis actuator developed by Heerema Marine Contractors and the University of Dundee used servomotors and a National Instruments control system to effectively simulate the push-in concept of the pile group.

Instrumentation of the individual piles included displacement and axial force measurements. Additionally, digital laser time of flight sensors, located in the pile head, reliably and accurately measured the depth of soil inside each pile to provide essential information on pile plugging behaviour during installation of the pile group. This was demonstrated through presentation of load-displacement and plug length data from a 1/50th scale centrifuge test of the pile group in dense sand.

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