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Experimental apparatus and instrumentation for a centrifuge study on soil plugging during pile installation in clay

P. Wiesenthal, S. Henke
Helmut-Schmidt-University, Hamburg, Germany, p.wiesenthal@hsu-hh.de, s.henke@hsu-hh.de

B. Bienen
The University of Western Australia, Perth, Australia, britta.bienen@uwa.edu.au

ABSTRACT: A study on soil plugging in open-ended piles in normally and over-consolidated clay was carried out to enhance the understanding of mechanisms governing the installation of pipe piles into cohesive soils via jacking, cycling and impact-driving. For this purpose, model piles of different diameters were instrumented with total stress sensors, fibre optics for pore pressure measurement and a time-of-flight laser distance sensor to determine the plug height. One major challenge of optical laser sensors in combination with clays involves the water table above ground level, which can lead to light reflections and erroneous measurements. To address this problem, a lightweight spacer was used to raise the sensor's reference point above the water table. With this configuration, plug heights were successfully recorded in tests performed at 50 g in 500 mm long model piles with inner diameters of 14 mm and larger. This paper presents the experimental apparatus and instrumentation, discusses challenges and solutions, describes settings of the laser distance sensor as well as its calibration procedure and provides exemplary results for jacked piles.

1 INTRODUCTION

Soil plugging in open-ended piles increases pile resistance during and after installation. With plug formation, soil ingress can be reduced or even prevented, which increases pile base resistance and may also affect shaft friction due to soil displacement and increase in effective stresses (Miller and Lutenegger, 1997; White et al., 2005). Compared to non-cohesive soils, soil plugging in clay is rarely investigated and less well understood.

In clays, a pile becomes plugged if the resistance from internal shaft friction exceeds the bearing resistance of the underlying soil (Paikowsky and Whitman, 1990). Inner resistance is a function of skin friction and pipe diameter (Randolph et al., 1991; Wiesenthal and Henke, 2025). Favourable circumstances for plugging are expected for overconsolidated clays and small internal diameters with proportionally high pile length (Miller and Lutenegger, 1997). Shaft friction depends on effective stresses and is therefore significantly influenced by development of excess pore pressure (Bond and Jardine, 1991; Jardine et al., 2005) and therefore by the installation method. Monotonically jacked piles are most prone to plugging (Miller and Lutenegger, 1997; Doherty and Gavin, 2011). In contrast, impact driving introduces inertia forces, which make plugging less likely to occur (Randolph and Gourvenec, 2011; Qin et al., 2023). Vibratory driving leads to soil compaction and reduction of effective radial stresses, resulting in fully unplugged (or coring) mode with the soil potentially rising above ground level (Xu et al., 2006; Henke, 2013).

To the authors' knowledge, no study has yet compared soil plugging in clay for different installation methods such as monotonic, vibratory and impact driving under comparable conditions. A corresponding investigation exists only for sand (Henke and Bienen, 2014). This paper describes the experimental setup of a centrifuge study on soil plugging in normally and overconsolidated kaolin clay, with emphasis on the overconsolidated case. The setup, instrumentation, experimental challenges, and representative results on pile resistance, plug height, total stress, and pore pressure development during monotonic jacking are discussed. A detailed examination of all centrifuge experimental results is beyond the scope of this paper and will be presented in future publications.

2 EXPERIMENTAL SETUP

2.1 Geotechnical centrifuge

Tests were performed in the C72 geotechnical centrifuge at the National Geotechnical Centrifuge Facility (NGCF), Centre for Offshore Foundations

Systems at The University of Western Australia. The C72 has a total radius of 5 m.

Scaling laws after Taylor (1995) were applied: model dimensions were reduced by a factor N relative to the prototype to achieve similar stress conditions. The most pivotal depth for plugging was expected to be around 2/3 of the total pile length. To ensure that the stress state corresponds to the prototype at this depth, the sample was accelerated to 50 g at a depth of 1/3 of the pile embedment depth. Regarding time-dependent effects, the dissipation time in the model was accelerated by a factor of N^2 compared to the prototype, enabling the monitoring of pore pressure equalization after pile installation. For cyclic pile jacking, the amplitude of each displacement cycle is scaled by a factor of N, while the frequency is scaled by a factor of $1/N$ to obtain prototype values. Slight scaling distortions arise due to the centrifugal acceleration with depth. This results in a minor underestimation of stresses in the upper portion of the sample and a slight overestimation in the lower portion. However, given the relatively large centrifugal radius compared to the small sample height, these effects are considered negligible for experiments focused on soil plugging.

2.2 Soil sample

For the samples, a strongbox with side dimensions of 1 m and a filter layer at the bottom was prepared. For the overconsolidated clay, kaolin powder was mixed at a water content of around 210 %. The strongbox was then placed in a consolidation press and a pressure of 400 kPa was applied for three to five weeks. After this duration, a top up was performed by adding a new layer of slurry on top of the consolidated sample reaching the top of the strongbox. Consolidation in the press was then continued as before. In total 4 top ups were added with the last consolidation stress being 500 kPa applied for two weeks. The final soil sample height was around 360 mm. The soil sample was transferred to the centrifuge and spun at 50 g for 18 hours before conducting the first experiments. Above the soil, a constant water level was maintained to avoid drying.

The kaolin clay exhibits a plasticity index of $PI = 30$ % with liquid limit of $w_L = 74$ % and plastic limit of $w_P = 44$ %, and a specific gravity of $G_s = 2.60$ (Reid et al., 2024). Distributions of water content and void ratio for the overconsolidated sample, obtained from coring, are depicted in Figure 1. Coefficients of consolidation. $c_v = 0.33$ mm²/s and $c_h = 2$ mm²/s, were determined from cone penetrometer dissipation tests (Wiesenthal et al., 2026b). The undrained shear strength, obtained from T-bar tests using a bearing capacity factor of $N_{kt} = 10.5$ (Martin and Randolph, 2006) is presented in Figure 2. The T-bars were jacked at a rate of 1 mm/s. Over the course of testing, the undrained shear strength decreased due to swelling. T-bar 5 and T-bar 6 were performed two and three days after T-bar 4, respectively. To account for the temporal decrease in shear strength, multiple T-bar tests were performed throughout the testing period, and tests used for comparative analysis were performed in close temporal proximity.

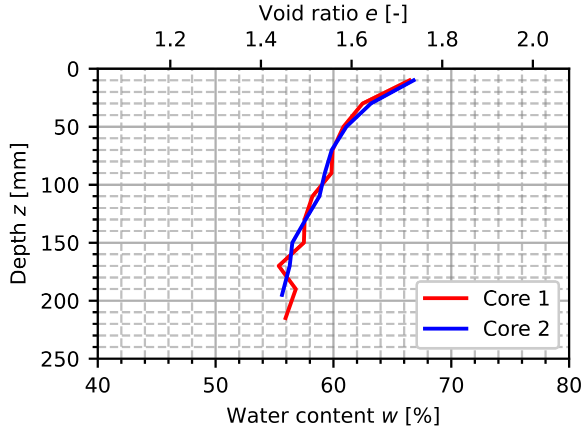

Figure 1. Water content and void ratio.

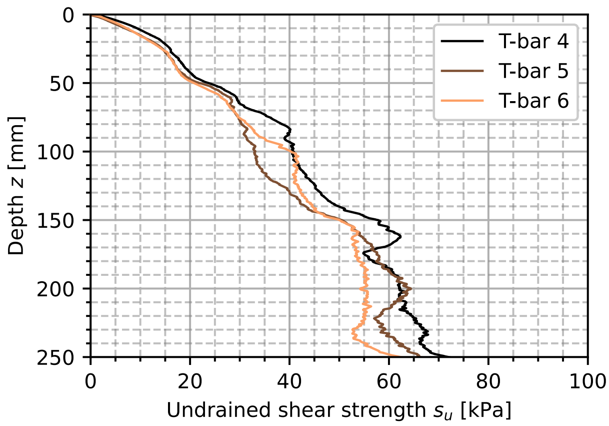

Figure 2. Undrained shear strength from T-bars.

2.3 Model piles

Three model piles were manufactured from aluminium pipes with lengths of 500 mm, a wall thickness of 3 mm and an outer diameter of 20 mm, 25 mm and 30 mm. Dimensions are displayed in Figure 3. The piles were connected to a load cell (section 3), equipped with a laser distance sensor (section 4) and pressure sensors (section 5).

2.4 Pile installation

A 2D actuator was mounted onto the strongbox. Horizontal movements allow for change of location in-flight, while vertical movements enable jacking of T-bars, CPTs and model piles with a maximum velocity in vertical direction of 10 mm/s. Besides monotonic jacking, vibratory driving idealised through cyclic jacking as well as impact driving were considered. For cyclic jacking, a constant downward velocity of 0.3 mm/s was applied, superimposed with sinusoidal cyclic movements. Due to the maximum velocity limitation, the sinusoidal motion was defined with a frequency of 2 Hz and a displacement amplitude of 0.5 mm. Pile impact driving was performed after initial self-weight penetration, as the pile was not firmly attached to the actuator as during jacked installation. A 184 g mass was repeatedly dropped from a falling height of 13 mm until final penetration depth was reached. In this paper, results from monotonic jacking with a velocity of 0.3 mm/s are discussed. Further results on installation techniques are presented in Wiesenthal et al. (2026a), while the influence of penetration rate during monotonic jacking is discussed in Wiesenthal et al. (2026b).

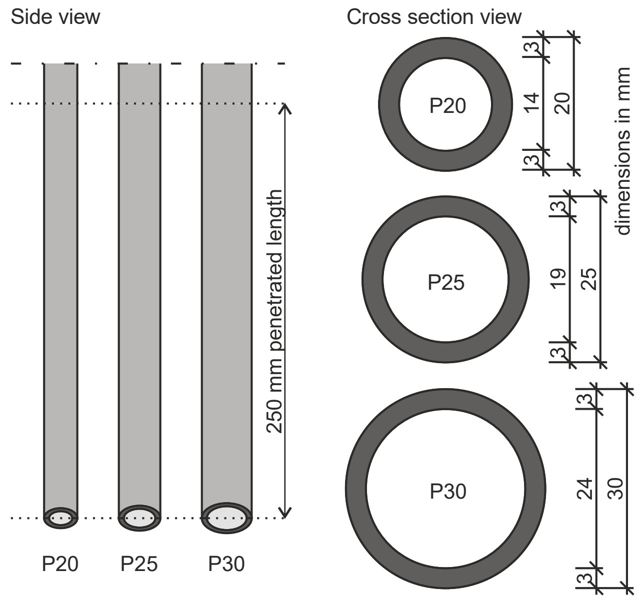

Figure 3. Schematic overview of model piles.

3 PILE RESISTANCE

The piles were attached to a load cell for determining pile resistance during and after installation. The load cell was initially calibrated at 1 g. To account for effects of higher accelerations due to the increased distance of the load cell and pile from the centrifuge's centre and for buoyancy of water acting on the pile, all model piles were jacked into water at 50 g. For each pile, a depth-dependent offset factor was determined based on the observed changes in resistance. This factor was subsequently applied to calibrate the pile resistance measurements.

Exemplary results for pile resistance during monotonic jacking are displayed in Figure 4. The higher resistance of P20_03 compared to P20_07 is attributed to the decrease of undrained shear strength over time due to swelling, see Figure 2. The shear strength profile of T-bar 4 corresponds to P20_03 and those of T-bar 5 and T-bar 6 correspond to P20_07. This considered, results are well reproducable.

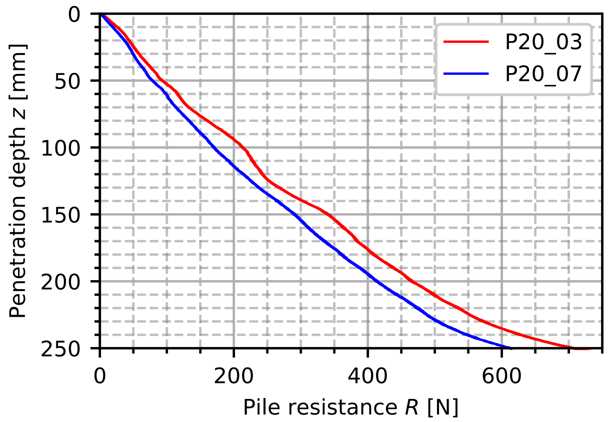

Figure 4. Pile resistance during monotonic jacking for P20.

4 PLUG HEIGHT MEASUREMENT

4.1 Background

Two different methods for determination of plug height during installation were considered. Method a) uses a laser distance sensor, measuring the time required for light to be emitted, reflected by the plug surface and received by the sensor. Method b) uses a pore pressure transducer on top of the soil plug to determine water pressure inside the pile.

The drawback of method b) is that it requires the water level inside the pile to match that outside of the pile. Otherwise, the water level and pore pressures would just be constant due to the low permeability of the clay throughout installation, making any measurements obsolete. To ensure equal water level, holes must be drilled into the pile wall with a maximum vertical distance being less than the water depth around the pile. These holes would have to be small enough to not interact with the clay inside or outside the pile, but also large enough to ensure laminar water flow. Another problem arises from the low bearing capacity of the soil at the surface, which could lead to the sensor being buried inside the clay. Similarly, the cable to the sensor would need to be free inside the pile, which could also cause some additional (excentric) vertical load on the sensor.

Thus, method a) was selected as the preferred option, as no such issues as for method b) were expected. Here, the question was how a time-of-flight sensor can be mounted inside the pile and if the laser signal can travel from the top to the bottom of the pile, which is around 500 mm, and return while not being disturbed by the relatively thin inner diameter of only 14 mm for the smallest pile. The first time a TOF laser distance sensor was successfully installed into an open-ended pile in a geotechnical centrifuge for plug height measurement was by Davidson et al. (2024), which provided confidence in this method to also be successfully implemented in this study.

4.2 Instrumentation

The setup for plug height measurement consists of a time-of-flight laser distance sensor VL53L1X, which was connected to a signal booster (Davidson et al., 2024), see Figure 5. Due to limited space inside the pile, a housing cap was manufactured at the NGCF. The piles are connected to the cap via fittings for larger diameter piles and screws. The laser was emitted from the sensor and travelled through the pile, where it was reflected from the top of the spacer. The height of the spacer was selected to 75 mm to ensure that the reference surface always stayed above the water table.

4.3 Settings

The main challenge for the laser distance sensor was a reliable measurement through a 500 mm long pile only 14 mm in internal diameter. The smooth aluminium surface of the inner pile wall easily reflects light, potentially altering the results and leading to erroneous measurements. Therefore, correct settings were required to obtain reliable results. Two parameters were investigated, namely the region of interest (ROI) controlling the field of view (FoV) of the receiving array and the time budget, while short distance mode was active. The smallest pile P20 was laid on a table and a surface, similar to that of the spacers, was pushed inside the pile. At several points, the surface was held in place for a few seconds to investigate how the readings change over time.

The selected ROI controls the angle over which the laser signal is received by the sensor. A low value relates to a narrow angle. A small study with a time budget of 200 ms is displayed in Figure 6. The best performance was achievied with a ROI of 4x4 (15° FoV), while a ROI of 12x12 and 16x16 (27° FoV) suffers from reflections, giving even negative values for the plug height.

The time budget sets the duration for signals to be considered for a reading. The duration was varied between 33 ms and 200 ms. Due to the previous study, the 4x4 ROI was selected. The results are shown in Figure 7. Displayed is the mean value of the obtained measurements for different plug heights. Apart from the test with 200 ms, results are similar.

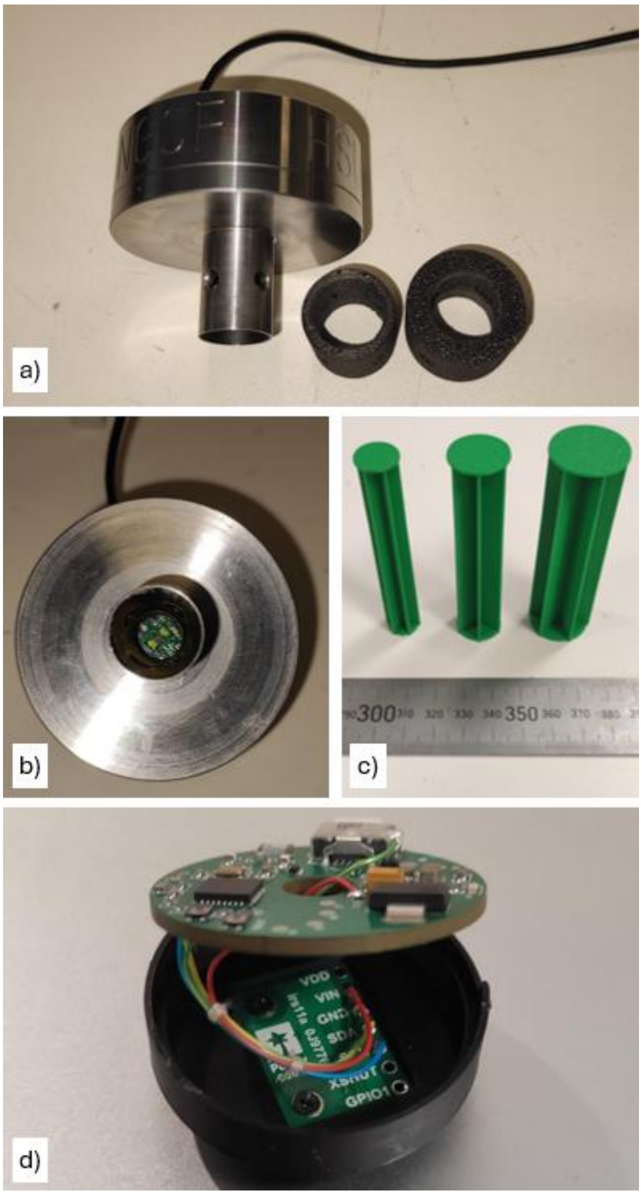

Figure 5. Time-of-flight sensor: a) side view of housing, b) bottom-up view, c) spacers for each pile and d) interior of the instrumentation with signal booster above the sensor's board.

The scatter of sensor readings over time at constant displacement is considered in Figure 8, displaying the coefficient of variation CV. Small values of CV indicate less scatter. The best performances are achieved with 100 ms and 150 ms time budgets.

For the centrifuge study, the setting of short distance mode, 150 ms time budget, 4x4 ROI and 5 Hz for the data acquisition rate were chosen. Tests with all piles at 1 g showed linear relationships between measurement and actual distance.

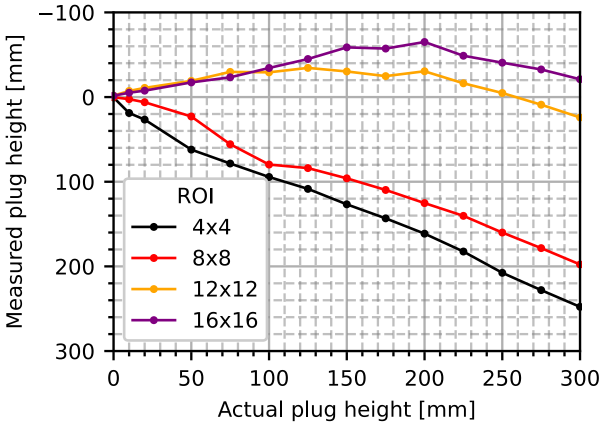

Figure 6. Study on ROI settings with 200 ms time budget for laser distance sensor.

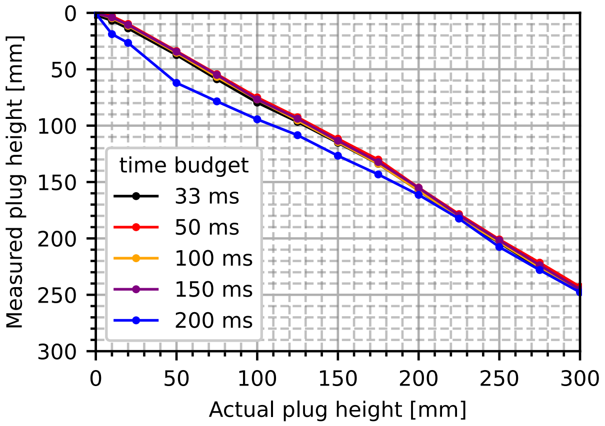

Figure 7. Mean values from study on time budget with 4x4 ROI for laser distance sensor.

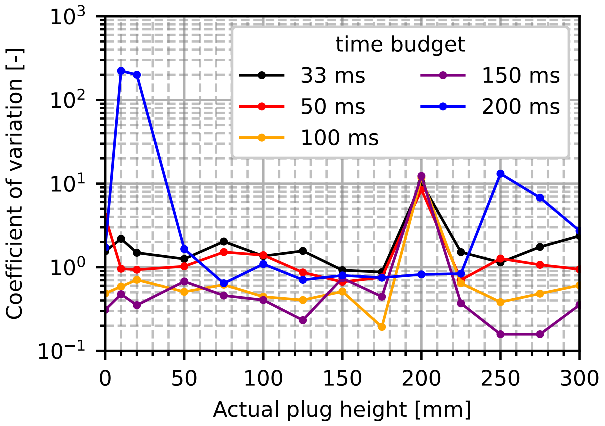

Figure 8. Coefficient of variation from study on time budget with 4x4 ROI for laser distance sensor.

4.4 Calibration

Calibration of the time-of-flight sensor was performed after each test. Prior to installation, upwards and downwards movements at 50 g confirmed the starting location. After testing and pile extraction at 50 g, the final plug position was determined manually at 1 g. The test data indicated that this procedure was adequate for the tests in overconsolidated clay, as the plug remained inside the pile during extraction with negligible changes in plug height. The calibration factor for each test was determined from these two reference points. Additional reference points were not used, as their acquisition would have required spinning down the centrifuge during the test, potentially affecting the results. Moreover, 1 g trials demonstrated a linear sensor response, indicating that further calibration points were not necessary.

For tests in normally consolidated clay, the plug mostly failed to stay inside the pile during extraction, requiring spin down before extraction to manually measure plug height. Another problem was found in the soil's low undrained shear strength at its surface, which made the spacer prone to potential sinking under its own weight.

4.5 Exemplary results

Plug height measurements from two tests with identical setups in overconsolidated clay are shown in Figure 9. The readings from P20_03 exhibit almost no scatter at all, whereas P20_07 shows deviations up to 30 mm. Similar shifts were occasionally observed in 1 g trials and are thought to result from light reflections, which tend to increase for narrower longer piles and can introduce an apparent offset at certain distances. Fortunately, these offsets can easily be corrected. Figure 9 presents both the raw and interpreted plug height curves. Overall, the development of plug height in the two tests is similar, showing fully coring behaviour ($h = z$) at the start, followed by a reduction in soil inflow with increasing depth. The slight differences in plug height at specific depths are likely due to temporal decrease in undrained shear strength and natural variability of the soil. Nevertheless, some uncertainties in the plug height measurements due to the laser system remain.

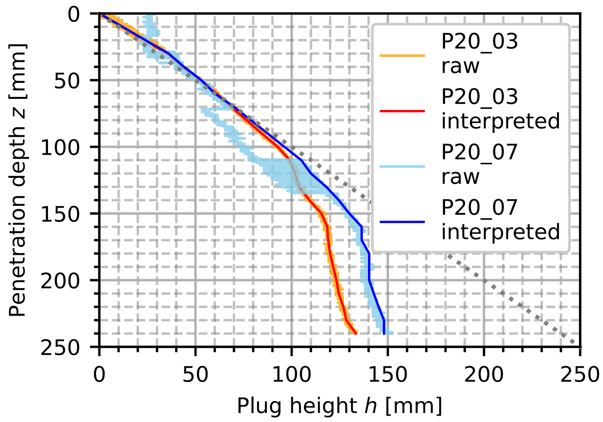

Figure 9. Plug height measurement and idealization.

From the interpreted plug height, the incremental filling ratio IFR as defined in Equation (1) is calculated (Figure 10).

$$IFR = \frac{\Delta h}{\Delta z} \quad (1)$$

Herein, Δh is the change in plug height and Δz the change in penetration depth. To reduce fluctuations, IFR was averaged over depth ranges of 30 mm (label: mean). A general trend of IFR can be identified with a starting value of around 1.2 followed by a nearly linear decrease towards zero with increasing penetration depth. This trend is in good agreement with expectations (Wiesenthal and Henke, 2025), giving confidence in the obtained results.

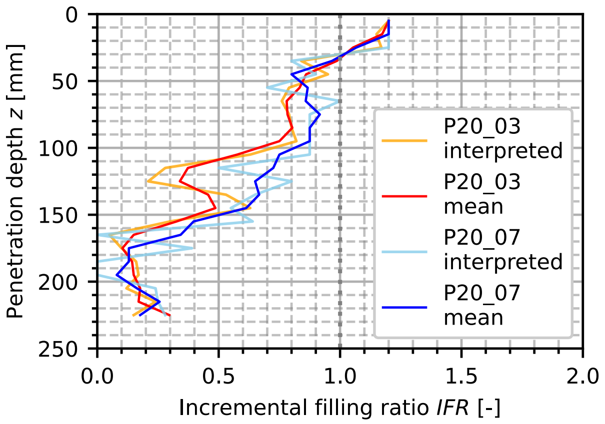

Figure 10. Incremental filling ratio determined from idealized plug height.

5 TOTAL STRESSES AND PORE PRESSURE

5.1 Setup

For total stress transducers and fibre optics for pore pressure measurement three different levels were chosen for sensor placement, see Table 1.

Table 1. Installed sensors.

Level	Distance from pile tip	Internal	External
1	6 mm	Total stress, pore pressure	Total stress, pore pressure
2	56 mm	Total stress	Total stress
3	112 mm		Total stress

For measuring total radial stresses, five Kyowa sensors were installed, of which two were inside the pile at level 1 and level 2, and three sensors were located outside the pile at all 3 levels. The two sensors at level 1 had a measuring range of up to 1000 kPa, while all other sensors had a maximum capacity of 500 kPa. The sensors were placed inside predrilled holes in the pile wall (Figure 11). The sensors and cables were covered with epoxy with the inside of the pile being kept completely clean off any epoxy resin.

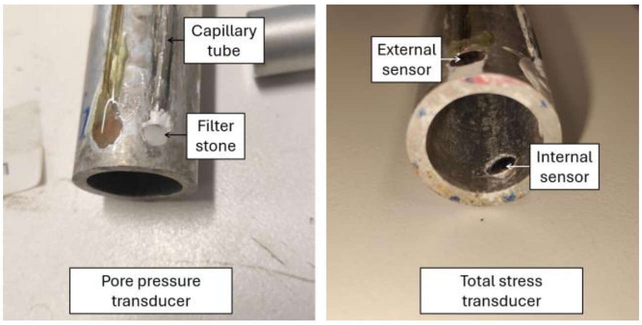

Figure 11. Tip of model pile P20 with sensors.

Two filter stones (Figure 11) made from polyethylene with a porosity of 35 µm were attached inside holes in the pile wall at level 1, of which one was connected to the inside and one was oriented to the outside of the pile. To each filter stone a capillary tube was laid, in which Fabry-Pérot fibre optic pore pressure sensors were plugged (Wiesenthal and Henke, 2024). The maximum capacity of the sensors is 345 kPa. The fibres were fixed at their tip with adhesive to the capillary tube, to prevent water from rising in the tubes, which is an improvement to the setup in Wiesenthal and Henke (2024). To ensure saturation of the filter and the space towards the sensor, as little space as possible was used and all openings were sealed off with epoxy resin.

The setup proved more challenging than initially anticipated. The fibres were prone to breakage during attachment of the filter stones. Further difficulties included achieving a reliable seal, ensuring full sensor saturation, and preventing clogging of the filter stones. Not all of these issues could be avoided during operation. Consequently, many of the pore pressure measurements were identified as unreliable, as indicated by delayed sensor responses and significantly lower recorded pressures during installation. The issues most likely originated from the construction of the measurement assembly, including the capillary tube, fibre optic, and filter stone, as similar behaviour was observed consistently across multiple experiments. It cannot be conclusively determined whether insufficient sealing or incomplete saturation was the primary cause. For future tests, the use of digital pressure transducers with integrated filters therefore is recommended, especially when the aim are pore pressure measurements in clay.

5.2 Exemplary results

Total stress and pore pressure measurements at the outer and inner pile shaft during monotonic jacking in overconsolidated clay are shown in Figure 12 for P20 and in Figure 13 for P30, respectively. In these tests, the pore pressure readings are considered to be realiable, allowing effective stresses to be interpreted and compared, even though measurements were obtained from different pile tests. At both the outer and inner pile shaft, excess pore pressures develop as a result of soil displacement and compression, leading to a reduction in effective stresses. Total stresses are consistently higher inside the pile. Moreover, excess pore pressures within the pile significantly exceed those outside, resulting in comparatively low effective stress levels wihtin the soil plug.

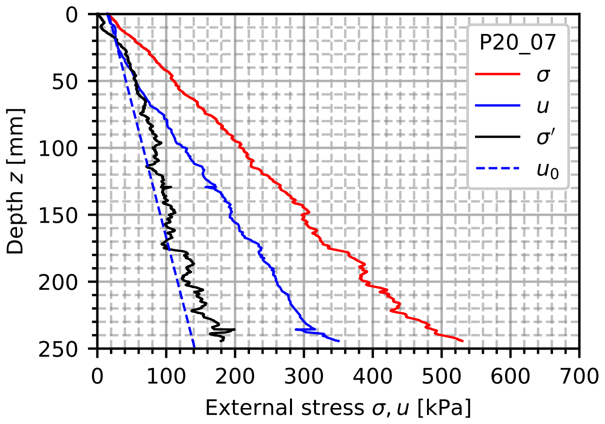

Figure 12. External pressure readings at level 1 during jacking of P20: total stresses σ, pore pressure u, effective stresses σ′ and assumed hydostatic pore pressure u_0.

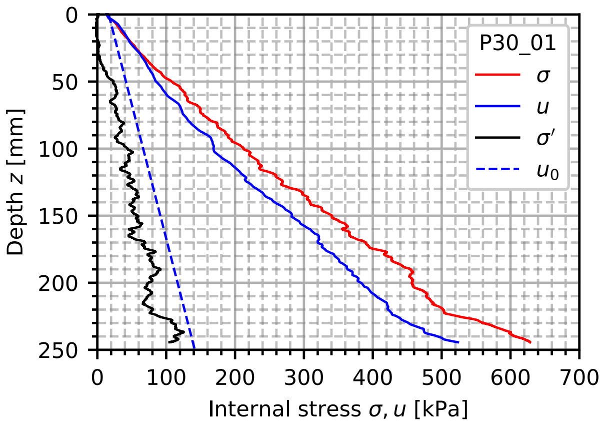

Figure 13. Internal pressure readings at level 1 during jacking of P30: total stresses σ, pore pressure u, effective stresses σ′ and assumed hydostatic pore pressure u_0.

6 CONCLUSIONS

A centrifuge study was conducted to investigate soil plugging in normally and overconsolidated kaolin clay. During and after installation, pile resistance, plug height, radial total stresses and pore pressure at different locations on the pile shaft were measured, giving valuable insights into the plug mechanism in cohesive soils. In overconsolidated kaolin clay, the experiments showed good reproducibility and plug development was successfully captured with the described setup.

During monotonic jacking in overconsolidated clay, the incremental filling ratio exhibited an approximately linear trend until plug height stabilized with further penetration. Excess pore pressures inside the pile exceeded those outside, resulting in relatively low inner shaft friction.

A constant water table was maintained on the soil surface to prevent drying. This initially complicated plug height measurements with a laser, which could be resolved using a 3D printed spacer. The final plug height was verified by manual measurements after pile extraction. Reliable measurements were obtained in overconsolidated clay. However, tests in normally consolidated clay revealed additional challenges, as the plug mostly detached during extraction. This required spin-down for manual measurement before extraction at g-level, resulting in longer operations.

Further improvements are recommended for pore pressure measurements. The employed fibre-optic sensors proved fragile and broke easily. Incomplete saturation and clogging of the filter stones further complicated the measurements, leading to unreliable results.

For future centrifuge studies on open-ended structures, the current setup, including a laser distance sensor for real-time monitoring of soil height, can be applied effectively. Such measurements can provide critical information on soil ingress and plug formation, enhancing the accuracy of experimental data and improving the calibration of numerical models for pile installation.

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