

Impact of installation method on soil plugging in clays

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ABSTRACT: For pile foundations, the type of installation dictates soil displacement around the pile and, in case of open-ended piles, the height of the soil plug inside the pile. The changes in soil state significantly influence the bearing capacity of the pile, but due to lack of insights, in design these installation effects are oftentimes neglected. Soil plugging in clays is of special interest, as a fully plugged pile enforces more soil displacement during installation, which leads to higher radial stresses after equalization but can also disturb highly sensitive clays. This paper aims to portrait impact of the installation method on soil plug development in clay during installation. The investigation features a centrifuge study on over-consolidated kaolin clay as well as numerical simulations using the coupled Eulerian-Lagrangian method. Monotonic jacking as well as vibratory (modelled in the centrifuge as cyclic jacking) and impact driving were considered for the installation procedure. For monotonic jacking a smooth transition from fully coring over partial plugging to fully plugged state can be observed with the incremental filling ratio decreasing continuously. At similar depths where monotonically jacked piles become fully plugged, piles that were cyclically jacked or vibrated remained fully coring with the soil column even reaching above ground level. The required penetration depth to reach partial plugging appears to be much higher than for jacked piles. The behavior of impact driven piles falls between that of monotonically jacked and cyclic jacked or vibrated piles regarding plug development.

KEYWORDS: Clays, soil plugging, piles, centrifuge modelling, numerical modelling, coupled Eulerian-Lagrangian.

1 INTRODUCTION

The resistance of open-ended piles during and after penetration is influenced by formation of a potential soil plug, which can reduce or even prevent further soil ingress. As a consequence, the pile base resistance increases for partially and fully plugged piles compared to fully coring piles. The maximum base resistance is limited by the bearing capacity of the underlying soil, while the plug resistance is the result of inner skin friction. Whether plugging occurs depends on these two components (Paikowsky and Whitman, 1990) and is therefore a phenomenon which can be understood through geomechanical principles (Wiesenthal and Henke, 2025a). The installation in clays is different compared to sands as undrained conditions can be expected and excess pore pressures will affect effective stresses and skin friction. In the past, the influence of the installation method on plug development has been investigated for sands, e.g. Henke and Grabe (2008), while this paper focuses on clays.

Soil plugging in clays is most likely to occur for monotonically jacked piles (Miller and Lutenegeger, 1997; Doherty and Gavin, 2011). Smaller pile diameters and higher over-consolidation ratios increase the tendency towards full plugging (Miller and Lutenegeger, 1997). For impact driven piles, the tendency towards plugging is lowered due to expected inertia effects (Randolph and Gourvenec, 2011; Qin et al., 2023). Vibratory driving induces dynamic effects, friction fatigue and high positive excess pore pressure preventing soil plug formation (Henke, 2013; Xu et al., 2006).

In this paper, soil plug development during installation is investigated. First, experimental tests in a geotechnical centrifuge are examined considering monotonic and cyclic jacking as well as impact driving. Secondly, numerical simulations using the coupled Eulerian-Lagrangian method assuming fully undrained conditions were performed to model quasi-static jacking, vibratory as well as impact driving.

2 CENTRIFUGE TESTING

2.1 Experimental setup

Experimental tests were performed in the 5 m radius beam centrifuge of the National Geotechnical Centrifuge Facility hosted

at the University of Western Australia with accelerations of 50 g applied at 1/3 of the final pile penetration depth to obtain the desired stress level (Taylor, 1995). The clay sample was prepared by mixing kaolin (Reid et al., 2024) at around 210 % moisture content followed by consolidation in a press at up to 500 kPa with four top ups being required to achieve the final sample height of 360 mm. Before any testing was conducted, the soil sample was unloaded, taken out of the press and spun at 50 g to allow the soil to swell. The undrained shear strength profile displayed in Figure 1 was determined from T-bar tests at penetration velocities of 1 mm/s with a bearing capacity factor $N_{kt} = 10.5$ (Martin and Randolph, 2006).

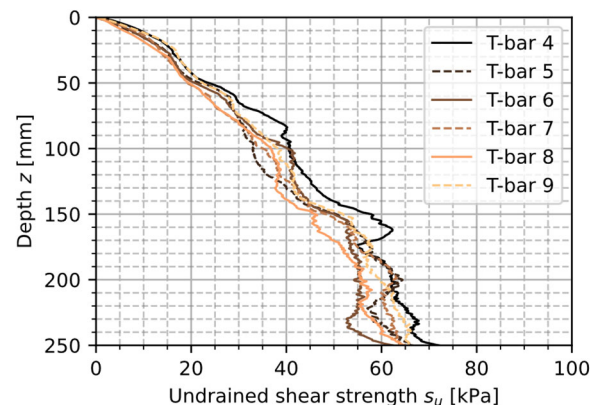


Figure 1. Undrained shear strength profile for kaolin clay used in the centrifuge tests.

Three model piles with outer diameters of 20 mm (P20), 25 mm (P25) and 30 mm (P30) and a wall thickness of 3 mm illustrated in Figure 2 were instrumented with total stress and pore pressure sensors. To capture the plug height during penetration, a time-of-flight (TOF) laser distance sensor was mounted at each pile head, which was inspired by the setup of Davidson et al. (2024). Calibration of the TOF-sensor at 1 g showed good accuracy even for the smallest model pile with an internal diameter of 14 mm and a total length of 500 mm.

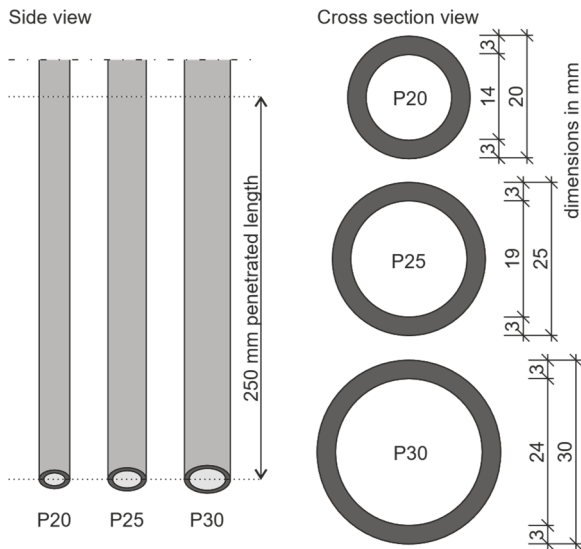


Figure 2. Model piles used in centrifuge study (schematic)

The in-flight installation tests included constant-velocity jacking at 0.3 mm/s, cyclic jacking at 2 Hz with a 0.5 mm amplitude superimposed on the same downward velocity, and impact driving achieving a comparable penetration rate. Although fully undrained conditions were not reached and partial drainage occurred, the results are still considered comparable. As driven piles were not fixed to the actuator, self-weight penetration during spin-up was expected until system stabilization.

2.2 Experimental results

The pile penetration resistance displayed in Figure 3 was captured during displacement-controlled installations (i.e. monotonic and cyclic jacking) using a load cell above the pile head. Pile resistance increases with depth, whereas under cyclic jacking the pile resistance is only 45 % compared to that of the monotonically jacked piles. Due to the rather low employed frequency of 2 Hz, which corresponds to 0.04 Hz at prototype scale, dynamic impacts are expected to be highly underestimated in the experiments compared to vibrated piles under real conditions. The experiments captured destructuring of the over-consolidated clay and excess pore pressure built-up, which are seen as the main causes for the decrease in pile resistance.

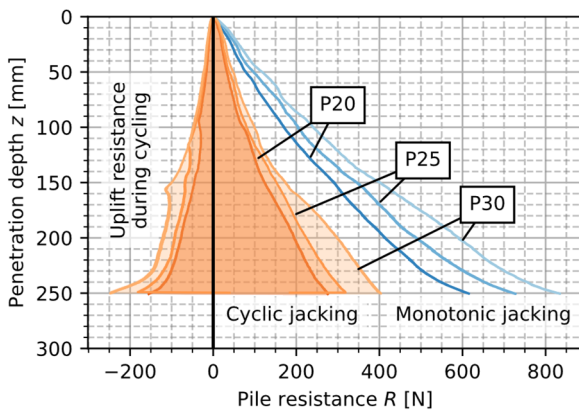


Figure 3. Pile resistance during installation during centrifuge tests.

The results for the plug height over the penetration depth are displayed in Figure 4. The plug heights of the monotonically jacked piles are approximately equivalent to the penetration depth over the first 100 mm. Thereafter, the plug height increase drastically reduces for the smallest pile P20 indicating partial plugging to fully plugged behavior. This transition is delayed for the larger piles which is expected due to the lower L/D

ratio. The cyclically jacked piles show fully coring behavior with plug height being higher than penetration depth, meaning that the soil inside the pile reached above ground level. As expected from their lower L/D ratio, larger piles showed a reduced tendency for plugging. Interestingly, the smallest pile had the largest annular area relative to its total cross-sectional area, which would favor higher plug formation if all displaced soil entered the pile – a scenario that could occur under idealized, frictionless conditions. However, this was clearly not the case.

Due to the self-weight penetration of the driven piles during spin-up, monitoring of the impact driven piles started at a depth around 150 mm. After 50 g was reached, the soil was given sufficient time for stabilization and dissipation of excess pore pressures before driving was started. This also includes the plug inside the pile, which could consolidate and potentially exert higher inner skin friction and lower compressibility. However, the initial plug height is lower than that of the jacked piles at corresponding depths while final plug heights tend to converge with those of monotonically jacked piles. The course for P20 suggests that, if penetration had continued, the plug height from impact driving could exceed that of monotonic jacking

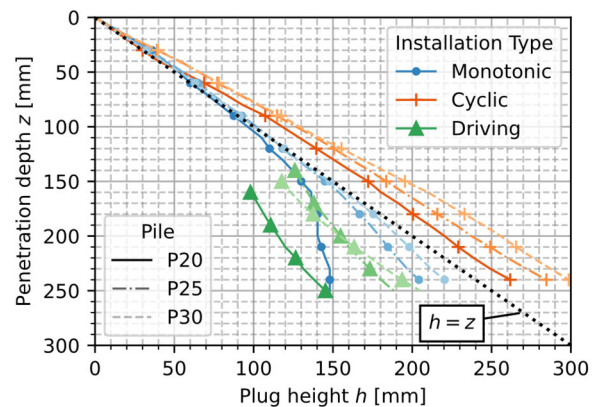


Figure 4. Plug height over penetration depth as result from centrifuge tests.

Figure 5 illustrates the incremental filling ratio IFR , which is the rate of plug height increase Δh over penetration depth Δz . For monotonically and cyclically jacked piles, IFR decreases over depth, while for impact driving results start between 6 to 12 z/D_i and IFR increases with penetration. The increase in IFR observed during impact driving is attributed to the setup of the soil plug before the start of installation followed by the decrease of plug resistance due to friction fatigue and excess pore pressure built-up as the underlying soil's bearing capacity increases during impact driving.

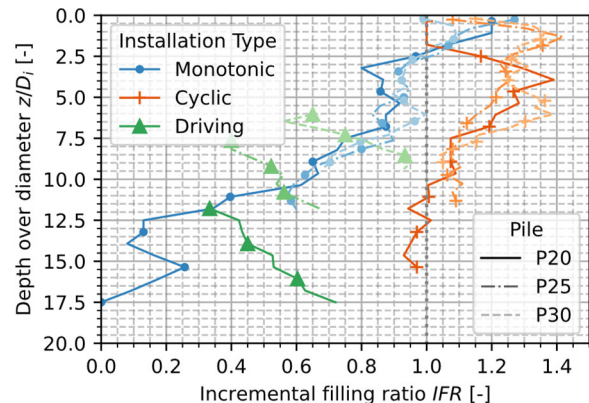


Figure 5. Incremental filling ratio (IFR) over depth normalized by internal pile diameter resulting from the centrifuge tests.

This is very different to the monotonically and cyclically jacked piles where the installation results show a decrease of IFR over depth as penetration depth, which is attributed to an increase in plug resistance. For the monotonically jacked piles, IFR starts above unity and tends to decrease to zero at $z/D_i = 17.5$. In contrast, the lowest recording of IFR for cyclic jacking is around 95 %. Interestingly, due to normalization of penetration depth by the internal diameter, the results for the different pile diameters fit very well together.

Plugging occurs the earliest for monotonically jacked piles, followed by impact driven piles and then by cyclically jacked piles, which is in good agreement with the literature described at the beginning of the paper.

3 NUMERICAL SIMULATIONS

3.1 Numerical model

A numerical study was performed based on the experimental tests described above. The simulations are performed using the coupled Eulerian-Lagrangian (CEL) method, which allows for large deformation analysis. The pile is modelled as a rigid body with Lagrangian elements, while the soil material is modelled in a Eulerian environment, where the material may move through the mesh. Due to a remapping process after each increment, large deformations do not result in high mesh distortions as in typical finite element simulations (Qiu et al., 2011). The model dimensions and mesh are illustrated in Figure 6.

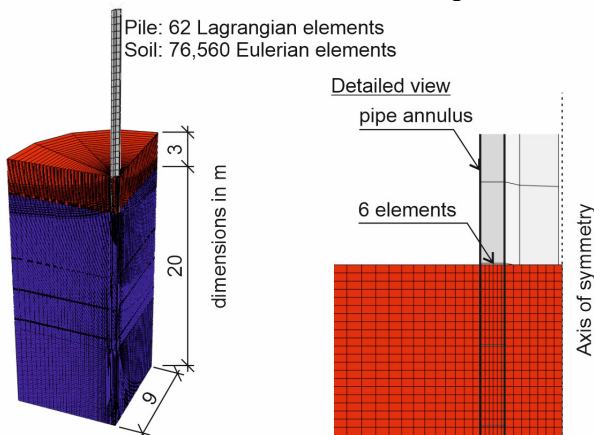


Figure 6. Dimensions and mesh of the numerical model.

For the soil, a constant undrained shear strength $s_u = 60$ kPa and a unit weight $\gamma' = 6.5$ kN/m³ are assumed to match with the experiments. The constitutive behaviour is captured by employing Tresca material behaviour with a Young's modulus $E = 12,000$ kPa and a Poisson's ratio $\nu = 0.49$ to account for undrained conditions. Lateral stresses are calculated assuming $K_0 = 1.0$ to not expose the soil with its constant undrained shear strength over depth to initial deviatoric stresses. Excess pore pressures are not explicitly calculated. The contact behaviour is defined with a friction coefficient $\mu = 0.25$. This is a realistic value for a friction coefficient observed in ring shear tests under undrained conditions (Singh et al., 2024), but may lead to an overestimation of internal skin friction inside a pile (Wiesenthal and Henke, 2025b).

The pile geometry was taken from the smallest model pile in prototype scale, which features an outer diameter of 1 m, a wall thickness of 0.15 m and is penetrated to a depth of 12.5 m. The pile installation process is modelled for a) a quasi-statically monotonically jacked piles, b) a vibrated pile and c) an impact driven pile. To obtain quasi-static conditions for the monotonically jacked pile, parametric studies on mesh and jacking velocity were performed. It was found that a velocity of 2 m/s is

sufficient to obtain stable results regarding plug height and vertical stresses. Therefore, the displacement-controlled penetration time was 6.25 seconds. For the vibrated pile, a sinus curve was added to the displacement curve with a frequency of 29 Hz and a velocity amplitude of 4 m/s. Pile impact driving was also simulated displacement controlled with strikes modelled by applying a downwards velocity of 10 m/s for 0.15 seconds followed by 3 seconds of resting time with zero velocity. This led to a total duration of 27 seconds to reach final penetration depth. This approach may not fully capture the true driving process but it is seen as sufficient for these qualitatively comparative simulations as dynamic forces are introduced from the sudden jumps in velocity.

3.2 Results

Figure 7 illustrates calculated plug height development over penetration depth for the three simulations. For the monotonically jacked pile fully plugged behaviour can be observed after only 2 m of penetration after which the plug height stays approximately constant. This can also be observed from Figure 8 with the incremental filling ratio being near zero at this depth. The plug height is slightly larger for the impact driven pile with IFR converging towards zero at much deeper depths (Figure 8). Remarkably, a constant IFR of 0.1 seems to be approached after 9 m of penetration. For the vibrated pile, the incremental filling ratio also decreases over the penetration depth with much higher values leading to the highest observed final plug length.

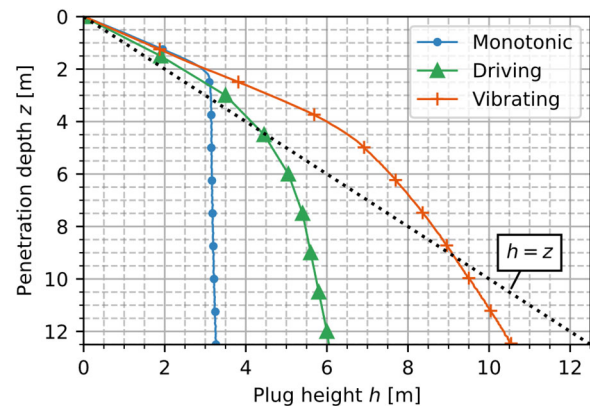


Figure 7. Plug height over depth as a result from numerical modelling.

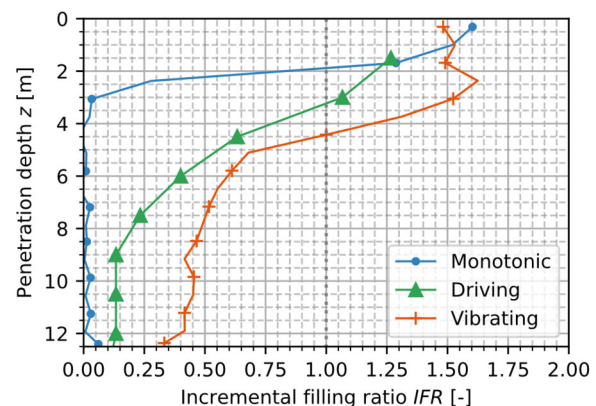


Figure 8. Incremental filling ratio (IFR) over depth as a result from numerical calculations.

As excess pore pressures are not explicitly considered in the simulations, the differences of plug height development are seen to result from dynamic effects, which are introduced from the peaks in accelerations during driving and the accelerations

as well as upwards and downwards movements during vibratory driving.

4 DISCUSSION

From the experimental tests and the numerical simulations, similar trends can be observed of the plug development with installation method, but there are some limitations in both studies which need to be recognized.

In the centrifuge tests, vibration could not be modelled due to limitations of the actuator velocity. The chosen settings correspond to a frequency of only 0.04 Hz at prototype scale which very much limits dynamic effects. Therefore, this installation process is labelled as cyclic jacking. In contrast to the numerical simulations, excess pore pressure built-up as well as destructuring of the over-consolidated clay, which can be summed up under ratcheting, are captured. Under real conditions the effects of inertia and ratcheting are expected to add up and even intensify the delayed plugging response. Additionally, due to the relatively low penetration velocity employed in the centrifuge tests, pile installation was partially drained overall, whereas fully undrained conditions were assumed for the numerical models.

The impact driving process modelled in the centrifuge is limited from self-weight penetration, which creates different initial conditions compared to the other installation techniques and complicates evaluations. It is expected that plugging of driven piles can be ranked between monotonically jacked and vibrated (or cyclically jacked) piles with a trend towards the jacked variant. This is also supported by the numerical simulations. For the numerical model the penetration process involves simplifications and does not consider excess pore pressure built-up as discussed above.

5 CONCLUSION

In this paper, the pile installation process of open-ended piles into over-consolidated clay was analyzed with a focus on plug development using centrifuge and numerical modelling. Each method involves certain limitations compared to reality. While in the centrifuge tests dynamic effects during vibration are underestimated and initial conditions differ for the driven piles due to self-weight penetration, in the numerical simulations simple Tresca-material was used without explicit consideration of excess pore pressures. Despite this, the investigations come to similar conclusions:

- Jacked piles can become fully plugged after reaching sufficient penetration depth. A continuous decrease in incremental filling ratio to zero was observed in the experimental as well as numerical studies.
- In impact driven piles, plug formation is delayed by inertia effects. The tendency towards plugging can be ranked between that of jacked and vibrated piles, though closer to jacked piles.
- Vibrated piles experience mostly fully coring behavior which comes from cyclic movements introducing ratcheting and dynamic effects.

Soil flow into the pile depends on plug resistance from internal skin friction and the bearing capacity of the underlying soil below the pile tip. A strength increase of the underlying soil leads to a higher incremental filling ratio and vice versa. Therefore, the ratio of pile length to internal diameter should always be considered together with the installation method to evaluate or predict potential soil plugging in clay. Further research should also focus on the implications on long-term bearing capacity after equalization, which was not covered by this study.

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