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Analysing hammer impact duration on driveability resistance through instrumented field tests

S. Banaei Moghadam
Delft University of Technology, Delft, Netherlands

K. Duffy, L. Flessati, K. Gavin
Delft University of Technology, Delft, Netherlands

C.J. Stokman, J.M van Wijk
IQIP, Sliedrecht*, Netherlands*

[*]*S.BanaeiMoghadam@tudelft.nl*

ABSTRACT: To reduce noise and minimize fatigue damage during pile driving, a new installation method has been developed that differs from conventional pile driving with high-frequency impact blows. This method prolongs the hammer blow, causing a slower pressing force. As a result, it reduces stress waves and imposes a quasi-static loading process on the pile. Consequently, this approach may induce different soil response phenomena compared to conventional pile driving. For instance, friction fatigue is a well-known phenomenon whereby the shaft resistance during installation is affected by cyclic loading and geometrical effects. With this in mind, this paper presents field tests on a pile installed with this new piling method in the port of Rotterdam. Using this field test data, this research will explore the differences in soil response between the prolonged-blow installation technique and conventional driving methods, focusing on friction fatigue.

Keywords: pile installation, offshore pile, friction fatigue, pore water pressure, radial total stress

1 INTRODUCTION

The increasing size of monopile foundations, spurred on by the expansion of offshore wind farms into deeper waters, presents new challenges for pile installation. Conventional driving methods must overcome issues related to installation efficiency and environmental impact such as installation noise. These challenges have led to the development of alternative installation techniques that modify the characteristics of hammer impact. A key distinction in these techniques is the blow duration, which can influence soil behavior, pile resistance during installation and noise. One such phenomenon affected by the different impact characteristics is friction fatigue, where cyclic loading under pile driving can affect the shaft resistance.

To address these installation challenges, a new piling technology has been developed and named EQ-Piling. EQ-Piling incorporates a pneumatic damping system to improve energy transfer and control. This system features a water-filled hammer that moves along a central guide tube. In operation, the hammer is lifted to a specified height and dropped onto a pneumatic buffer filled with pressurized nitrogen gas, which absorbs impact energy and extends the blow duration over approximately 200 milliseconds. This prolonged impact reduces peak forces while enhancing pile penetration efficiency and limiting noise and vibration. However, this method may also introduce different soil-structure interaction mechanisms compared to conventional pile driving. Therefore, further research is necessary to understand the implications of this approach, particularly regarding soil response and long-term pile behavior.

It is generally accepted that the shear stress at the external pile-soil interface is governed by the Mohr-Coulomb criterion as:

$$\tau_f = \sigma'_{rf} \tan(\delta_{cv}) \quad (1)$$

In the equation τ_f is the peak shaft resistance, σ'_{rf} is the radial effective stress acting on the pile shaft at failure and δ_{cv} is the constant volume friction angle. Determining σ'_{rf} is challenging as this value is known to reduce under cyclic loading which also happens during the pile dynamic installation. Friction fatigue is defined by Vesić as the reduction in shaft resistance at a given depth in the ground as the distance (h) from the pile base increases (Vesić, 1970). Overall, the technical literature presents two perspectives on evaluating friction fatigue. The first approach associates the degree of friction fatigue with the distance between a given soil horizon and the pile tip, normalized by the pile diameter (*h/D*) (Heerema, 1978, Toolan et al., 1990, Randolph et al., 1994, Alm and Hamre, 2001). The second approach links friction fatigue to the number of load cycles applied during installation (White and Lehane, 2004, Lehane et al., 2005). White and Lehane investigated how different pile installation methods—including monotonic, jacking, and pseudo-dynamic techniques—affect cyclic degradation of the shaft resistance. They measured stationary radial effective stress along the pile shaft during drum centrifuge tests, finding that monotonic and jacking installations resulted in higher stress levels. Their study showed that shear amplitude and load path contribute to accelerated stress decay, emphasizing the impact of stress history and installation method on friction fatigue. They noted that the number of load cycles is a more significant factor in friction fatigue than the *h/D* ratio, aligning with DeJong and Frost's (2002) findings that friction stabilizes beyond three diameters from the pile tip (DeJong and Frost, 2002). Gavin and O'Kelly conducted field tests comparing monotonic and cyclic installations and used static and cyclic load tests to evaluate axial capacities. The results indicated a clear friction fatigue trend for both installation methods, with monotonically installed piles showing higher stationary horizontal effective stress at given depths. Both in situ (Gavin and O'Kelly, 2007) and centrifuge (White and Lehane, 2004) test results highlighted that cyclic loading leads to a reduction in effective stresses.

Patently, different pile installation techniques lead to varying soil-pile interactions due to differences in cyclic degradation. EQ-Piling, with its unique blow impact and energy transfer characteristics, therefore may also affect the degree of friction fatigue created during installation. This study aims to explore this by addressing the research question: how does EQ-Piling perform in comparison to conventional hydrohammer installation method?

2 MAASVLAKTE 2 TEST PROGRAM

2.1 Site description

In November 2022, field tests were carried out at the Maasvlakte peninsula in the Port of Rotterdam. A prototype EQ-Piling hammer was used to drive a steel pipe pile, 1.22 meters in diameter D and 21 millimeters in thickness, to a depth of 9 meters. Two additional techniques, conventional hammering and vibratory installation, were also used to compare different installation methods on the pile response. The same tubular pile was installed and extracted at different locations across the site, alternating between installation methods each time. In this study, a prototype of the EQ-Piling hammer (EQ) and S-30 Hydrohammer (HH) have been investigated. To characterize the geotechnical properties of the test site, the Cone Penetration Tests (CPTs) in Figure 1 show a generally consistent soil stratigraphy dominated by sandy deposits with occasional silt and clay inclusions. The upper layers (0–2 meters) have moderate to high q_c values, indicating dense sand with some gravel. Intermediate layers (2–5 meters) with variable q_c values suggest sandy layers with occasional silt or clay and deeper layers (5–10 meters) with higher, more consistent q_c values indicating denser sand except for a clay layer at around around 8 meters. The groundwater table was 2 m below the surface. In Figure 1, the black line represents the chosen CPT profile for data analysis, while the grey lines represent other CPTs available from the test site.

2.2 Pile instrumentation

KPE-PB Small Pore Pressure Gauge and PDB-PB miniature pressure transducers (Athen Sensors) were used for pore pressure and lateral earth pressure measurements, respectively. Also shown in Figure 2, these sensors were installed at three different levels along the pile: LVL5 (*h/D* = 0.4), LVL4 (*h/D* = 2.3), and LVL3 (*h/D = 4.1*). Strain gauges and accelerometers were also used although are not presented in this paper.

2.3 Pile driving parameters

The comparison of pile driving parameters between the EQ and HH, as outlined in Table 1, highlights key differences during installation. While the maximum acceleration of the Hydrohammer was over three times greater than that of the EQ hammer, the average penetration for each blow was much lower as a result of the lower inertia of the pile-hammer system. Therefore, the EQ hammer also required much less blows to reach its final penetration depth of 8.8. Installation took 16 minutes longer for the EQ hammer, although this was a result of driving stops performed during installation.

Table 1- Pile driving parameters

Parameters	EQ	HH
Average penetration per blow	0.025 m	0.0041 m
Installation overall time	74 mins	58 mins
Max. acceleration	164 m/s^2	560 m/s^2
Number of blows up to 8.8 m depth	280	2093
Final penetration depth	8.8 m	9 m

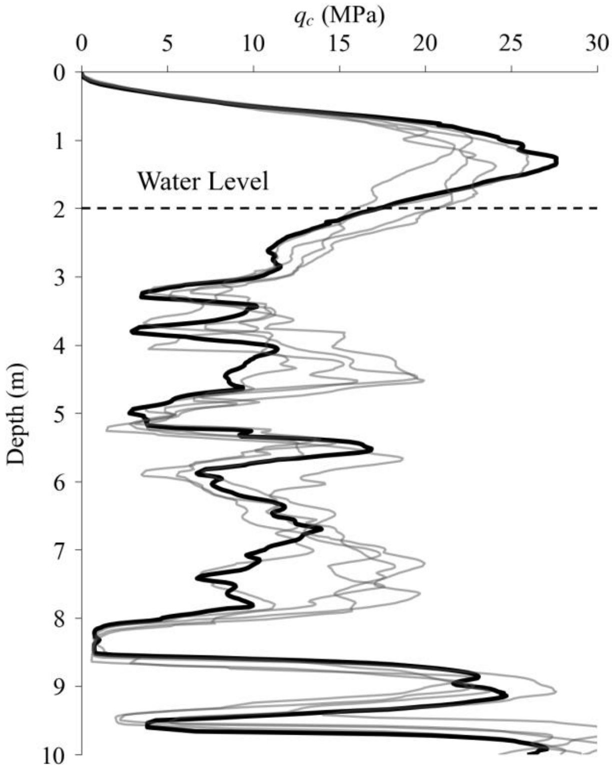

Figure 1-CPTs at the test site

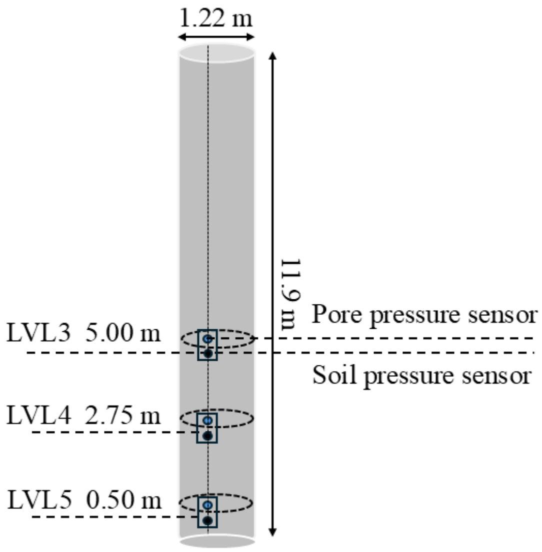

Figure 2-Schematic of pile instrumentation

2.4 Lateral total stress and pore water pressure variations

Once the target depth was reached for the EQ and HH installations (8.8 m and 9 m below ground level, respectively), measurements continued for an additional 10 minutes to collect radial stress measurements and to assess the dissipation of excess pore water pressure following driving.

Figure 3 illustrates the variation in pore water pressure (PWP) relative to the hydrostatic pressure over this ten-minute period. Each plot compares the trends observed in the HH and EQ installations to provide insights into the build-up of PWP during installation and its dissipation following the end-of-driving. While the PWP trends for HH and EQ are similar at LVL3, the PWP levels associated with the EQ installation appear to reach equilibrium more effectively at LVL4 and LVL5.

For visualization, the last datapoint from each sensor's measurements over this 10-minute period were chosen for both PWP and total stress and plotted alongside the corresponding calculated radial effective stress in Figure 4, allowing comparison of these values for the two installation methods.

In terms of radial total stress, the final values were generally higher for the EQ installation compared to HH, except at LVL3. For EQ, LVL4 and LVL5 reached values of 198 kPa and 539 kPa, respectively, while for HH, these values were significantly lower at 84 kPa and 135 kPa.

The PWP generated during EQ-Piling installation (Figure 4b) returned to the hydrostatic pressure within ten minutes after driving. However, in contrast, only one of three sensors reached an equilibrium with the hydrostatic pressure after installing with the hydrohammer. At LVL4 and LVL5, excess pore water pressures remain lower than the hydrostatic pressures.

Translating both the total stress and PWP measurements to an effective stress (Figure 4c), considerably higher effective stresses are recorded at LVL5 and LVL4 of the EQ installation when compared to HH installation (473 kPa and 157 kPa, respectively). However, at LVL3, the HH installation records a higher effective stress of 98 kPa compared to 51 kPa for EQ. This comparison suggests that piles installed with the EQ-piling hammer exhibit higher radial effective stresses than those installed by HH, which, according to Equation 1, implies higher end-of-driving shaft resistance and potentially greater bearing capacity.

Based on Equation 1, the higher radial effective stresses may suggest that piles installed with EQ-Piling may exhibit higher shaft resistance, and thus subject to less friction fatigue. Nevertheless, research is ongoing regarding this, particularly with regards to the depth-dependent trend and with analyzing the complete dataset.

3 CONCLUSION

This study looks at the influence of prolonged hammer blowers on the soil and pore pressure response after pile installation, comparing this with conventional pile driving. A preliminary analysis of the measured radial total stress and radial effective stress at three levels along the pile shaft, taken during a 10-minute measurement period following a penetration stop, reveals that prolonged hammer blows may result in higher effective stresses when compared to conventional installation methods, although research is still ongoing into the friction fatigue mechanisms that govern driven pile installation. These findings will later be incorporated into a static resistance to driving formulation and a complete life cycle assessment of pile installation.

AUTHOR CONTRIBUTION STATEMENT

First Author: Formal Analysis, Writing, Original draft. Second, third and fourth authors: Supervision, Reviewing and Editing.
Fifth and sixth authors: Data Collection, Technical support, Reviewing

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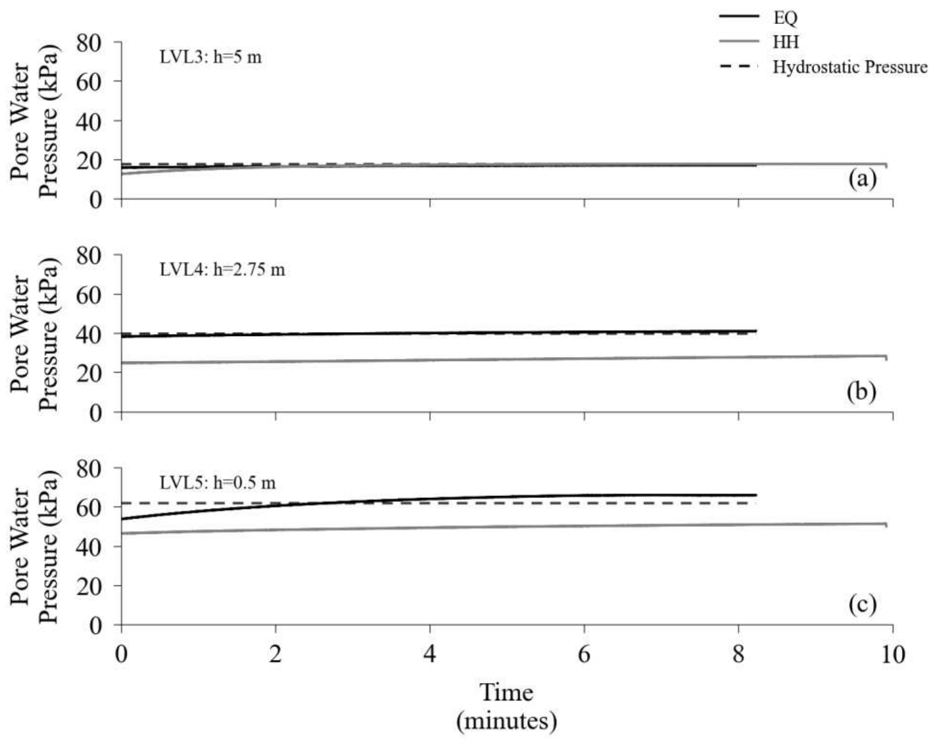

Figure 3-Variation of pore water pressure recorded 10 minutes after the end-of-installation, measured by the (a) LVL3 (b) LVL4 and (c) LVL5 sensors.

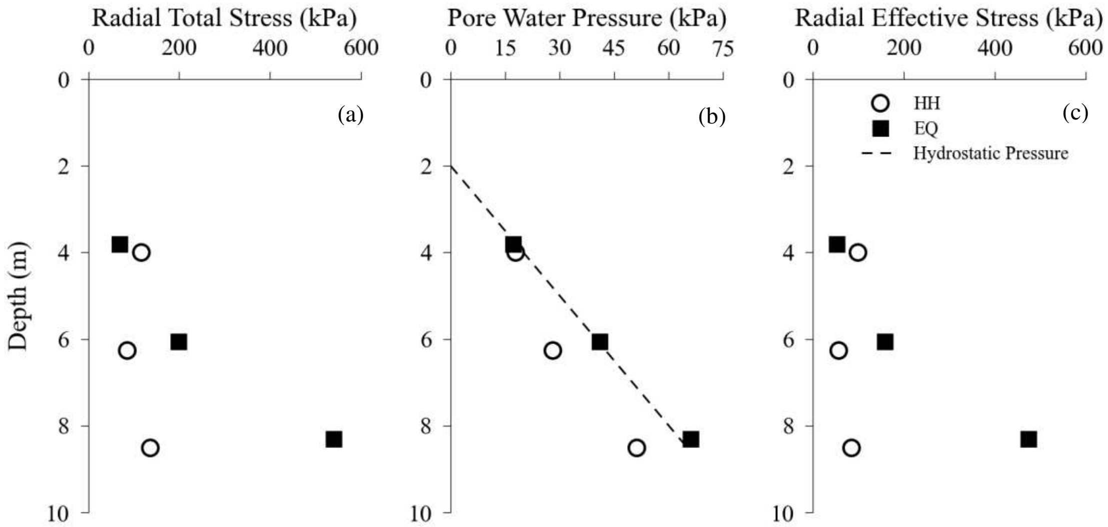

Figure 4-Comparison of the measured radial total stress, pore water pressure and calculated radial effective stress, recorded 10 minutes after the end of installation

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