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Duffy, Kevin J.

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Improving axial pile design through full-scale field testing and fibre optic sensing

Kevin J. Duffy[a]

[a] *Delft University of Technology, Delft, The Netherlands*

ABSTRACT

Recent advancements in fibre optic sensing have increased the range of monitoring techniques available for measuring the axial response of full-scale piles. For instance, distributed fibre optic sensing gives a continuous measurement of normal force with depth in a pile, meaning the shaft resistance of a pile can be accurately quantified in each soil layer. Other fibre optic sensing methods, such as Fibre Bragg Gratings, have been shown to provide accurate and robust high-frequency measurements of pile installation. With these improved measurement techniques, detailed insights can be obtained into not just the geotechnical response of the pile, but also the structural response. Presented in this paper is some first-hand fibre optic data collected from axial load tests on piles founded in dense to very dense sand, ranging from driven piles to screw displacement piles. Using fibre optic sensing, key insights could be gained into both the structural and geotechnical response of these piles at large base and shaft resistances, facilitating changes to CPT-based pile design methods at a site-specific and nationwide level.

KEYWORDS

Fibre optic sensing; Cone Penetration Test; Axial pile design; Pile design;

1. INTRODUCTION

Recent changes to the Dutch design code (NEN, 2017; Gavin, Kovacevic and Igoe, 2021) has prompted a large amount of research (Duffy et al., 2022) in recent years into the axial capacity of piles in sand, through field testing, numerical modelling (both finite and discrete element modelling) and laboratory testing (calibration chamber and centrifuge). In terms of field testing, static load tests were performed on full-scale piles representative of typical piles installed in practice. Four of the most common pile types in the Dutch piling industry were tested:

- Driven closed-ended piles
- Driven open-ended piles
- Driven cast-in-situ piles
- Screw displacement piles

The research focused on specific aspects of axial pile behaviour and how these aspects are integrated into design method which use the Cone Penetration Test (CPT) to predict the pile base and shaft capacity. One aspect included an investigation into pile-specific design factors and how depth-dependent effects, such as friction fatigue, should be incorporated into design, particularly for driven cast-in-situ piles (Flynn and McCabe, 2016). Another aspect focussed on the necessity of limiting resistances for piles in dense to very dense sands.

In total, twenty full-scale piles were tested, spread across three different test sites. Uniquely, all piles were instrumented with state-of-the-art fibre optic sensors, giving detail insights into the pile base and shaft response under axial compressive loading. A short summary of these results are provided in this paper and for further information, readers should refer to Duffy et al. (2022; 2024a; 2024b).

2. FIBRE OPTIC SENSING

Fibre optic sensing techniques look at small changes in the frequency of scattered lightwaves within an optical fibre. Many different types of fibre optic sensing techniques are available, although two types of fibre optic sensors tend to be the most prevalent in geotechnical monitoring: Fibre Bragg Gratings (FBG) and distributed fibre optic sensing (DFOS, Brillouin-based sensing). Both sensing techniques were used during the research programme to monitor the change in strain or deformation of each test pile under axial compressive loading.

FBG and DFOS technologies provide complimentary benefits in the context of pile testing. FBGs are similar to traditional strain gauges in that they are short-gauge sensors, comprising a small grating that is laser-etched into an optical fibre. FBGs also allow for high frequency measurements (>5 kHz) and have been successfully used in monitoring stress wave propagation along a pile during installation (Doherty et al., 2015; Buckley et al., 2020). In contrast, DFOS uses the entire length of the fibre optic cable as a sensing element, measuring the strain acting on every single portion of the cable. However, while DFOS gives spatially rich data, the measurements come at a much lower frequency compared to FBG sensors—two minutes per measurement in the case of the pile load tests.

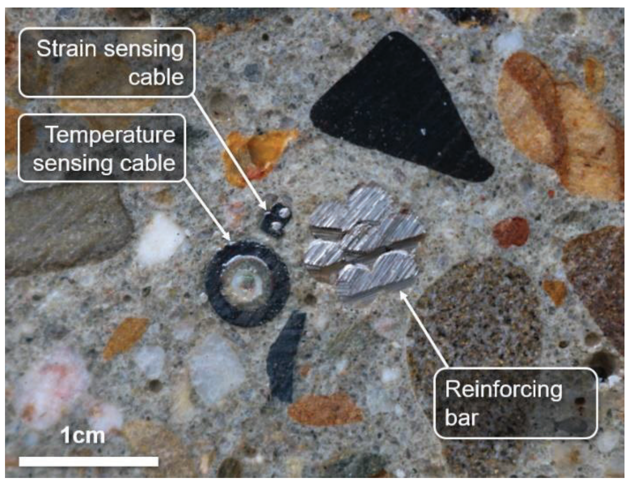

Figure 1. Fibre optic sensors embedded in a concrete pile

The fibre optic cables used for both DFOS and FBG are not much different to standard telecommunication cables. However, pile hammering or concrete pouring can be particularly harsh environments for fibre optic cables. Steel-reinforced fibre optic cables were used to provide more robustness, whilst sacrificing very little in terms of their sensing capabilities. The small size of the fibre optic cables (Figure 1) reduces the space required for instrumentation within a pile. As a result, fibre optic instrumentation provides little impedance to concrete flow and maximises the structural stiffness and integrity of the pile.

Strain is the primary measurement quantity in pile load tests and gets subsequently converted to a normal force based on the assumed cross-sectional stiffness of the pile. Temperature-induced changes on the strain measurements are generally considered to be negligible during a load test. However, the installation of a driven pile also results in locked-in stresses along the pile shaft and underneath the pile base, known as residual stresses. To accurately measure these stresses, a reference measurement should be made before installation with the pile above ground and with a known load acting on the pile, if any load at all. The temperature change between the measurement periods can be substantial, and so thermistors or "loose-buffered" fibre optic cables (Figure 1) were used to correct for the temperature change in the pile between the reference measurement and any measurement after pile installation, described in Duffy et al. (2022).

3. LOAD TEST PROGRAMME

Two different types of test frames were used across the different test sites, one with grout reaction anchors (Figure 2a) and another with heavy concrete blocks, also known as kentledge (Figure 2b). The choice of test frame was dependent on the local site conditions and mobilisation cost. Both test frames used hydraulic jacks to generate the load on the pile, with each pile loaded incrementally to a pile base displacement of 10% of the pile diameter, referred to as pile failure.

During each load-holding increment, the fibre optic sensors measured the pile response in each soil layer. The test results of a cast-in-situ pile (Figure 3) gives a comparison between the DFOS and FBG sensors. Both sensors compare well, showing a gradual reduction in normal force across the looser upper layers. A sharp reduction in force is seen at a depth of 28 m, corresponding to the top of a very dense sand layer. The DFOS readings also shows deviations between FBG measurement points. For instance, the small, localised reduction in load between 15 m and 20 m depth could suggest local deviations in pile diameter or stiffness. These deviations would otherwise not be picked up by FBG sensors and can be crucial in identifying outliers or discrepancies in the measured data.

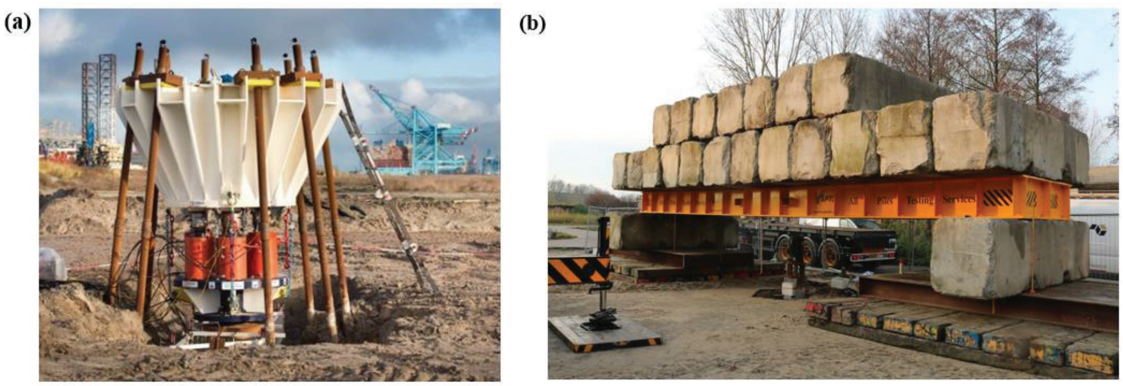

Figure 2. Load test frame (a) with grout reaction anchors (b) with kentledge

4. RESULTS

At one of the test sites (Duffy et al., 2024a), three driven closed-ended piles were installed in very dense sand, where the average CPT cone resistance was 45 MPa at the base of each pile. Crucially, the measurements in the pile prior to load testing showed that at least 10 MPa of residual base stresses were already present (Figure 4) in the piles. To sustain an equilibrium with this 10 MPa base load, negative shear stresses were mobilised all along the upper part of the pile.

From a starting point of 10 MPa, all three piles reached peak of loads of around 30 MPa (Figure 4), mobilising this load within a displacement of 15 mm or 3% of the pile equivalent diameter. Notably, these base stresses were well in excess of limiting resistances prescribed in design standards, such as the Dutch design standard (NEN, 2017) or the API RP 2A standard (API, 2011). Similar findings were also shown for the measured shaft resistance, suggesting pile design methods could be refined to account for this overconservatism.

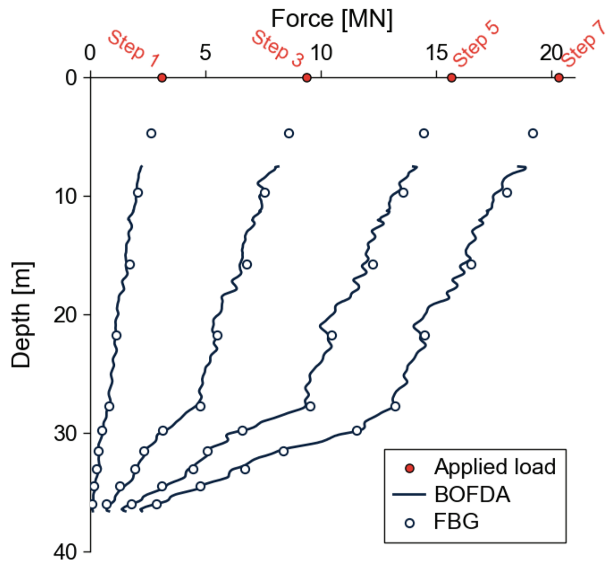

Figure 3. Fibre optic measurements during a load test on a cast-in-situ pile (850 mm diameter)

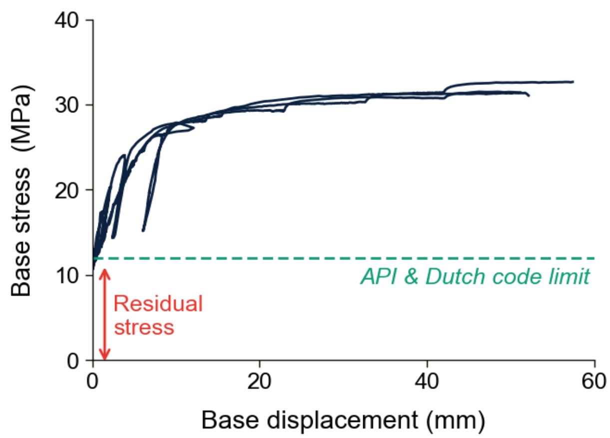

Figure 4. Mobilised base resistances of three driven closed-ended piles (400 mm square) in very dense sand

5. IMPLICATIONS FOR DESIGN

Some of the load tests were performed as part of the construction of 1.8 km long deep-sea quay wall in the port of Rotterdam (Figure 5), to be used as a berth for some of the largest container ships in the world. Around 2,600 foundation piles have recently been installed on the site, all being used to support the target retaining height of 29 m. The results of the driven pre-cast piles, along with tests on other pile types, showed areas in which the design method could be improved. This included a change in the pile base and shaft limiting resistances, along with pile-specific design factors. Specifically for the quay wall project, optimisation of the pile design led to financial savings of roughly €11 million and an 8 kton reduction in carbon emissions associated with pile manufacturing. Clearly, well-instrumented pile testing can be hugely beneficial, both from a research and industry context, and work is ongoing at TU Delft in improving the understanding of pile behaviour and pile design.

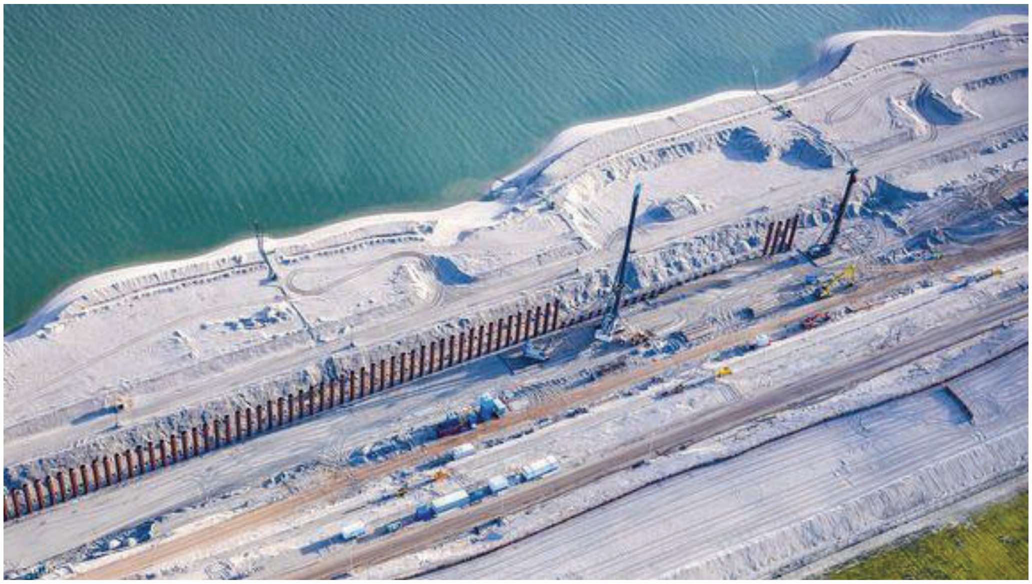

Figure 5. Tubular pile installation at Amaliahaven in the port of Rotterdam

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