Residual stress measurement of driven precast piles using distributed fibre optic sensors

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ABSTRACT

Stresses generated from pile installation are a critical component in understanding pile behaviour. These are known as residual stresses and in Delft, the Netherlands, the response of three driven precast piles founded in sand was measured using distributed fibre optic sensing as part of a series of full-scale static load tests. The instrumentation set-up and analysis is discussed in this paper, highlighting the uncertainties with developing an appropriate residual stress distribution and in particular, how instrumentation selection, positioning and calibration can influence the interpretation of the residual stress profiles. The resulting profiles shows a substantial development of residual stress in the pile, an important consideration to take into account when preparing and analysing full-scale load tests on driven precast piles.

Keywords: piles, residual loads, field monitoring, distributed fibre optic sensing, static load testing

1 INTRODUCTION

Driving a precast concrete pile is an energy-intensive operation, generating a substantial amount of stresses in the pile and the surrounding soil. Under each blow, the pile body and soil beneath the pile base compress and deform, partially rebounding after each blow. During rebounding, negative shear stresses mobilise along the pile shaft whilst stresses at the pile base reduce. Resistance along the pile shaft can lock-in some of these stresses, reaching an equilibrium condition between the stresses along the pile shaft and underneath the pile base. These are known as residual stresses and are crucial for interpreting load tests on driven piles. Failure to do so can result in a misinterpretation of the pile shaft and base capacities and lead to inappropriate and unsafe design methods.

Nonetheless, describing the litany of effects on a pile’s residual stress development is difficult and not well understood (Paik *et al.*, 2003) and so directly measuring this response is imperative. But this can also be challenging for two reasons: (i.) an appropriate reference strain must be made of the piles before installation and (ii.) compensation for the thermal gradient between measurements before and after installation must be carried out. Additional instrumentation is required for this, increasing the complexity of the test programme and bringing additional measurement uncertainty. On top of this, the harsh conditions of concrete casting and pile hammering demands the use of more robust sensors that are carefully placed and well-protected, coming at the cost of measurement sensitivity and reducing the ability to instrument piles within the financial and time constraints of a typical testing programme.

Recent advances in fibre optic (FO) strain sensing provide an opportunity to accurately and effectively measure residual stress development. Distributed fibre optic sensing (DFOS) provides a quasi-continuous profile of strain across the measurement length and a wide range of FO cables are available which can suit a variety of instrumentation conditions. Nonetheless, the process of deriving the stress distribution is not often described and so practitioners do not get a thorough understanding of the uncertainties which exist behind an analysis.

This paper takes an example of residual stress measurements made in full-scale driven precast piles at a test site in Delft, the Netherlands, piles which have been instrumented with DFOS along their entire length for the purposes of measuring strain and temperature. The test site provides a unique design scenario for piles

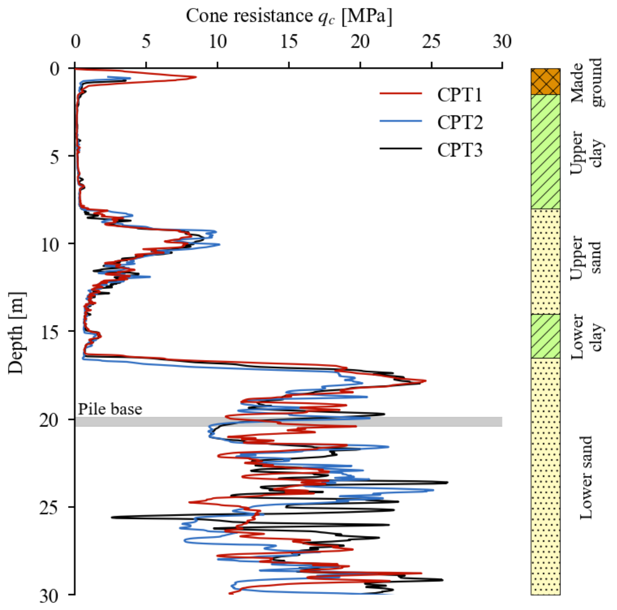

Fig. 1: CPT cone resistance profiles along the central axis of each pile. The zone within which all three piles are founded is indicated.

founded in medium dense sands, deep below the surface.

2. DELFT TEST SITE

The Delft test site was established as part of the Improved Axial Capacity of Piles in Sand (InPAD) project (Duffy et al., 2022). The project was initiated to refine the Dutch pile design standard and contribute to the global understanding of pile behaviour across a wide range of pile types founded in medium dense to very dense sands. Key research areas for driven precast piles include residual stress development, the influence of ageing on pile capacity and the determination of a suitable averaging method to assess the pile base capacity based on the cone penetration test (CPT) tip resistance q_c.

The three test piles were 350 mm square (equivalent diameter D_{eq} of 395 mm) and had an embedded length of approximately 20 m. During the load tests, all three piles were axially loaded in compression, with capacities ranging between 1.3 MN and 1.8 MN.

2.1 Ground conditions

The test site features soil conditions typical of western Netherlands. The surface layer is a shallow sand fill, underlain by 7 m of very soft to soft highly organic clay ($q_c \approx 0.2$ MPa), followed by a 5 m thick upper sand layer and then a second layer of slightly firmer clay ($q_c \approx 0.7$ MPa). Underneath this lies a layer of dense sand, with q_c values of 10–25 MPa. The piles were driven to a penetration depth of 9 D_{eq} into this sand layer (Fig. 1). The average cone resistance $q_{c,avg}$ around the pile base is 10–12 MPa, determined by the method of van Mierlo & Koppejan (1953), also known as the 4D/8D or Dutch averaging method.

2.2 Measurement system

To measure the strain response of the piles, a polyethylene cable with two strands of reinforcing on either side of the cable was used, provided by Fujikura Ltd. (Fujikura, 2015; Fig. 2). The reinforcing improves cable robustness under the high impact forces and bending stresses experienced during instrumentation, concrete casting and pile installation. The cable was attached to the reinforcing along the centre of all four sides (Fig. 2), giving a complete profile of bending stresses in the piles.

Two loose-buffered FO cables were included to compensate the strain measurements for temperature effects. These cables are theoretically isolated from external mechanical strains by surrounding the optical fibres with a gel (Fig. 2). Thermistors were also installed at discrete intervals, acting as a second measurement system for temperature.

Each pile also contained a reservation tube along its central axis as a contingency measure in the event of fibre damage. A new FO cable could be inserted into this tube and grouted in-place in order to measure the response of the pile during the static load tests, albeit without residual stress measurements. Ultimately, all fibres survived and during load testing, the tube instead housed a long steel rod known as a tell-tale which could infer the settlement of the pile base during the test.

Fibre optic measurements were performed using the fibrisTerre fTB 2505 interrogator with Brillouin Optical Frequency Domain Analysis (BOFDA). To perform this, the interrogator injects a lightwave into each end of the optical fibre and tunes the frequency difference between the two light waves so that the maximum intensity of scattered light is found. This maximum intensity correlates to both the strain and temperature at a certain point in the fibre (Nöther et al. 2008).

As a result of this dual influence, temperature compensation needs to be applied for the purposes of strain monitoring. Two components should be considered for this: a temperature-induced apparent strain in the bare optical fibre ($\Delta\varepsilon_{app}$) and an actual thermally-induced strain $\Delta\varepsilon_{therm}$ caused by the difference in thermal expansion coefficients in the materials surrounding the bare optical fibre, such as the plastic sheathing or concrete (Kurashima et al. 1990). After converting from Brillouin frequency shift to strain, the interrogator output can be summarised by Eq. 1:

$$\Delta\varepsilon_{int} = \Delta\varepsilon_{mech} + \Delta\varepsilon_{therm} + \Delta\varepsilon_{app} \qquad (1)$$

Given that the cross-sectional stiffness of a concrete pile is substantially larger than that of the FO cable, the thermal response of the FO cable is considered negligible and only that of the pile needs to be considered when assessing $\Delta\varepsilon_{therm}$ (Mohamad, 2012).

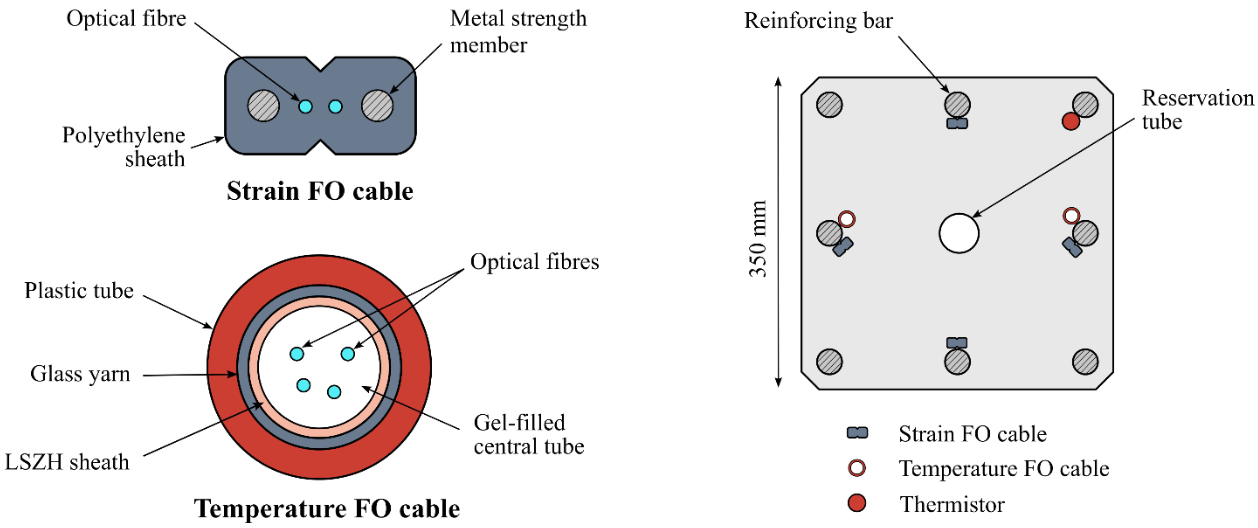

Fig. 2: Instrumentation used during the study, indicating the fibre optic cables used and their configuration within the pile. Drawing is not to scale.

The calculation of $\Delta\varepsilon_{therm}$ is non-trivial. A simple approach would be to assume unrestrained thermal deformation of the pile and taking the coefficient of thermal expansion for concrete. However in reality, there will be some degree of restraint in the structure due to the surrounding soil and reinforcing and therefore the development of stresses both within the pile and outside the pile can be difficult to identify from an embedded FO cable, especially when the priority is to assess the soil response. Therefore, it is expected that $\Delta\varepsilon_{therm}$ will lie in between zero (the fully restrained condition) and the fully unrestrained condition.

The result of the instrumentation system at Delft is a complete profile of the strains and temperatures on all four sides of the pile, indicating the bending stresses in the pile and the temperature compensation required.

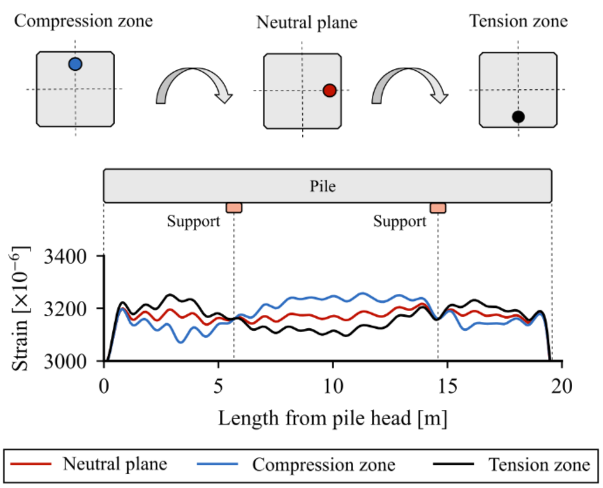

Fig. 3: Reference strain measurements of a single FO cable in one of the piles, showing the strain reading for each rotation of the pile. Positive strains denote compression.

3. RESIDUAL STRESS MEASUREMENTS

3.1 Reference measurements

Stresses of varying magnitudes can be incurred on FO cables prior to residual stress measurement. For instance, manufacturing or storage procedures of FO cables can lead to periodic or complete changes in strain levels across the optical fibre (Mamdem *et al.*, 2012; Kishida et al. 2014). Additional stresses can also develop during the instrumentation process. This can come through pre-stressing of the FO cable or the concrete reinforcing within the pile. Alternatively, thermal changes during concrete casting or the positioning of aggregates within the concrete mix can also create localised strains on the FO cable. To accurately distinguish the soil response from these strains, a reference measurement must be made. Often this is done at the start of a load test but in the case of driven precast piles, it is imperative that a reference measurement is made prior to pile installation so that the stresses imposed by pile hammering can be measured.

At the Delft test site, reference measurements were made with the piles resting horizontally on the ground surface on top of two supports (Fig. 3). To compensate for bending between the supports, multiple measurements were made with different orientations of the piles. At least one strain measurement was made with the FO cables between the compression and tension zones with respect to pile bending, known as the neutral plane. A measurement was also performed while the FO cables were in the compression and tension zones themselves, the average of which is equal to the measurement on the neutral plane. This allows for internal strains incurred by concrete curing, pre-stressing or the manufacturing of the FO cable to be identified and compensated for, whilst accounting for bending stresses present during the reference measurement.

The measurements show that with each rotation of the pile, a clear shift in the strain readings is observed (Fig. 3). Focusing on the point of maximum bending in the centre of the pile, a demonstrable increase in compressive strain is seen as the FO cable enters the compression zone, reducing as it rotated into the tension zone. When the fibre is rotated onto the neutral plane, there is little deviation in strain along the pile length in comparison. At the supports, the deviation in strain is also minimal throughout all three rotations of the pile.

A periodic noise can also be seen in the reference measurements. These can be caused by localised strains within the fibre optic core or inhomogeneities in the pile body and render it difficult to distinguish between soil behaviour and structural behaviour. Taking a reference measurement allows for a degree of compensation for these effects and improve the interpretation of soil behaviour.

Temperature measurements made during this process would be expected to be constant along the length of the pile, provided that every part of the pile was uniformly affected by shadow and sunlight. This is well demonstrated by the thermistor measurements which show a constant temperature of 11°C along the length of the pile (Fig. 4). In contrast, data from the loose-buffered cable varies by up to 3°C along its length. A 90° rotation of the pile shows a clear deviation of the temperature readings from the same FO cable despite the negligible change in ambient temperature between each pile rotation. Clearly, obtaining accurate measurements of temperature in the loose-buffered fibres with Brillouin-based interrogation techniques is not sufficient, suggesting the loose-buffered cable is affected by strains induced by bending in the pile itself.

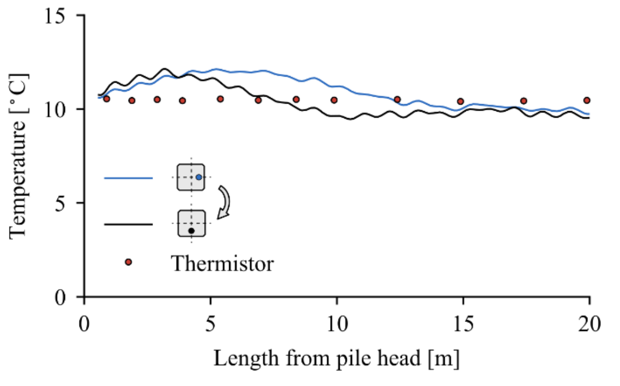

Fig. 4: Temperature response of a loose-buffered FO cable before and after a 90° rotation of the pile, compared to thermistors placed at discrete intervals along the pile. The ambient air temperature was 11°C at the time of measuring.

3.2 Residual strain measurements

Two weeks after installation, strain measurements were made with no external load on the pile (Fig. 5). Large differences between strain readings are evident: the sides directly opposing one another (e.g. Side A vs. Side B) exhibit opposite strain states with one side in

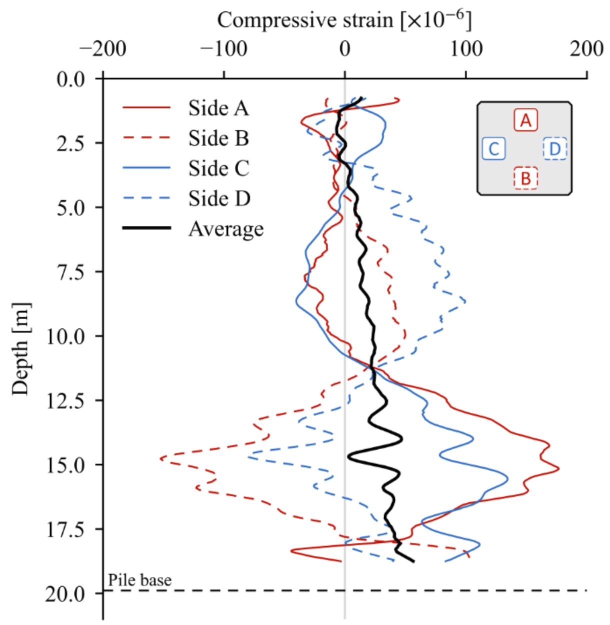

Fig. 5: Readings from each measurement axis during a residual stress measurement, including the average of all four measurement axes. Temperature compensation has been applied.

tension and the other in compression. This is unsurprising given the soft upper layers and dense lower layers at the site, increasing the likelihood of the pile bending.

For each side of the pile, the peak of its compressive and tensile strains occur just before the interfaces of the upper and lower sand layers at 8 m and 16 m respectively. A degree of fluctuation within each strain reading is also carried through to the combined average strain profile. Indeed, a misallocation of the measurement depths of the fibres would increase the influence of the fluctuations on the combined strain profile and thus, measurement placement and depth identification is crucial for ensuring an accurate monitoring programme.

Focusing in on the averaged strain profile (Fig. 6b), the initial readings of the interrogator can be decomposed into the components presented in Eq. 1. The initial readings of the interrogator $\Delta\varepsilon_{int}$ suggest that the pile is in tension along most of its embedded length. By incorporating the thermistor measurements (Fig. 6a) and removing the apparent strains $\Delta\varepsilon_{app}$ on the optical fibre, a completely different interpretation is obtained: one where the compressive strain is close to zero at the pile head and increases with depth to a maximum strain value at the pile head. The effect of this correction is greatest at the pile head due to the effect of ambient temperature fluctuations on the first few metres of soil. Beyond these depths, the influence of temperature fluctuation over time is expected to be relatively small.

Going a step further and removing thermal strains, $\Delta\varepsilon_{therm}$, the influence of the thermal contraction/expansion of the pile body on the

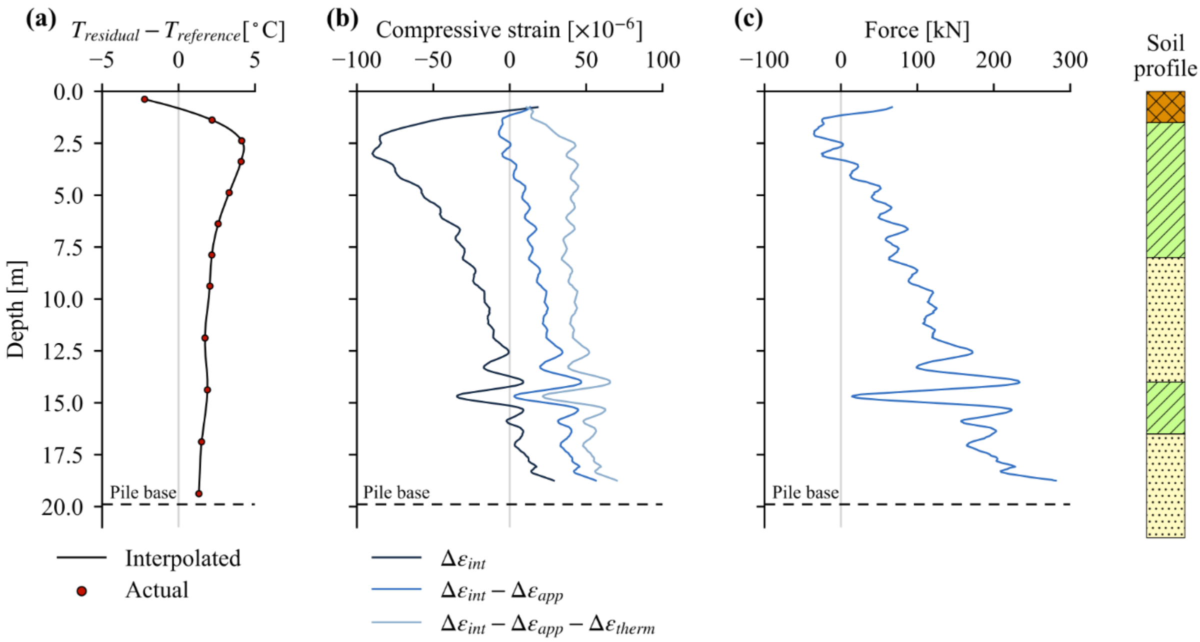

Fig. 6: (a.) Thermistor readings used for temperature compensation. (b.) Results of the temperature compensation, illustrating the profiles after removing the apparent strains and thermal strains. (c.) Residual load distribution, applying compensation for $\Delta\varepsilon_{app}$.

surrounding soil is removed, assuming unrestrained deformation. The resulting profile (Fig. 6b) shows a large increase in compressive strains in the first 2.5 m below ground level. The strain is then relatively constant through the upper clay layer, increasing gradually thereafter until the pile tip. Nonetheless, assuming $\Delta\varepsilon_{therm}$ as unrestrained expansion is perhaps an over-simplification since a degree of restraint is present in both the horizontal and vertical directions on the pile, something which is also dependent on the surrounding soil layers and the degree of mobilised shear strength. As a result, $\Delta\varepsilon_{therm}$ provides an upper bound estimate for the thermal strains developed and an approximation of the potential influence of thermal deformation.

3.3 Residual stress distribution

Conversion from strain to force can be performed based on the cross-sectional stiffness of the pile, resulting in a representation of the normal force along the pile shaft (Fig. 6c). Considering just the profile corrected for $\Delta\varepsilon_{app}$, the data shows an unusual distribution of load near the top of the pile, wherein a normal force of +70 kN is evident near the top, reducing to −20 kN at a depth of 2 m below ground level. These readings are believed to be a relic of the temperature compensation process, suggesting further laboratory testing is required to determine the strain and temperature calibration parameters for the specific FO cable batch used for the test site. Potential influence from overlying surcharge loads near the pile (e.g. the load test frame and its ballast) or tension cracks developed in the pile head during the hammering process could also be responsible for these loads.

The residual load profile below a depth of 3 m increases at a relatively constant rate to the top of the lower sand layer. The load distribution suggests that negative shear stresses of 10–15 kPa are mobilised throughout the soft clay layer. The residual load then builds up at a larger rate in the lower sand layer, to a load at the pile base of at least 300 kN. This corresponds to a locked-in residual base stress of 2.3 MPa, or 20% of the averaged cone resistance $q_{c,avg}$. Evidently, this is a substantial component of the base resistance that would be unaccounted for if neglected during the load test itself.

For further analyses, smoothing of the distribution is often carried out or portions corresponding to an actual soil layer are taken to remove noise from the measurements and distinguish the true geotechnical response of the pile following installation. This is being considered as part of the extended analysis of the results.

4. CONCLUSION

This paper has provided an overview of a case study in Delft, the Netherlands where distributed fibre optic sensing was used for monitoring the residual stress response of driven precast piles after installation. Particular focus was drawn on the instrumentation and interpretation processes, two steps which are crucial in developing an accurate assessment of the residual load response and can generate a significant amount of uncertainty in an analysis.

The case study highlights the implications that may arise with instrumentation selection, positioning and calibration. Temperature compensation was also shown to be a crucial factor in accurately determining the residual load profile and should not be underestimated when approaching a monitoring programme. While this paper focussed on distributed fibre optic sensing, the learning points are applicable to a wide range of sensing instruments and should be carefully considered in devising the monitoring programme and interpretation of the results.

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