Distributed fibre optic sensors for measuring strain and temperature of cast-in-situ concrete test piles

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ABSTRACT In this paper we present the use of distributed fibre optic sensor (DFOS) technology to measure the temperature and strain of reinforced concrete test piles during construction and during static load tests. Eight test piles were recently instrumented with DFOS, on three construction sites in London, by the Cambridge Centre for Smart Infrastructure and Construction (CSIC), in collaboration with Ove Arup & Partners Ltd. The concrete curing temperature profiles of the piles were used to detect the presence of significant defects in the piles. The load test strain profiles along the length of the piles were used to determine the load capacity of the piles and estimate the design parameters of the various soil strata, as well as the internal relative displacement of the piles under various loads. Being distributed in nature, DFOS give a much more detailed picture of the performance of a test pile, as compared to traditional embedded point sensors, such as vibrating wire strain gauges and extensometers. This is demonstrated with a sample of data obtained from one of the instrumented test piles.

1 INTRODUCTION

Full-scale testing of pile foundations is a well-established technique for validating foundation design before construction, as well as for quality control and continuous improvement in pile design and construction practices. Clause 7.5 of Eurocode 7 lays down requirements for pile load testing (British Standards Institution 2004), which accounts for a considerable proportion of the total value of the piling market in the UK (Federation of Piling Specialists 2006). It is imperative that pile testing translates into real value, both for specific projects and for the construction industry as a whole. This relies on the amount of useful knowledge that can be obtained from the pile testing process, as compared to the cost incurred.

This paper deals with the pile testing instrumentation of cast-in-situ reinforced concrete piles, constructed using bored or continuous flight auger (CFA) methods. We focus in particular on how distributed fibre optic sensors (DFOS) can be used to supplement traditional pile testing instrumentation, and potentially replace embedded point sensors in the future. The added value that DFOS technology can bring is demonstrated with extracts of monitoring data from recent pile tests carried out in London.

2 TESTING OF CAST-IN-SITU CONCRETE PILES

The fitness for purpose of a reinforced concrete pile depends on two aspects, both of which can be investigated with testing: pile integrity, which deals with the dimensional accuracy, structural quality and homogeneity of the pile; and pile stiffness, which defines the load-carrying capability of the pile for a range of displacements.

Pile integrity can be checked through site observations and inspection of pile records. It is also commonly inferred indirectly from the acoustic response of the pile to sonic waves introduced externally (e.g. low-strain integrity testing) or internally, via steel tubes cast into the pile (e.g. cross-hole sonic logging). Thermal integrity profiling (TIP) is becoming a more common method to infer integrity and uses the concrete curing temperature measured by three or more strings of closely-spaced temperature sensors embedded along the length of the pile (Piscsalko et al. 2015). These tests are intended to detect significant defects in the pile composition, such as soil inclusions, overbreak or voids.

Pile stiffness can be determined through load tests, either on working piles or on trial piles, with the latter typically being tested to failure at loads well above their safe working load. The loading can be static or dynamic and, while the former generally requires a larger working area and takes longer to perform, it gives a more direct measure of pile performance.

In static maintained trial load tests, a controlled load is applied and removed in stepped stages. The load is applied either from a bi-directional load cell embedded within the pile (compression testing only), or from a loading frame above the pile (compression, tension or lateral testing) (Figure 1). At each loading and unloading stage, the applied load and displacement at the pile head are measured, from which the load/settlement relationship of the pile can be derived.

In addition to the load and pile head displacement, it is also common practice to measure the strain at various levels within the pile during trial load testing. Traditionally this is done using embedded strain gauges, typically vibrating wire strain gauges (VWSGs) which are either welded directly to the reinforcement or mounted on lengths of rebar ("sister bars") that are tied to the reinforcement before it is inserted in the pile bore.

By measuring the change in strain along the pile for any constant load, it is possible to estimate pile-soil interface properties in the various geological strata that the pile penetrates, as long as the strain gauges are installed in sufficient number and in suitable locations. In practice, aspects such as cost, cabling congestion and data acquisition equipment limit the number of strain gauges that can practically be installed; they are typically placed several meters apart along the length of the pile. Therefore the reconstruction of the strain profile from the individual strain gauge measurements is not always reliable, as the individual point measurements can be influenced significantly by localised effects in the pile or the ground. On the other hand, localised effects which are not close to any of the strain gauges, but which might be important for the assessment of the pile performance, will not be detected by the instrumentation.

Figure 1. Static load testing frame for a trial test pile.

Another common measurement that is made during each stage of a trial load test is the relative displacement between the pile head and a limited number of locations along the length of the pile. This is traditionally measured by means of retrievable extensometers which are lowered down steel tubes embedded within the pile. From the extensometer readings, one can derive the shortening of the pile between measurement locations, for each load. However, as with the strain gauges, it is not possible to detect any localised effects that could occur between measurement points.

In summary, a complete trial pile load test would involve at least five independent sensor systems, each measuring a different action or reaction parameter: two external systems to measure load (e.g. load cell) and top deflection (e.g. displacement transducer); and three internal systems to infer integrity (e.g. temperature sensor strings for TIP testing), and to measure strain (e.g. VWSGs) and displacement (e.g. extensometers). In the remainder of this paper, distributed fibre optic sensing is proposed as a single alternative to integrity, strain and displacement sensors.

3 DISTRIBUTED FIBRE OPTIC SENSOR TECHNOLOGY

Until recently, practically all the sensor systems in use in the civil engineering and construction industry consisted of point sensors, where a measurement from one sensor represents a physical parameter acquired at a single point in space. With point sensors, it is only by increasing the number of individual sensors that one can obtain a spatially distributed measurement set. Indeed, all the sensor systems mentioned in the previous section, in relation to traditional pile test monitoring, conform to this mode of operation.

Over the past few years, we have seen the emergence of a new paradigm in instrumentation, namely "distributed sensing", where a single measuring device can record data from a large number of spatially distributed points. These systems tend to be easily scalable at minimal increase in system cost. Some examples of distributed sensing are 3D laser scanning, nano-composite sensing skins and distributed fibre optic sensors (DFOS).

DFOS systems use the principles of photonics in order to locate and quantify changes in the molecular structure of the glass along an optical fibre. In civil engineering applications, and particularly in relation to pile testing, this change is generally associated with a change in strain or temperature of the optical fibre, or a combination of both. In turn, this can be equated to a change in strain and / or temperature of the structure to which the optical fibre is bonded (e.g. in the case of steel members) or in which it is embedded (e.g. in the case of a concrete member).

Various DFOS measurement techniques exist, as described by Kersey (2011). In this paper we present the application of the Brillouin optical time domain reflectometry (BOTDR) technique for measuring strain and temperature along a single-mode optical fibre (Kurashima et al. 1993).

A BOTDR-based DFOS system consists of a BOTDR analyser and one or more lengths of fibre optic (FO) cables connected together in series to form a single circuit that is attached to or embedded in the structure to be monitored. The analyser transmits thousands of short optical pulses per second into one end of the FO circuit. As the light travels through the optical fibre, molecular density fluctuations inherent throughout the fibre's silica core cause a small fraction of this light to scatter and reflect back towards the analyser, from every location along the fibre. The analyser measures the frequency spectrum of the backscattered light caused by the light pulses and calculates the distance to where the scattering originated from, based on the speed of light within the fibre.

The frequency spectrum of the backscattered light consists of a number of components, one of which is the Brillouin frequency. The peak Brillouin frequency is shifted from the frequency of the input pulse by an amount that is proportional to the strain and temperature of the fibre, at the location where the backscatter originated from.

By recording the peak Brillouin frequencies of the backscattered light coming from closely spaced intervals along the FO circuit, and comparing them to those recorded from the same points at a previous time, it is possible to derive the change in strain and / or temperature that occurred at every measurement point along the fibre. The strain and temperature effects can be deconvoluted by taking measurements simultaneously from a loose-tube FO cable (temperature cable) and a tightly bonded FO cable (strain cable), installed adjacent to each other in the structure (Mohamad 2012).

At the time of writing, off-the-shelf BOTDR analysers could record data from an FO cable several tens of kilometres long, with a sampling resolution of 5 cm, spatial resolution of 50 cm, strain precision of ±30 με and temperature precision of around ±1 °C.

4 TESTING CAST-IN-SITU PILES WITH DISTRIBUTED FIBRE OPTIC SENSORS

Following several years of lab development and field trials, the BOTDR DFOS technique has recently been used successfully to monitor eight cast-in-situ reinforced concrete trial test piles, at three different sites in London. Four piles were constructed using the CFA technique and the other four were bored piles. The piles were between 25.5 m and 33.7 m long, and 0.9m in diameter. The stratigraphy at the test locations comprised Made Ground, Alluvium, River Terrace Deposits, the Lambeth Group and the Thanet Sand Formation. The Engineer was Arup and the DFOS instrumentation and monitoring was carried out by the Centre for Smart Infrastructure and Construction (CSIC) from the University of Cambridge.

4.1 Instrumentation

The DFOS cables were installed within the piles in U-shaped loops, consisting of a leg along one side of the pile, a wrap around the bottom of the pile, and a leg along the opposite side of the pile (Figure 2). Each loop consisted of two FO cables: a loose-tube temperature cable and a tightly-bonded strain cable, with the latter being pre-tensioned by hand before being fixed in place. The two cables were fixed to the pile reinforcement at the top and bottom of each leg and held loosely along the reinforcement with intermediate cable-ties.

Each pile was instrumented with at least one DFOS loop on the reinforcement cage. Two of the bored piles were also instrumented with a second DFOS loop at right angle to the first. Two of the CFA piles, which included a central bundle of reinforcement bars in addition to the reinforcement cage, also had a DFOS loop installed on this bundle.

Figure 2. Distributed fibre optic sensor cables being installed on the reinforcement cage of a CFA pile (top) and wrapped around the bottom of the cage (bottom).

As well as the embedded DFOS instrumentation, traditional pile testing sensors were used in all eight piles. Strings of temperature sensors at 30 cm intervals were used for assessing the pile integrity during concrete curing by the TIP method, while embedded VWSG pairs and retrievable extensometers were used to measure the strain and relative displacement at up to seven points within the piles during load testing. Seven of the piles were subjected to maintained loading in axial compression to a maximum load of between 8 and 25 MN, and one pile was subjected to maintained loading in axial tension to a maximum load of 5 MN.

4.2 DFOS monitoring and results

The temperature and strain in all the piles were recorded at a minimum of once every 30 minutes during concrete curing, starting from a few hours after concreting until several hours after the peak temperature was recorded. During the load tests, the temperature and strain were recorded at suitable intervals such that at least one measurement was taken during each loading and unloading cycle. In this section we present a small selection of the DFOS monitoring results, pertaining to one of the CFA compression piles. The reinforcement of this pile consisted of a 20 m-long cage and a 25 m-long central bundle.

Figure 3 shows the temperature change profiles of this pile during concrete curing, with respect to a baseline measurement taken approximately 4 hours after pile completion. The profiles show the temperature of the pile increasing steadily over its entire depth, until a maximum temperature increase of 25.8 °C was reached, 18 hours after the pile reinforcement was inserted in the concrete.

A section of this pile that coincided with the Alluvium and River Terrace Deposits reached consistently higher temperatures than the rest of the pile during curing. This is an indication of a possible overbreak at these strata, as the larger volume of concrete is expected to result in a slower dissipation of the heat of hydration. This profile matched the data recorded from the TIP sensors, which also indicated a possible overbreak in the same strata.

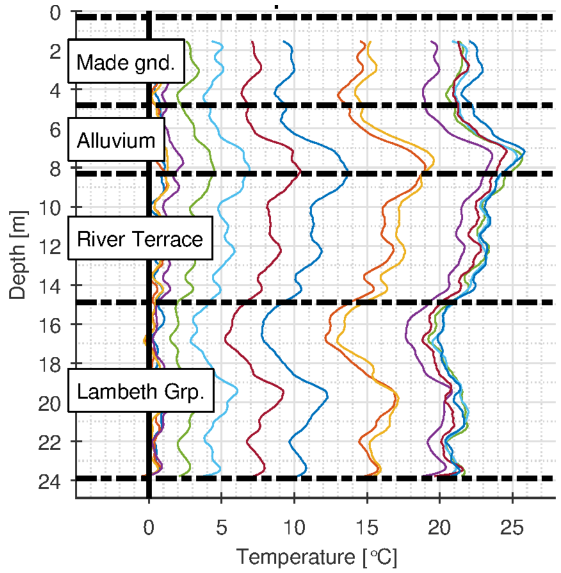

Figure 3. Temperature change profile of a CFA pile, recorded at hourly intervals in the centre of the pile during concrete curing, from 4 hours (baseline) to 18 hours after the pile was completed, when the concrete reached a peak temperature increase of 25.8 °C.

Figure 4 shows the strain change profiles recorded in the centre of the CFA pile, during the second (final) load increment cycle, with respect to a baseline taken before the loading started. This cycle was carried out over 28 hours and consisted of seven load stages, from 7.7 MN (100% design verification load (DVL)) to 20 MN (100% DVL + 165% specified working load (SWL)). Each of these stages is represented by a single strain profile in the figure, with increasing compressive strain corresponding to increasing load. A maximum compressive strain increase of 772 $\mu\varepsilon$ was recorded close to the top of the Alluvium stratum, under a load of 20 MN.

The strain profiles once again confirm the suspicion of an overbreak in the Alluvium and River Terrace Deposits strata. This is indicated by a sudden reduction of strain in the pile at these depths, when compared with the expected gradual reduction in strain. This is likely the result of a larger cross-section at these depths, hence a smaller strain for a given load.

By integrating the strain profile from top to bottom, it is possible to estimate the incremental internal displacement of the pile, relative to the pile head. This is

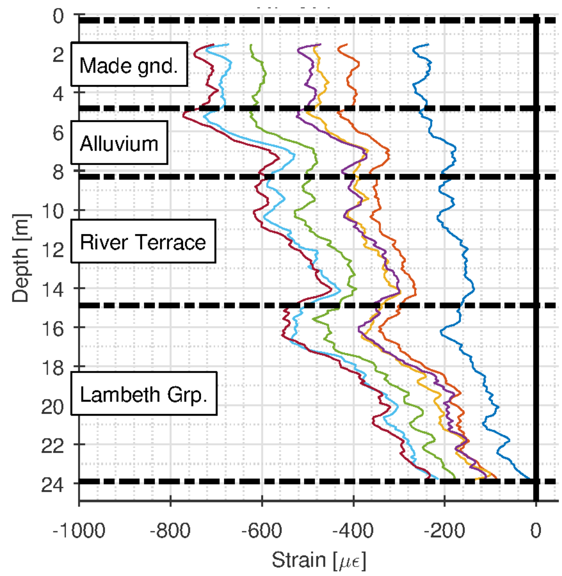

Figure 4. Strain change profile of a CFA pile, as it was incrementally loaded vertically in compression, with loads of 7.7 MN, 11.4 MN, 13.3 MN, 15.2 MN, 17.1 MN, 18.9 MN and 20.0 MN (corresponding to the strain profiles going from right to left). Negative strain indicates compression.

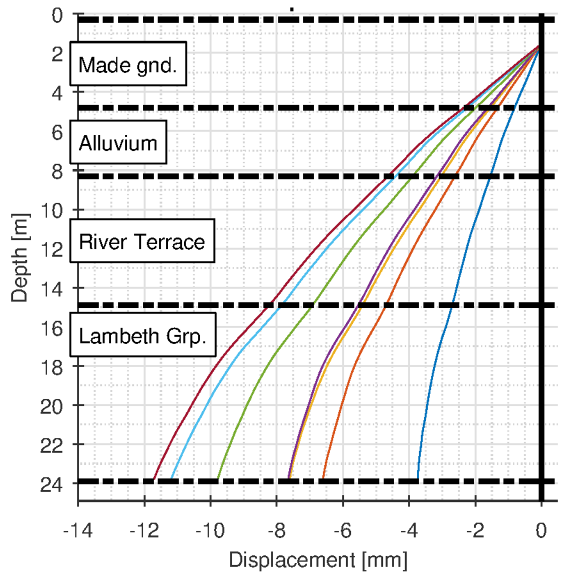

Figure 5. Displacement profile of a CFA pile, relative to the pile head, estimated from the recorded strain during vertical load testing as shown in Figure 4. Negative relative displacement indicates compression.

shown in Figure 5, where the displacement profiles were derived from the strain profiles of Figure 4.

From the strain and displacement data, one is able to estimate a number of design parameters, such as the pile modulus at the pile head, the limiting shaft friction for the different soil strata and the pile base displacement.

The data from the conventional VWSG and internal displacement transducers within this pile agreed well with the data acquired from the DFOS system. This was also the case for the other seven piles. A quantitative comparison of the different data sets will be the subject of a future, more detailed paper on these case studies.

5 CONCLUSION

In this paper we have presented the application of distributed fibre optic sensor (DFOS) technology for monitoring the temperature and strain of reinforced concrete test piles during curing and load testing. Following years of development and field trials, this technology has been used in full-scale static pile testing to inform foundation designers about the integrity and load capacity of four bored and four CFA test piles in London.

A typical set of results from one of these test piles was used to illustrate the unprecedented level of detail that can be obtained from a single instrumentation system. A more in-depth presentation of results and their interpretation will be the subject of a future publication.

From the plots shown in this paper, it is evident that a DFOS system can give much more information about the properties and performance of a reinforced concrete pile than traditional point sensors. Following the success of these test cases we envisage that DFOS will start being specified more often for test pile monitoring, eventually becoming standard instrumentation in test piles.

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