APPLICATION OF DISTRIBUTED FIBRE OPTIC SENSOR IN INSTRUMENTED PILE LOAD TEST

B.P. Tee¹, A.S.A. Rashid², R.A. Abdullah³, K.A. Kassim⁴, H. Mohamad⁵

¹,²,³Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia
⁴Department of Civil Engineering, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia

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ABSTRACT

In instrumented axial pile load test, obtaining reliable strain profile is crucial when analysing the load-transfer and shaft friction of the test pile. For conventional instrumented pile load test, point-based sensor such as vibration wire strain gauges and tell-tale extensometers were installed to measure strains and pile shortenings at designated pile depth. To obtain reliable strain profile, extensive quantity of point-based sensor need to be installed in the instrumented test pile especially when the test pile is long and with large variation in soil stratum. Recent technological advancement of optical fibre sensing has led new ways in measuring the performance of instrumented test pile. The distributed sensing, namely Brillouin Optical Time Domain Analysis (BOTDA) is a novel technique of measuring strains in a continuous manner which has inherent distinct advantages over conventional point-based sensors. This article presents one of the earliest deployment BOTDA optical fibre sensors in instrumented test pile in Malaysia. Comparison was made with conventional point-based sensor and it show excellent agreement. Interpretation of load-transfer and shaft friction based on distributed fibre optic sensor method was also discussed.

Keywords: Bored pile, BOTDA, Distributed Fibre Optic Sensor, Instrumented Load Test

Introduction

A new method to measure the performance of pile was developed by using a fibre optic sensing system which involves the unique marriage of fibre optics, optoelectronics and composite material science [1,2]. Several advantages could be gained from this fibre-optic sensor such as geometrical adaptability, dual task of sensor and path for transmission of the signal, precision and sensitivity over large measurement ranges, and immunity to electromagnetic interference and electrical hazard. In addition, this technology is capable to sense over its full length of the single optical fibre cable (potentially up to 100km long) against any strain and temperature changes. Therefore, a single optical fibre can substitute thousands point of strain gauges and could provide a cheaper sensing method to monitor deformation of large or long extended structures. Furthermore, distributed strain sensing is often considered more important than having a very accurate localized strain sensor but limited in numbers particularly when evaluating the interaction of forces between the structure and the soil [3]. This method has been widely use in measuring the performance of geotechnical structure such as piled foundations [4,5], retaining walls [6], and tunnels [7]. In this paper, an instrumented bored pile performed in Malaysia on the basis of distributed fibre optic strain sensing was explained which consist of the field study background, measurement principles, installation methods and data interpretation. The obtained result from the conventional vibrating wire strain gauges and tell-tale extensometer were compared with the data from the Distributed Fibre Optic Sensor.
Distributed Fibre Optic Sensing (FO) Technology

A commercially available Brillouin Optical Time Domain Analysis (BOTDA) interrogator (OZ Optic Ltd.) was used in this study to measure the load distribution characteristic along the pile shaft. Two different light sources were employed on the BOTDA system and launched from two ends of an optical circuit. The system uses the backward stimulated Brillouin scattering (SBS) where the pumping pulse light launched at one end of the fibre and propagates in the fibre, while the continuous wave (CW) light is launched at the opposite end of the fibre and propagates in the opposite direction. The pump pulse generates backward Brillouin gain whereas the CW light interacts (amplifies) with the pump pulse light to create stimulated Brillouin scattering. The Brillouin frequency shift in the single mode fibre is proportional to the change in the strain of that scattering location. By resolving this frequency shifts and the propagation time, a full strain profile can subsequently be obtained. The 5.0 mm diameter optical sensing cable arrangement is shown in Figure 1. It is specifically designed for embedded in cast-in-situ concrete pile. The fibre optic sensing cable consists of a single core single mode optical fibre reinforced with six strands of steel wires and polyethylene cable jacket. The external plastic coating and the inner glass core are fixed together so that the strain applied externally (from the concrete) is fully transferred from the coating to the inner core.

Figure 1: Arrangement of optical strain sensing cable.

Background of the Test Pile

A static load test was carried out on an instrumented bored pile with a dimension of 23.9m length and 1200mm diameter (Figure 2). It was encountered that the ground conditions consist of fairly uniform sandy silt residual soil with bedrock underlain the sandy silt layer. The test pile for this project was designed to undertake full shaft friction only by ignoring the contribution of base resistance.
Figure 2: Instrumentation setup, bored pile detail and standard penetration test (SPT-N) values of bored hole.

**Instrumentation**

Figure 3 shows the installation of vibrating wire strain gauges (VWSG), distributed fibre optic sensing cables for measuring strain changes in the pile. Tell-tale extensometers were also installed to measure pile shortening. As indicated in Figure 2, pairs of VWSG was tied to the main reinforcement bars at Level 1 to Level 5 and two pairs of VWSG were tied to Level 6. Two pairs of distributed fibre optic strain sensing cable (S1a-S1b & S2a-S2b) were also fixed to the main reinforcement bars from top to toe of pile (see Fig. 2). Another pair of distributed temperature sensing cable (T1a-T1b) was also installed side by side with the S2a-S2b cable to measure the temperature changes in order to compensate the differential temperature effect to strain reading during each round of measurement in case of any. All the fibre optic strain sensing cables were fixed straight along the main reinforcement placed at 90° separations. The VWSGs electrical lead wires were brought to the top of the pile with all the cables tied to the steel cage. The casing for rod extensometer (Galvanised iron) was mounted and installed on the reinforcement cages.

In order to load the pile to the designed load, a pair of 1500 tonnes hydraulic jack was used as shown in Figure 4. Load cell and Linear Voltage Displacement Transducers (LVDTs) were used to measure the amount of load transferred and pile top settlement to pile, respectively.
Figure 3: Installation of VWSG, extensometer, and optical fibre strain sensing cables.

Figure 4: Configuration of hydraulic jacks, load cells, LVDTs setup at pile top.

**Load Test Procedures**

ASTM D1143 (Standard Test Method for Piles Under Static Axial Compressive Load) standard was referred to conduct the maintained load test [9]. The test pile was loaded up to two load cycles. The deformation was taken for every 15 minutes during the loading and unloading stage and the transducer readings were taken at 15 minutes for the first hour and hourly interval thereafter at the maximum load at each cycle. A spatial resolution of 5ns was set on the BOTDA analyser, which is equivalent to a gauge length of 50cm. However, the reading trace can be plotted at every 5cm along the cable’s distance based on 10,000 averaging times (done automatically) to increase measurement accuracy. Prior to that, each optical sensing cable used in the field test must be calibrated in laboratory; in this case the strain coefficient obtained was 20µε/MHz.

**Data Analysis and Interpretation**

**Axial and bending strains**

The derivation of pile axial deformation from optical fibre sensor is done by averaging the strain along two fibres placed symmetrically (at 180° separation) with respect to the axis. As shown in Figure 9, the measured strains $\varepsilon_1$ and $\varepsilon_2$ can be used to derive the quantities of
axial components; axial strain in Eq. (1) and axial displacement, $u$ or elastic compression in Eq. (2).

\[ \varepsilon(z) = (\varepsilon_1 + \varepsilon_2)/2 \quad (1) \]
\[ u(z) = \int \varepsilon \, dz \quad (2) \]

In case when loading at the top of the pile is not symmetrical such as eccentric load, which can induce moment, the measurement of bending moment can be calculated by looking at the curvature changes, $\kappa$ between two opposite fibres [5].

\[ \kappa(z) = (\varepsilon_1 - \varepsilon_2)/D = M/EI \quad (3) \]

where, $D$ is distance between the two fibres or diameter of pile,

$M$ is bending moment, and

$EI$ is flexural stiffness of the pile.

**Measurement Results**

Figure 5 shows the pile load displacement curve. At the first cycle, test load of 11802kN induced settlement of 4.86mm, and at 22163kN in the second cycle, the settlement at the pile top was 14.5mm. The maximum pile top settlement was about 1.25% of pile diameter at 200% working load (WL).

![Figure 5: Load displacement for test pile.](image)

Figures 6(a) and (b) show comparison of the strain measurements from vibrating wire strain gauges (VWSG) and Fibre Optic (FO) sensors, both of which showed excellent agreement between them.
To convert strain measurement to the load distribution along the pile shaft, $P(z)$ at each level, the following formula was used:

$$P(z) = \varepsilon (E_c A_c + E_s A_s)$$  \hspace{1cm} (4)

where

- $\varepsilon$ = average change in strain readings
- $A_c$ = cross-sectional area of concrete
- $E_c$ = modulus of concrete
- $A_s$ = cross-sectional area of steel reinforcement
- $E_s$ = Young's Modulus of elasticity in steel (= 200 kN/mm²)

The modulus of concrete under loading, $E_c$ are known to be strain-dependent particularly at high stresses region [10]. $E_c$ is back-calculated by assuming that the load at near pile top was equal to the applied load at the pile top. Figure 7 shows the comparison of $E_c$ back-calculated based on both FO and VWSG that shows excellent agreement. By adapted the strain-dependent relationship of concrete modulus, the load distribution along pile shaft was computed as shown in Figure 8. It can be seen that the load transferred to the pile as being mainly through its shaft friction. Very little load is transferred to the base as the strain measured at pile base was very minimum. Further comparative plots of the field case study can be referred to [8].
Figure 7: Strained-dependent Concrete Modulus, $E_c$ (FO vs VWSG).

Figure 8. Load distribution along pile shaft (FO vs VWSG).
With the complete load transferred distribution along the pile, the mobilised shaft friction, $\tau(z)$ can be obtained by differentiating Eq. (4) as follow:

$$\tau(z) = \frac{1}{\pi D} \frac{\partial P}{\partial z} = \frac{EA}{\pi D} \frac{\partial \varepsilon}{\partial z}$$  \hspace{1cm} (5)

Mobilised shaft friction was computed and plotted as shown in Figure 9. The mobilised shaft friction was plotted against average strain measured at each designed level in order to observe the trend/stage of mobilised shaft friction. Generally, mobilised shaft friction computed from both FO and VWSG well matched except Level 1 to Level 2. From Figure 9, Level 2 to 4 (with SPT-N value range from 10 to 50) had achieved maximum shaft friction at range around 200 kN/m$^2$ to 275 kN/m$^2$ and mobilised toward residual stage. For Level 4 to 6, the ground condition is much better than level above with SPT-N value more than 50. Up to 200% WL, shaft friction at Level 4 to 5 achieved about 400 kN/m$^2$ and Level 5 to 6 about 300 kN/m$^2$. The trend of mobilised shaft friction at Level 4 to 6 is still increasing linearly and is yet to be fully mobilised. A parametric study was performed based on the computed mobilized shaft friction and stiffness of soils to match the measured load–displacement response [11]. Those parameter chosen well agreed with the parameter recommended by the researchers.

![Figure 9: Mobilised shaft friction at each designated level (FO vs VWSG).](image)

For the axial displacement, $u$ or pile shortening, it was computed based on Eq. (2) by integrate once the continuous strain profile measured from the fibre optic sensor. The pile shortening profile along pile depth was computed as shown in Figure 10. The shortening profiles were computed with reference to pile top. With the shortening profile, pile settlement at all interested level including pile toe can be calculated by deduct measurement of pile top settlement to pile shortening. For this test pile, maximum shortening achieved was 10.7mm at 200% WL. At similar load, pile top settlement recorded was 14.5mm. By consider pile shortening, pile settlement at toe was 3.8mm.

Pile shortening can also be computed at designated level as shown in Figure 11. Two pieces of tell-tale extensometer were installed for this test pile at similar level to level 1 and level 2 of VWSG. The measured result of tell-tale extensometer was included in Figure 11. Both measurement of tell-tale extensometer and FO are well matched.
Figure 10: Pile shortening profile along pile depth computed from FO.

Figure 11: Pile shortening at designated depth computed from FO.
CONCLUSION

A novel way of instrumenting bored pile using distributed optical fibre strain sensing has been successfully implemented for the first time in Malaysia. The field-test results generally showed very good agreement between the conventional and FO sensors. A particular advantage of using distributed measurement is that the full strain profile can be obtained quite easily instead of discrete data from conventional strain gauges, which often requires data extrapolation between limited sensing points, laborious installation time and data problems arising from local erroneous measurements. In addition, the sensor can be configured and integrated into the structure to measure three-dimensional deformation such as bending and shortening of the piles. This potentially eliminates the need to install various instrumentation schemes such as inclinometer, rod extensometers and minimisation of instrumentation cost.

References