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INSTRUMENTED PILE LOAD TESTING WITH DISTRIBUTED OPTICAL FIBRE STRAIN SENSOR

Hisham Mohamad*, Bun Pin Tee

UTM Construction Research Centre, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

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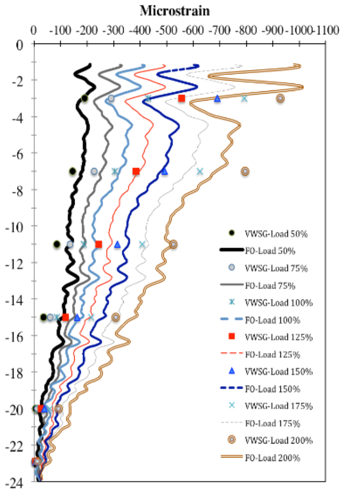
*Corresponding author
mhisham@utm.my

Graphical abstract



Abstract

An instrumented pile load test was conducted for a 1.2m diameter bored pile at Putrajaya to verify pile performance towards geotechnical design. This test pile was instrumented with new monitoring technique using distributed strain sensing known as Brillouin Optical Time Domain Analysis (BOTDA) and compared with conventional sensors, i.e. vibrating wire strain gauge, LVDT (linear variable differential transformer) and dial gauge. This manuscript includes the description of subsurface conditions consisting of weathered granitic residual soils, test pile installation and instrumentation setup of Maintain Load Test (MLT). Field measurement results such as the load transfer response and average unit shaft resistance using the distributed fibre optic strain sensor were well matched with the results using the conventional sensors. However, the distributed fibre optic strain sensor has the added advantage of detecting the localized defect such as pile necking, bending, and overall behaviour of bored pile effectively.

Keywords: Bored pile, Fibre-Optic sensing, BOTDA, maintain load test

Abstrak

Satu ujian beban cerucuk telah dijalankan di Putrajaya pada sebatang cerucuk terjara berukuran 1.2m diameter untuk mengesahkan prestasi cerucuk terhadap rekabentuk geotekniknya. Cerucuk yang diuji ini dipasang dengan jenis instrumen yang menggunakan teknik pemantauan baharu yang boleh mengesan terikan secara tersebar. Teknik ini dinamakan *Brillouin Optical Time Domain Analysis (BOTDA)* dan keputusannya dibandingkan dengan sensor konvensional seperti tolok terikan dawai bergetar, LVDT dan tolok dial. Kandungan manuskrip ini termasuk perihal geoteknik terdiri daripada tanah granit terluluhawa, kaedah pemasangan gentian optik dan persediaan instrumentasi untuk Ujian Cerucuk Statik. Keputusan ujian tapak seperti tindak balas pemindahan beban dan unit rintangan aci purata menggunakan kaedah terikan tersebar gentian optik adalah memadani keputusan yang menggunakan sensor konvensional. Walau bagaimanapun, sensor terikan tersebar gentian optik mempunyai kelebihan tambahan yang mana ia boleh mengesan kecacatan setempat seperti perleheran, lenturan dan pergerakan keseluruhan cerucuk terjara secara berkesan.

Kata kunci: Cerucuk terjara,sensor gentian optic, BOTDA, ujian beban statik

1.0 INTRODUCTION

Recent advancement in photonics and optoelectronic devices has led to new applications of fibre-optic sensors in the field of civil engineering. The advantages of fibre-optic sensors include 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. Distributed optical fibre strain sensing is one of the many types of optical fibre technology that have been increasingly applied in geotechnical fields such as piled foundations [1,2], retaining walls [3], and tunnels [4]. The novelty of this technology is that a single optical fibre can sense over its full length of the cable (potentially up to 50km long) against any strain and temperature changes. This means a single optical fibre can replace thousands of point-wise strain gauges and potentially provide an economical method to monitor deformation of large or long extended structures. Moreover, 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 [5].

This paper provides the first ever instrumented bored pile performed in Malaysia on the basis of distributed optical fibre strain sensing. Background of the field study, measurement principles, installation methods and data interpretation are described accordingly. Particular attention is made to compare the data between vibrating wire strain gauges and Fibre-Optic sensors.

2. DISTRIBUTED OPTICAL FIBRE TECHNOLOGY

2.1 Brillouin Optical Time Domain Analysis (BOTDA)

In this study, a commercially available Brillouin Optical Time Domain Analysis (BOTDA) interrogator (OZ Optic Ltd.) was used to determine the load distribution characteristic along the pile shaft. The BOTDA sensor uses two different light sources, launched from two ends of an optical circuit. The system utilizes the backward stimulated Brillouin scattering (SBS); i.e., 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 (Figure 1). In this configuration, 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 or temperature of that scattering location. By resolving this frequency shifts and the propagation time, a full strain profile can subsequently be obtained. One particular advantage of BOTDA over other type of distributed strain sensing system such as BOTDR (Brillouin Optical Time Domain Reflectometry) is that the technique produces strong signal, which can reduce averaging times (faster acquisition time) and longer measurement distances capabilities (for up to 50 km).

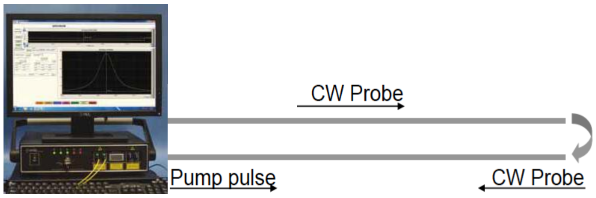


Figure 1 Principle measurement of a BOTDA system

2.2 Optical cable

Figure 2 shows the configuration of a 5.0 mm diameter optical cable specifically designed for embedment in cast-in-situ concrete piles. It consists of a single core single mode 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.

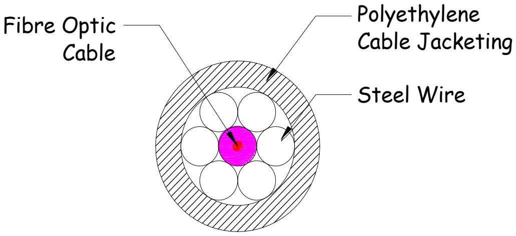


Figure 2 Configuration of strain sensing optical cable

3.0 BACKGROUND OF FIELD SITE

Static Load Test on Instrumented Test Pile was carried out by Dynamic Pile Testing Sdn Bhd from 5th to 8th February 2015 on a 1200 mm diameter pile as part of a new 1500 housing units development for government officers at Presint 17, Putrajaya. The ground conditions consisting of fairly uniform sandy silt residual soil with no encountering of bedrock. The piles for this project were designed to undertake full shaft friction only (ignored the contribution of base resistance). Figure 3 shows the construction of 23.9m test pile bored using dry hole method.

3.1 Instrumentation

A pair of vibrating wire strain gauges (VWSG) was tied to the main reinforcement bars (T25) at Level 1 to Level 5 and two pairs of VWSG were tied to Level 6 as indicated in Figure 3. Two pairs of distributed fibre optic strain sensing (S1a-S1b & S2a-S2b) cable were also fixed to the main reinforcement bars from top to

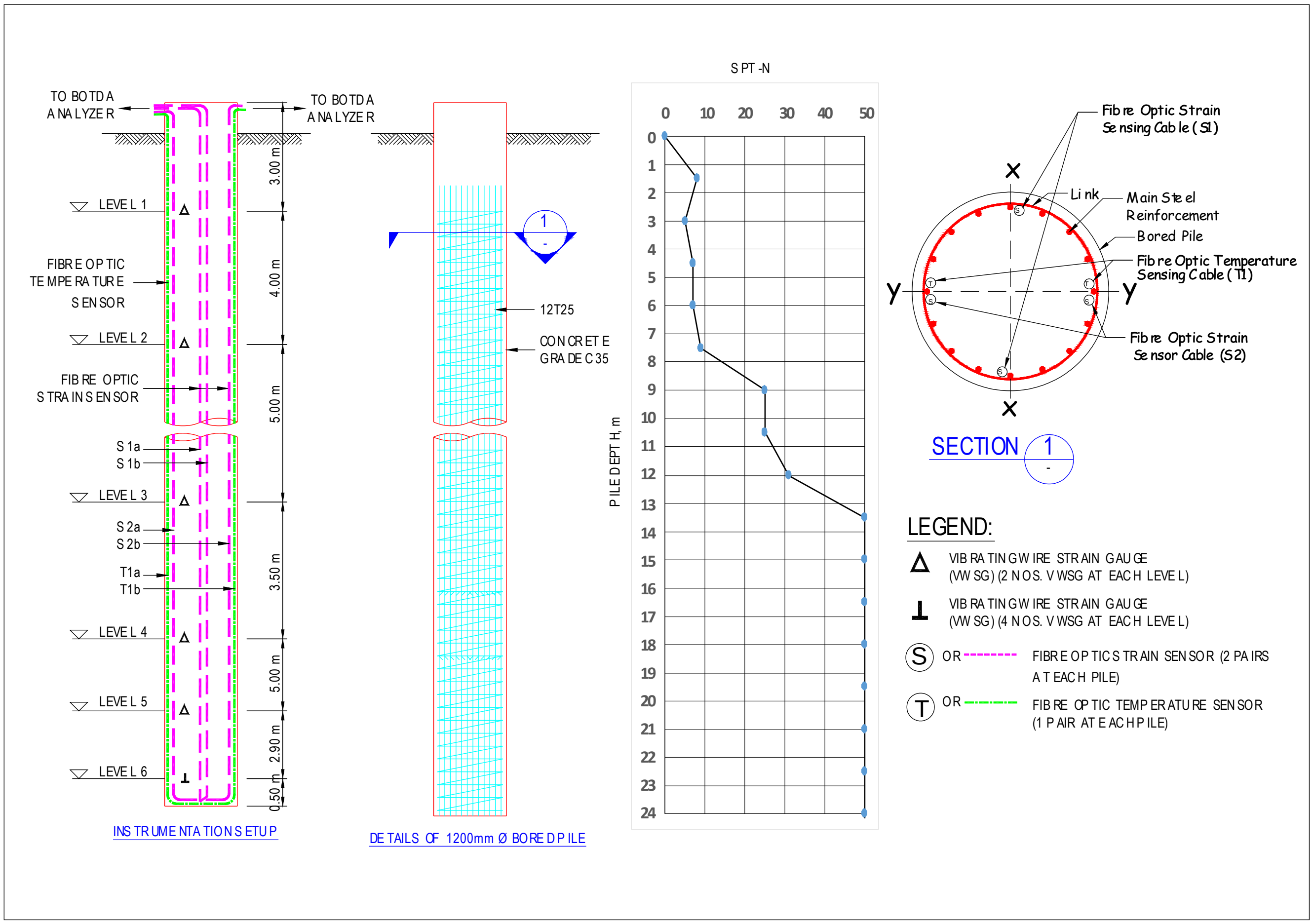


Figure 3 Instrumentation setup, bored pile detail and SPT-N value of bored hole

toe of pile (see Figure 3). Another pair of distributed temperature sensing (T1a-T1b) cable was also installed side by side with S2a-S2b. Temperature measurement was used to compensate differential temperature effect to strain reading during each round of measurement in case if any.

A pair of 1500 tonnes hydraulic jack was used to load the pile to the designated load (refer Figure 4). Load cells were used to measure the amount of load transferred to pile. Linear Voltage Displacement Transducers (LVDTs) was used to measure pile top settlement.

The electrical lead wires from the VWSGs and the optical cables were brought to the top of the pile with all the cables tied to the steel cage. Galvanized iron pipes (to locate the rod extensometer) were mounted and installed on the first and second main reinforcement bars. Figure 5 shows the various instrumentation devices mounted on the steel cage prior to the concrete casting.

3.2 Load Test Procedures

The maintained load test was conducted in accordance to ASTM D1143 (Standard Test Method for Piles Under Static Axial Compressive Load) [6]. The

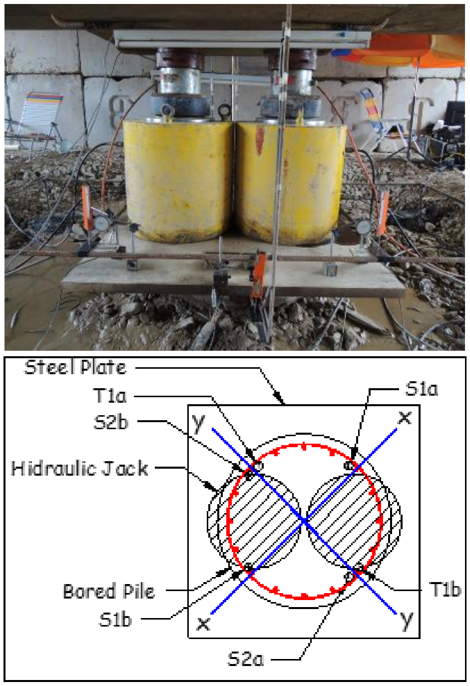


Figure 4 Configuration of hydraulic jacks, load cells, LVDTs and steel plate setup at pile head

pile was loaded in two cycles. LVDTs reading were taken at interval of 15 minutes for each loading and unloading steps. While maintaining of the maximum load at each cycle, transducer readings were taken at 15 minutes for the first hour and hourly interval thereafter.

The BOTDA analyser was set with spatial resolution of 5ns, which is equivalent to a gauge length of 50cm. However, the reading trace can be plotted at every 5cm along the cable's distance as shown in Figure 6. Figure 6 shows the typical raw data of BOTDA measured continuously along the strain sensing cable in two loops inside the pile. The first loop consists of sections marked as S1a and S1b and the second loop as S2a and S2b. In this study, each reading was 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. Calibration in laboratory was performed beforehand by applying consistent strain increment to the sensing cable for up to 3000 με and relate the quantity of strain changes to the quantity of frequencies shifted. In this case, the strain coefficient obtained was 20με/MHz.

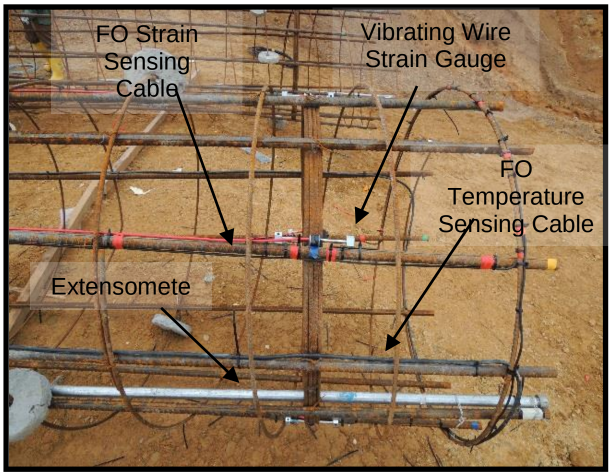


Figure 5 Installation of VWSG, extensometer, and DOFSS cables

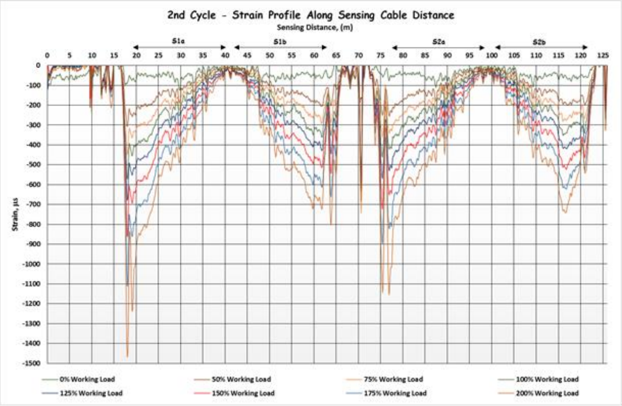


Figure 6 Example of raw data from BOTDA trace

4.0 CALCULATION

4.1 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 with respect to the axis. As shown in Figure 9, the measured strains ε_1 and ε_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).

$$\varepsilon(z) = (\varepsilon_1 + \varepsilon_2)/2 \qquad (1)$$

$$u(z) = \int \varepsilon dz \qquad (2)$$

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, κ between two opposite fibres [3].

$$\kappa(z) = (\varepsilon_1 - \varepsilon_2)/D = M/EI \qquad (3)$$

where,

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

M is bending moment, and

EI is flexural stiffness of the pile.

4.2 Shaft friction

For soil-structure interaction problems, the interaction forces, P(z) acting on a pile shaft (Eq. (4)) are evaluated by accurate evaluation of the strain distribution within the pile. If a complete distribution of strain along the pile is given, the skin stress, τ and displacement can be obtained by differentiating (Eq. (5)) and integrating (Eq. (2)) the distributed strain data, which in turn results in transfer load functions.

$$P(z) = \varepsilon EA \qquad (4)$$

where EA is the pile's axial stiffness.

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

5.0 MEASUREMENT RESULTS

Figure 7 shows the pile load displacement curve. At the first cycle, ultimate load of 11802kN induced maximum settlement of 4.86mm, and at 22163kN in the second cycle, the settlement at the top was 14.5mm. Figure 8 shows the mobilisation of unit shaft frictions calculated from the vibrating wire strain gauges (VWSG) and Fibre-Optic (FO) sensors. Both calculated unit shaft frictions are well matched except at Level 1 (-3m)to Level 2 (-7m). In general, the shaft frictions were fully mobilised on the upper portion of pile (first 15m) while the skin frictions from the bottom half adequately able to carry the two times of the pile's designed load.

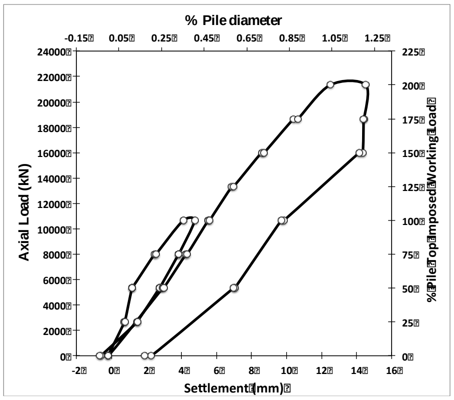


Figure 7 Load - displacement for test pile

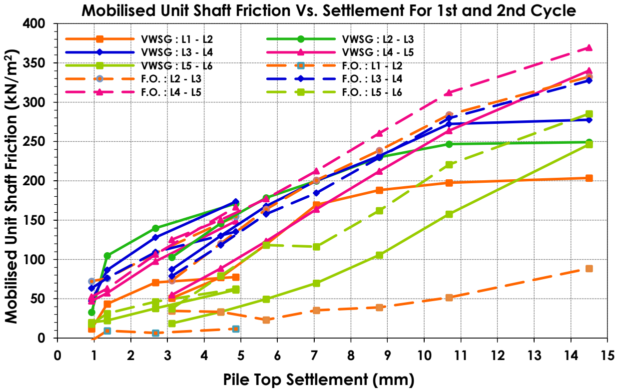
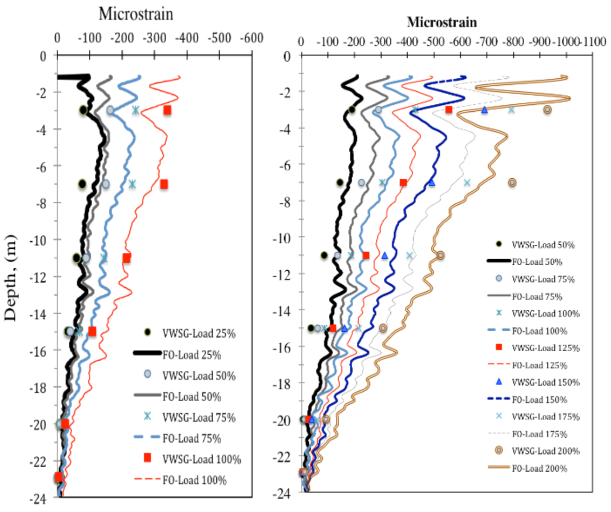


Figure 8 Mobilised unit shaft frictions calculated from VWSG & Fibre-Optic Sensor

Figure 9 compares the strain measurements from VWSG and Fibre-Optic (FO) sensors, both of which showed excellent agreement between them. It can be seen that the load transfer of the pile as being mainly through its shaft friction and very little load is transferred to the base. However, there were some sorts of noise or anomalies in the strain regime recorded by FO sensors, i.e. a distinctive zigzag pattern at the earlier depths (first 4m) and localised spikes at depths of -13m and -16m.

The main problem of such strange strain readings recorded at the top is attributed to the cable being in the loose condition and not tied to any reinforcements. It was reported during pile construction that the placement of steel cage has sunken a few metres deeper than the specified depth prior to the concreting. This has left the borehole with no reinforcements in the first three metres and no instrumentation to record the topmost movement of pile except FO sensors which gave incorrect strain distributions (from 0 to -3m) from its loose condition.

In addition, the odd strains at the top can also be attributed to the uneven jacking forces between the pair of load cells (one of the cells was malfunctioning and did not achieve the prescribed force).The hydraulic jack jammed and restarted after 7 hours. This eccentric loading would have caused the pile to slightly bend (as depicted in FO data in Figure 10) and consequently affected the axial force distribution near the pile's top. Moreover, FO strain pattern from two fibres of each loop is not identical at the first 6m as indicated Figure 11(a) and Figure 11(b).



(a) (b)

Figure 9 Strain distribution of pile during loading test of (a) cycle 1, (b) Cycle 2 from Loop 1

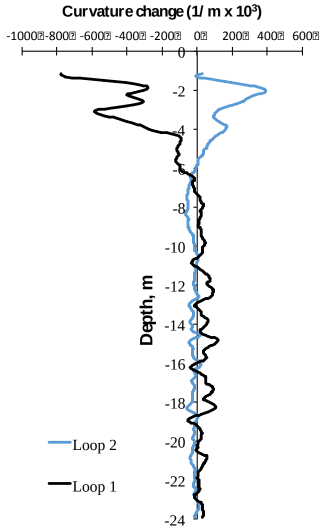
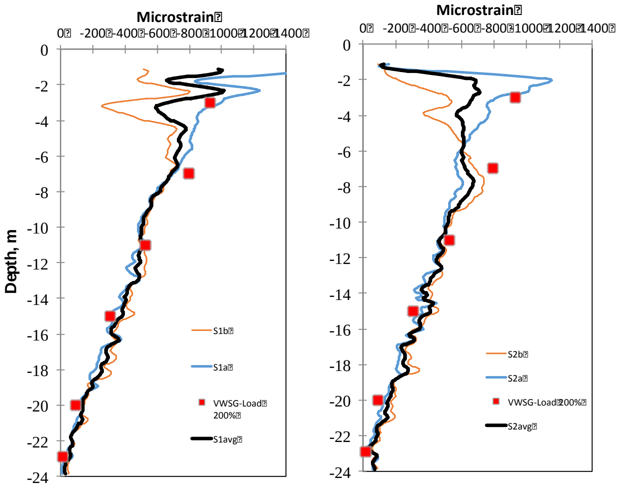


Figure 10 Curvature profiles of the pile in both directions

Evidence of the pile's bending can be observed in the curvature plots (Figure 10) which can be calculated from Eq. (3) between the two sets of fibres. The FO data indicate existence of minor bending strains from top to -6m for Loop 1 and -10m for Loop 2. Note that for data consistency, only data from Loop 1 are used for further analysis (less noisy compared to Loop 2) in this article.



(a) (b)

Figure 11 Strain distribution of individual fibres of (a) Loop 1, (b) Loop 2 measured at 200% Working Load

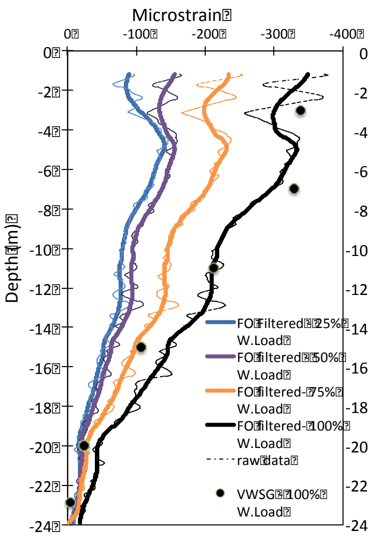


Figure 12 Example of FO filtered data from the first cycle

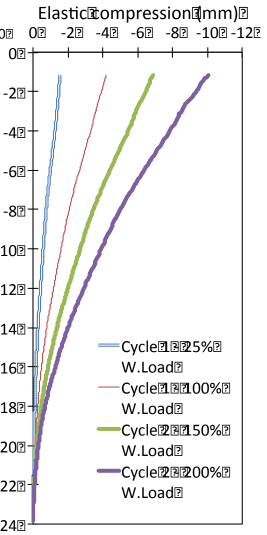
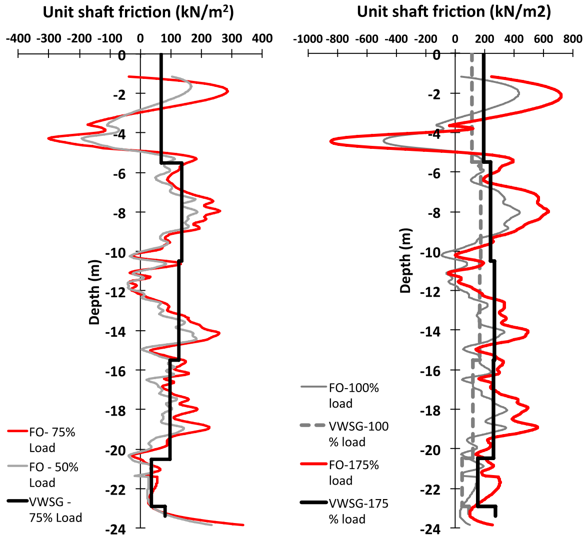


Figure 13 Example of FO data converted into displacement

5.1 Comparison Of Unit Shaft Frictions

In order to perform derivative of the pile load function or strain distribution into shear resistance, τ (Eq. (5)), the FO data must firstly be filtered in order to get a meaningful data and to eliminate any random noise (Figure 12). In this study, a third order Savitzky-Golay polynomial curve is adopted [7] that is averaged over 5 m length (101 data points). The mathematical algorithm was performed using MATLAB program. Other filtering technique is possible, such as moving average, smoothing spline, etc., however, further study is needed to check the influence of such method to the derivative results. Conversely, when analysing the displacement (elastic compression) of the pile, the noise from FO data are automatically eliminated from the integration process (Eq. (2)), hence no data filtering is needed in this case. Figure 13 presents the measured elastic compression obtained from FO sensor, numerically integrated using trapezoidal rule.



(a) First cycle (b) Second cycle

Figure 14 Derivative of the pile's skin friction

Figure 14 compares the unit shaft frictions of instrumented pile between VWSG and FO sensor. The elasticity modulus of the pile is taken as 30GPa. The obvious differences between the sensors are that VWSG data are discrete and limited to 6 depths, meaning only a constant shaft friction profile can be obtained between each depth, whereas in FO sensors, the derivative profile is continuous and changes at every 5cm along the shaft. In general, the VWSG's shaft frictions are rather constant; an averaged roughly of 100 kPa in the first cycle and 200 kPa in the second cycle, whereas FO's shaft friction (disregarding the fact that the top part of the pile measurements from FO were incorrect, i.e. 0 to -4m) can vary ±300kPa in Figure 14(a) and ±800kPa in Figure 14(b). Nevertheless, the overall averaged unit shaft frictions from FO are fall within the same region as VWSG data. The FO negative shaft frictions at -4m depths is clearly attributed to the optical cables being slack and not representing the true performance of the pile.

Some other parts of the pile shaft also exhibit negative value in the unit shaft friction (i.e. at depth -10m to -12m in Figure14(a) and Figure 14(b) and at depth -20m in Figure 14(a)). Localized spikes (sudden increase of strain at short distance) had been measured during the load test at those depth. Those localized spikes were likely caused by sudden decrease of bored pile cross sectional area in short distance (necking). When differentiating strain profile at depth with spike, resulting gradients of negative values which are not really the true negative shaft friction.

6.0 CONCLUSION

A novel way of instrumenting bored pile using distributed optical fibre strain sensing has been successfully implemented for the first time in Malaysia. Although there were some problems of pile construction which have affected the strain measurements (no steel bars in the upper portion of the pile), the field-test results generally showed very good agreement between the conventional and Fibre Optic sensors. The main 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 require data extrapolation between limited sensing points, laborious installation time and data problems arising from local erroneous measurements. In addition, the FO sensors can also describe clearly how the out-of-plane deformation of the pile (bending) affects the load transfer performance of the pile (more field trials are needed for pile bending tests). Such information was not possible to obtain from conventional measurement system.

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References

[1] Klar, A., Bennett, P. J., Soga, K., et al. 2006.Distributed strain measurement for pile foundations. Proc. ICE, *Geotech. Engng. 159*(3): 135–144.

[2] Mohamad, H., Soga, K., and Bennett, P.J. 2009. Fibre optic installation techniques for pile instrumentation. *Proceedings of the 17th International Conference on Soil Mechanics on Soil Mechanics and Geotechnical Engineering: The Academia and Practice of Geotechnical Engineering*, IOS Press. 3: 1873-1876.

[3] Mohamad, H., Soga K., Pellew, A. and Bennett, P.J. 2011. Performance Monitoring of a Secant Piled Wall Using Distributed Fiber Optic Strain Sensing, *Journal of Geotechnical and Geoenvironmental Engineering*. 137(12): 1236-1243.

[4] Mohamad, H., Bennett, P. J., Soga K., Mair, R J and Bowers, K 2010. Behaviour of an old mansonry tunnel due to tunnelling induced ground settlement. *Géotechnique*. 60(12): 927–938.

[5] Soga, K., Mohamad, H. and Bennett, P.J. 2008. Distributed fiber optics strain measurements for monitoring geotechnical structures. *6th International Conference on Case Histories in Geotechnical Engineering (Symposium in honor of Professor James K Mitchell)*, Arlington, USA.

[6] ASTM D1143/D1143 – 07 (Reapproved 2013) *Standard Test Methods for Deep Foundations Under Static Axial Compressive Load*, ASTM International.

[7] Savitzky, A. and Golay, M. J. E. 1964. Smoothing and differentiation of data by simplified least squares procedures. *Analyt. Chem*. 36(8): 1627–1639.