Investigation of shaft friction mechanisms of bored piles through distributed optical fibre strain sensing

Etude de mécanismes de frottement d'arbres de pieux forés par détection de déformation de fibre optique distribuée

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ABSTRACT: Recent technological advancement of optical fibre sensing has led new ways in measuring the performance of geotechnical structures. 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. In bored pile instrumentation particularly, obtaining distributed strain profile is important when analysing the load-transfer and shaft friction of a pile, as well as detecting any anomalies in the strain regime. Features such as defective pile shaft necking, discontinuity of concrete, intrusion of foreign matter and improper toe formation due to contamination of concrete at base with soil particles, among others, may reduce the pile capacity. The objective of this article is to present one of the earliest deployed BOTDA optical fibre sensors in rock-socketing bored piles in Malaysia and share invaluable lessons learned from the instrumentation process. Data from the instrumented pile was used to estimate the shaft resistance of rock-socketing pile and issues related to locked-in stresses and creep are highlighted. Excellent agreement of strain measurements was recorded between fibre-optic sensors and vibrating wire strain gauges.

RÉSUMÉ : L'évolution technologique récente des systèmes de détection à base de fibres optiques a permis de mesurer les performances des structures géotechniques. La détection distribuée, à savoir l'Analyse de Domaine de Temps Optique de Brillouin (BOTDA) est une nouvelle technique continue de mesure de contraintes qui présente des avantages distincts par rapport aux capteurs à points classiques. Dans l'instrumentation de forage en particulier, l'obtention d'un profil de déformation distribué est important lors de l'analyse du transfert de charge et du frottement d'arbre d'une pile, ainsi que la détection de toute anomalie dans le régime de déformation. Des caractéristiques telles que l'étouffement du fût, la discontinuité du béton, l'intrusion de corps étrangers et la formation inappropriée des pieds par la contamination du béton à la base par des particules de sol, entre autres, peuvent réduire la capacité du pieu. L'objectif de cet article est de présenter l'un des premiers déploiements de capteurs de fibre optique BOTDA dans les pieux forés en roche en Malaisie et de partager des leçons précieuses tirées du processus d'instrumentation. Les données de la pile instrumentée ont été utilisées pour estimer la résistance de l'arbre de la pile à roche et les problèmes liés aux contraintes et au fluage sont accentués. Des très bonnes corrélations sur les mesures de contraintes ont été obtenues entre des capteurs à fibres optiques et des jauges de contrainte à fil vibrant.

KEYWORDS: fibre-optics, BOTDA, bored piles, instrumentation, soil-structure interactions

1 INTRODUCTION

Applications of distributed optical fibre sensing, namely Brillouin Optical Time Domain Analysis (BOTDA) or Brillouin Optical Domain Reflectometry (BOTDR) in piled foundations have been reported by many researchers in the past years (*e.g.* Ohno *et al.*, 2002, Klar *et al.* 2006, Tee *et al.*, 2016). The technology has been proven to have superior measurement capabilities compared to the conventional geotechnical instrumentation. These include (i) simple installation procedure (Mohamad *et al.*, 2009), (ii) simultaneous temperature and deformation measurements (Mohamad *et al.*, 2014), (iii) simultaneous axial and bending monitoring (Mohamad *et al.*, 2011), (iv) cracking or deformities detection in bored piles (Mohamad *et al.*, 2016) and (v) ability to measure continuous strain profile as compared to discrete data such as Vibrating Wire Strain Gauges (VWSG). Measuring full strain regime of a foundation structure is important as it enables a more accurate interpretation of soil-structure interaction such as unit shaft frictions, and hence correct determination of the pile capacity (Soga *et al.*, 2008).

This paper presents a real project of instrumented 800mm diameter bored pile in Kuala Lumpur with rock socketing 6m into limestone formation (Figure 1).

1.1 *Project Background*

In this project, the foundations were designed to support a 50-storey high residential building. The soil profile consists of 5m thick of shallow silty sand with some gravel (SPT values 4-7) overlying slightly to moderately fractured weak limestone formation (Figure 2). Accordingly, the pile foundations were designed mainly to rely on rock socketing friction but with no base resistance. The limestone for this site is generally consistent and the measured Rock Quality Designation (RQD) was around 70%. The design engineer adopted an initial ultimate rock friction value of 1000 kN/m^2 and proposed this instrumented preliminary test pile to verify the design parameters.

The total length of the test pile is 13.2m. Debonding zone or double steel casings were provided down to 7.2m depth. The rock socket length is 6m. The concrete is of Grade 50 and the main reinforcement consists of 11 nos. T32 steel bars (Figure 1) extending from top to toe of pile.

Down The Hole (DTH) hammer (mounted to rig LB 36) was used to drill the 800mm diameter hole. The DTH technique provides fast drilling into rocks and is uncommon in Malaysia. For this pile, the 6m length of rock coring took less than 3 hours to complete compared to normal rotary drilling method where the process may take one or two days.

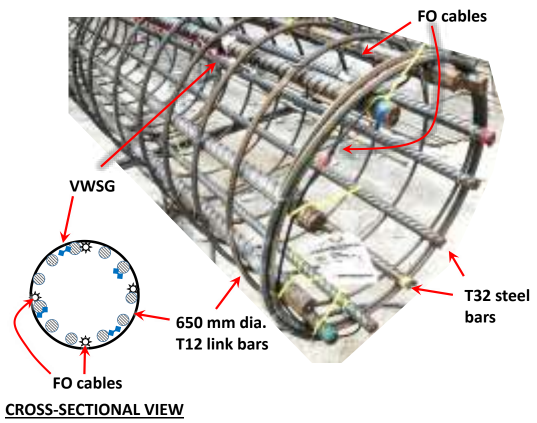


Figure 1. Instrumentation of steel armoured optical fibre cables (FO) and Vibrating Wire Strain Gauges (VWSG) on the main reinforcement bars. The FO needs only cable ties assembly whereas VWSG mounting requires steel welding.

2 STATIC PILE LOAD TEST

This static pile load test was carried out according to ASTM D 1143/D 1143/M – 07. The instrumentation setup in the pile is shown in Figures 1 and 2.

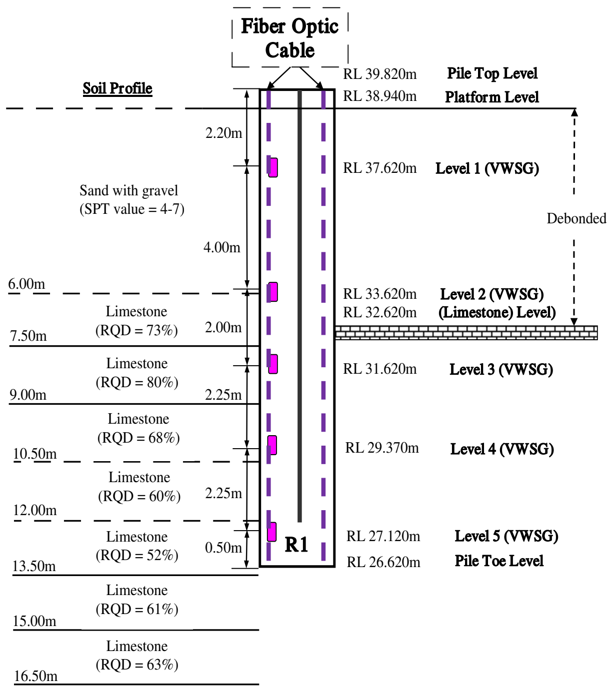


Figure 2. Instrumentation setup in test pile with 5 levels of strain gauges

The test pile was instrumented with distributed fibre-optic sensor (FO) and conventional sensors, i.e. vibrating wire strain gauges (VWSG), tell-tale extensometer and Linear Voltage Displacement Transducers (LVDTs).

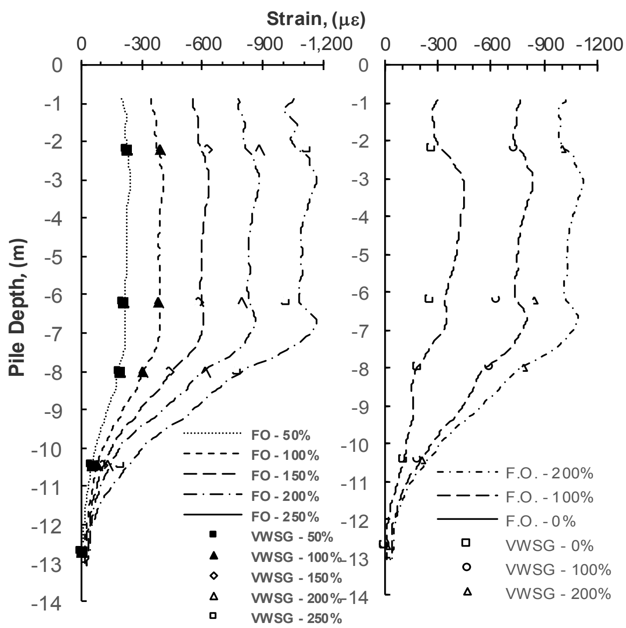
Two pairs (two loops) of distributed optical fibre strain sensing cable were fixed to the main reinforcement bars from top to toe of pile. These two pairs of distributed optical fibre sensor provide continuous strain profile along the four sides of the pile, which data are then averaged for further analyses on shaft friction (distance derivative of the strain profile) and to obtain the elastic shortening profile of the pile (integral of strain). Four sets of VWSG were installed at five different levels as indicated in Figure 2. A tell-tale extensometer was also installed in the test pile.

Four sets of hydraulic jacks were used to jack the pile to the designated load. Load cells were used to measure the amount of load transferred to pile. Linear Voltage Displacement Transducers (LVDTs) were used to measure pile top settlement.

The static load test was conducted in accordance with the load cycle and load programme given by the consultant. The pile Working Load (WL) is 6,900kN. The test pile was loaded to maximum 3 times WL or 20,700 kN in three load cycles. For the 1st cycle, the maximum test load was 1 × WL with 2 steps of load increment. For the 2nd cycle, the maximum test load was 2.5 × WL with 8 steps of load increment, and for the final cycle, the maximum test load was 3 × WL with 9 steps.

2.1 *Strain profile*

Figure 3 compares the strain measurements from the vibrating wire strain gauges (VWSG) and Fibre-Optic (FO) sensors, both of which showed excellent agreement between them. It can be observed that no shaft friction (constant strain) on the first 7m of the debonded pile with the use of double steel casings. The shaft friction development is mainly through the limestone layer with very little load transferred to the base. Figure 3(a) shows the unloading strain profile. After completion of 2nd cycle (0% load), both VWSG and FO data indicate there is a significant residual strain recorded along the shaft. This observation is further analysed in Section 3.



(a) (b)

Figure 3. Strain distribution of test pile measured during (a) Loading, and (b) Unloading cycles

2.2 *Back calculated concrete modulus*

Concrete modulus is not constant through the range of compressive loads during the load test. To compute load transfer curve (*t-z*), back calculated concrete modulus is required, assuming cross-sectional area of the concrete is uniform throughout the pile length. Figure 4 is a comparison of back-calculated concrete modulus analysis based on "Secant Modulus" approach proposed by Fellenius (2001). Both back-calculated concrete moduli are well matched. The authors used the first layer of VWSG near pile top to calibrate/back calculate secant concrete modulus. In this study, it is assumed that the "back-calculated strain dependent concrete modulus *E*" is uniform throughout the pile length.

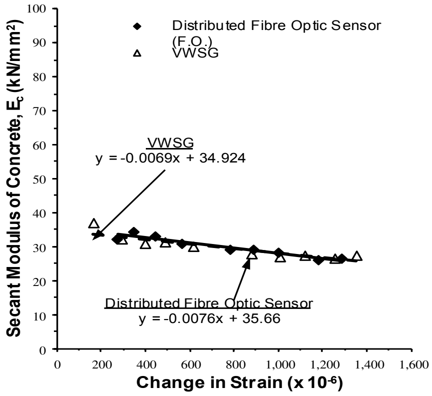


Figure 4. Back-calculated secant modulus of concrete

2.3 *Shaft friction*

Figure 5 shows the corresponding mobilised shaft friction. Both the computed shaft frictions derived from the fibre-optic and VWSG strain data are in good agreement. As expected, Level 1 to 2 which was debonded did not show any significant shaft friction. For Level 2 to 3 and Level 3 to 4, the mobilised unit shaft friction of limestone is approximately 700 kN/m^2 and 1800 kN/m^2 respectively. In the case of Level 2 to 3, a lower mobilisation of unit shaft friction was observed, may be due to mobilisation of end bearing by permanent casing. For Level 4 to 5, the unit shaft friction continues to rise even when the pile was tested at 3 times working load. This indicates that the actual rock friction could be higher and the load applied was insufficient to mobilise the ultimate shaft friction.

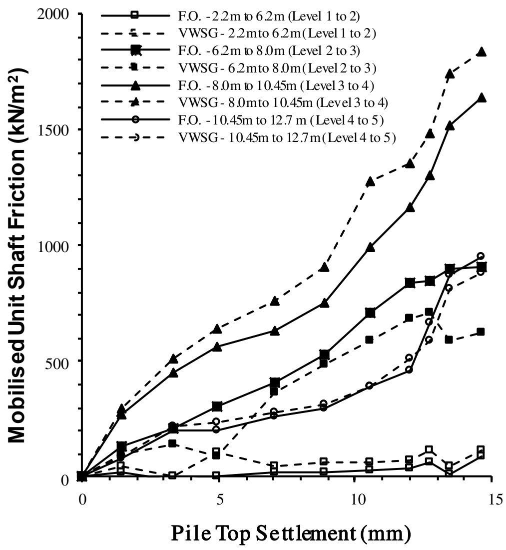


Figure 5. Mobilised unit shaft friction

2.4 *Comparison with Extensometer*

By numerically integrating the FO strain data along the pile shaft, one can obtain the total compression or elastic shortening of the pile which can yield comparable result with the tell-tale rod extensometer (Mohamad et al., 2016). This is demonstrated in Figure 6 as pile top settlement at peak load. As can be seen in the figure, the graph plotted using FO sensor data showed a more linear response and more realistic trend than that of tell-tale extensometer, which is a bit "wavy" or non-linear. Under the load of maximum 22 MN, the FO sensor recorded compression of 13.2 mm as compared to 15.7 mm by the extensometer. In addition, one can easily obtain any displacement points along the pile using FO data, and can avoid the use of tell-tale extensometer.

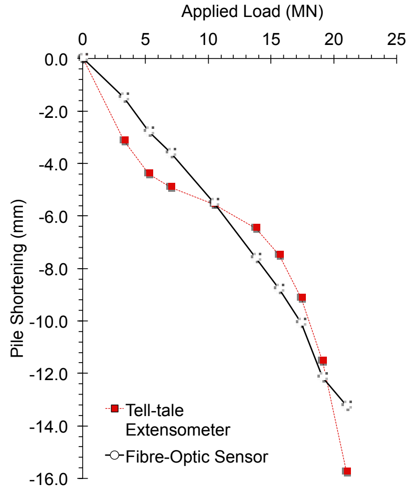


Figure 6. Measurement of elastic compression of the pile with increasing load

2.5 *Calibration/ Accuracy with VWSG*

Figure 7 shows a summary of all the measurement points between FO and VWSG at five different depths measured during the three loading cycles. Excellent agreement and measurement consistency can be observed in the strain data, meaning the observed deformation of the pile can be assumed to be real.

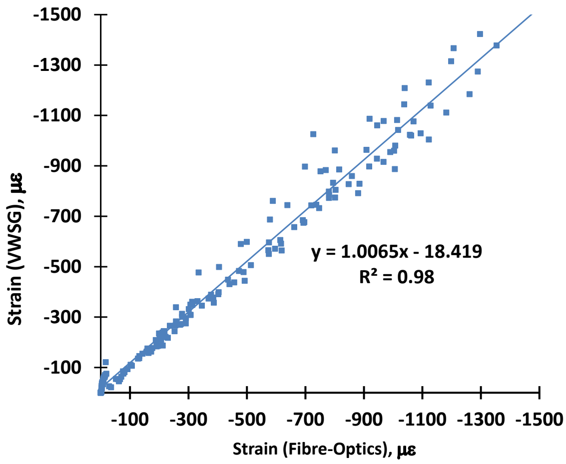


Figure 7. Agreement of strain reading points between VWSGs and FO located at the same depths of various loading cycles.

3 LOCKED-IN STRESSES DUE TO CYCLIC LOAD

Ideally, cycling of load should be avoided especially for instrumented test pile with main objective to measure pile shaft resistance. With unload-reload cycle, locked-in stresses or additional internal compressive load, or commonly referred to as residual settlement, may develop in the pile. This locked-in stresses vary disproportional throughout the pile. During unloading, internal compressive load develops because the lower portion of pile tends to force the pile moving upward, while negative skin friction develops along the upper portion of pile. The distribution and direction of shaft resistance will vary with depth which lead to difficulties in the interpretation of the strain data (Siegel, 2010).

Locked-in stress distribution along the pile shaft and toe during unloading can be clearly seen from the continuous strain profile (Figure 3(b)). Conventional point sensor is not able to provide this type of continuous strain profile unless installed at very close spacing, which is not practical and too costly. With better understanding of locked-in stresses distribution, interpretation of strain data can be greatly improved.

4 CREEPING BEHAVIOUR

Creep occurred during the pile load test when the tester attempted to maintain a constant load for a longer time interval. Siegel (2010) suggested that this attempt is not necessary. Once the pile moves approximately 2.5 to 5mm, shaft resistance along the upper portion of pile will begin to decrease after its peak value. Each attempt to re-establish the target load will result in further decrease in shaft resistance along the upper pile due to remoulding at the shaft-soil interface which may be offset by the mobilisation of additional shaft resistance in the lower pile and/or toe resistance.

With continuous strain profile obtained from BOTDA, the creep effect can be seen clearly throughout the whole length of pile. Figure 8 shows a few sets of data recorded with constant load maintained for 6 hours at 2×WL and 24 hours at 2.5×WL respectively. The strain in the pile increased without additional load which is clear evident of creep effect occurred. The upper debonded portion shows constant increasing creep rate (purely structural creep). For the rock socketing zone, the upper portion experienced slightly higher strain increment compared to the lower part and contributed to additional mobilised shaft resistances.

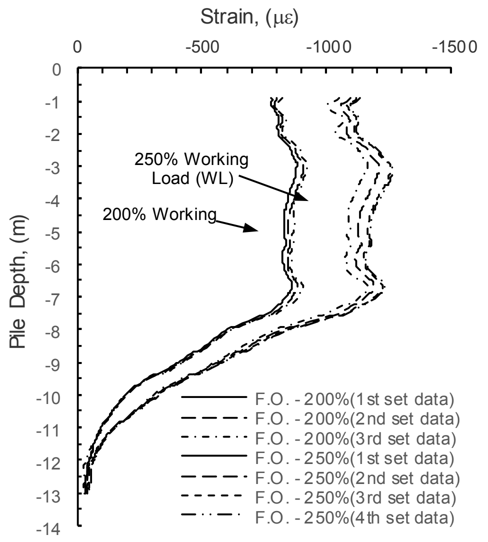


Figure 8. Example of creeping behaviour observed during data acquisition from BOTDA measurements under constant loading.

5 CONCLUSION

A novel way of instrumenting bored pile using distributed optical fibre strain sensing has been successfully implemented for the rock socketing pile. It was concluded that the pile design was safe. The ultimate unit shaft friction mobilised of the limestone was recorded approximately 1800kN/m^2 which was higher than the initial design ultimate rock friction of 1000kN/m^2. The value of load transfer at Level 5 (which is 500mm away from toe of the pile) recorded from both VWSG and FO sensors was apparently very small. It was considered there is no load transfer to the base. This observation supports the initial design philosophy that not to allow load to transfer to the pile base.

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 require data interpolation between limited sensing points, laborious installation time and data problems arising from local erroneous measurements. In addition, FO sensor can be configured and integrated into structure to measure three-dimensional deformation such as bending and shortening of piles. This potentially eliminates the need to install various instrumentation schemes such as inclinometer, rod extensometers and minimisation of instrumentation cost.

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