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Special Contribution

Enhancing Bored Pile Integrity Evaluation and Anomaly Issues with Disturbed Fibre Optic Sensor Technology: A Case Study

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Abstract

The integrity of cast-in-place foundation piles is a major concern in geotechnical engineering. This study outlines a method for identifying common defects in bored cast-in-situ piles during instrumented load tests using Distributed Optical Fibre Strain Sensing (DOFSS) technology. DOFSS technology relies on Brillouin Optical Time Domain Analysis (BOTDA), which offers the advantage of recording continuous recording strain profiles, in contrast to traditional discrete sensors like Vibrating Wire strain gauges. In the context of pile instrumentation, obtaining a distributed strain profile is crucial for analysing a pile's load transfer and shaft friction while detecting irregularities in the strain pattern. Defects such as necking of the pile shaft, concrete disruptions, foreign material intrusion, and improper toe formation due to soil particle contamination at the base can potentially lead to pile failure. This study introduces a novel approach to detecting such defects using DOFSS technology, which may serve as a valuable addition to existing non-destructive testing (NDT) methods. Additionally, the paper includes discussions on the performance of instrumented piles based on maintained load tests.

Keywords: Pile, Fibre Optic Sensor, Integrity testing

1. Introduction

Pile foundations have a rich history spanning thousands of years, but the last five decades have witnessed a significant increase in the usage of concrete piles. As we've embraced larger diameter and longer piles, concerns about the quality and integrity of cast-in-place foundation piles have grown. This concern is exacerbated by the inherent challenges in inspecting these piles, given their substantial depth, limited accessibility, and the potential instability of the shafts. Furthermore, repairing pile foundations can be a complex and expensive endeavour, especially when addressing significant defects. As a result, there is a substantial demand for effective testing techniques to assess the integrity of bored piles. Traditional methods for evaluating pile integrity include cross-hole sonic logging (CSL), sonic echo (SE) testing, radiation-based gamma-gamma logging (GGL), and, more recently, thermal integrity testing methods like thermal integrity profiling.

In civil engineering, the use of Distributed Fibre Optic Strain Sensing Systems (DFOS) has only gained traction in the past decade. Initially, universities and research institutions were the primary adopters of DFOS for academic investigations (Iten, 2012). Over time, this technology has started to garner interest from the industry, gradually shifting from a purely research-oriented tool to one with practical applications. Notable references include the works of Feng et al. (2013), Gao et al. (2015), Glisic and Inaudi (2012), Hoult et al. (2014), Leung et al. (2015), and Zeni et al. (2015). The increasing recognition of DFOS in the domain of structural health monitoring can be attributed to its numerous benefits, which include a dense collection of spatial data, straightforward installation, and dependable performance.

Instrumented test piles are vital in validating pile performance and assessing geotechnical capacity. One major disadvantage of using conventional instruments such as strain gauges in instrumented pile load tests is that each sensor requires an individual cable for measurement. It ends up with complicated cable management required during the measurement process. To enhance the efficacy of instrumented test piles and achieve more precise geotechnical parameter determination through load-transfer analysis, there is a need for a more comprehensive and dependable system. This research introduces a novel approach by utilising DFOS with Brillouin Optical Time Domain Analysis (BOTDA) technology to enhance the functionality of instrumented test piles. BOTDA is an advanced technique for measuring continuous strains, with inherent distinct advantages over conventional point-wise sensors (Mohamad and Tee, 2015). This paper presents a case study of an instrumented load test carried out on top loaded bored pile using a DFOS technique. This innovation improves accuracy in load transfer analysis for piles and complements the existing pile integrity testing methods.

2. Principle Measurement and Pile Instrumentation

2.1. Brillouin Optical Time Domain Analysis (BOTDA)

In this research, a commercially available BOTDA from OZ Optic Ltd. was employed to assess the distribution of loads along the pile shaft. The BOTDA sensor operates by utilising two distinct light sources launched from opposite ends of an optical circuit. The system relies on the principle of backwards stimulated Brillouin scattering (SBS), where a pumping pulse light is launched from one end of the optical fibre and travels within the fibre, while a continuous wave (CW) light is launched from the opposite end and propagates in the opposite direction (as illustrated in **Fig. 1**). In this setup, the pump pulse generates backward Brillouin gain while the CW light interacts and amplifies the pump pulse light, creating stimulated Brillouin scattering. The Brillouin frequency shift within the single-mode fibre is directly proportional to changes in strain or temperature at that specific scattering location. A complete strain profile can be subsequently determined by precisely measuring these frequency shifts and propagation times. One notable advantage of BOTDA, compared to other distributed strain sensing systems like BOTDR (Brillouin Optical Time Domain Reflectometry), is its capacity to obtain data with greater precision.

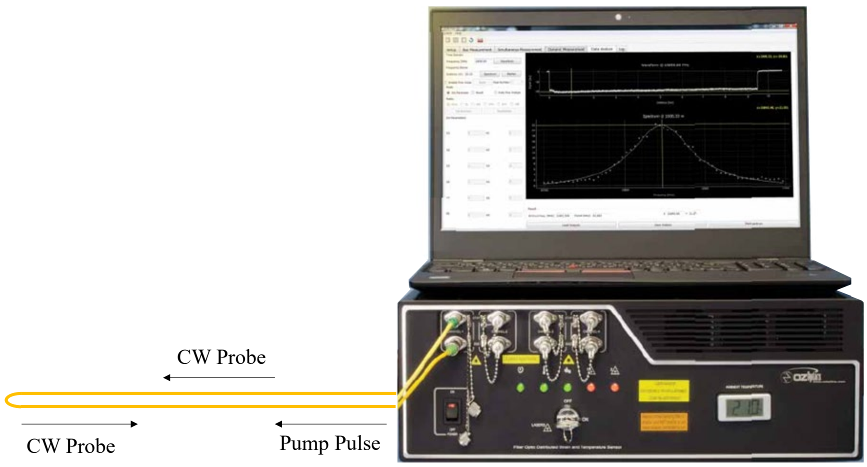

Fig. 1. Principle measurement of the BOTDA system

2.2. Distributed Fiber Optic Strain (DFOS) Sensing Cable

A 5.0 mm diameter optical cable that was designed to be embedded inside cast-in-situ concrete piles is shown in **Fig.2**. Six strands of steel wire reinforce the single-core, single-mode optical fibre in this cable, and it is covered in a polyethylene cable jacket. To make sure that any external strain caused by the concrete is ultimately transferred from the exterior coating to the inner core, the inner glass core and the outer plastic sheath are securely linked (Mohamad et al., 2011).

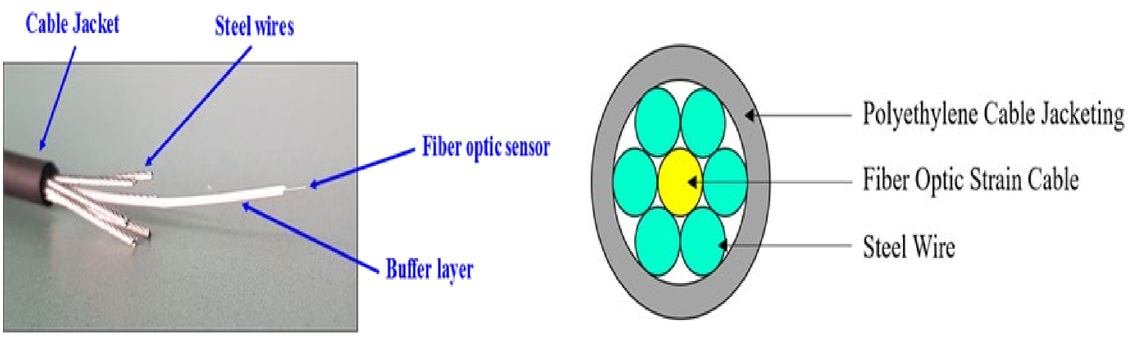

Fig. 2. Fiber optic strain sensing cable

3. Installation and Procedure

This study aims to develop a method of instrumented test pile on the cast in-situ bored pile by using a distributed fibre optic sensor via BOTDA. Two study areas, Bangi (TL1) and Kuala Lumpur Town Centre (TL2), have been chosen to test the pile.

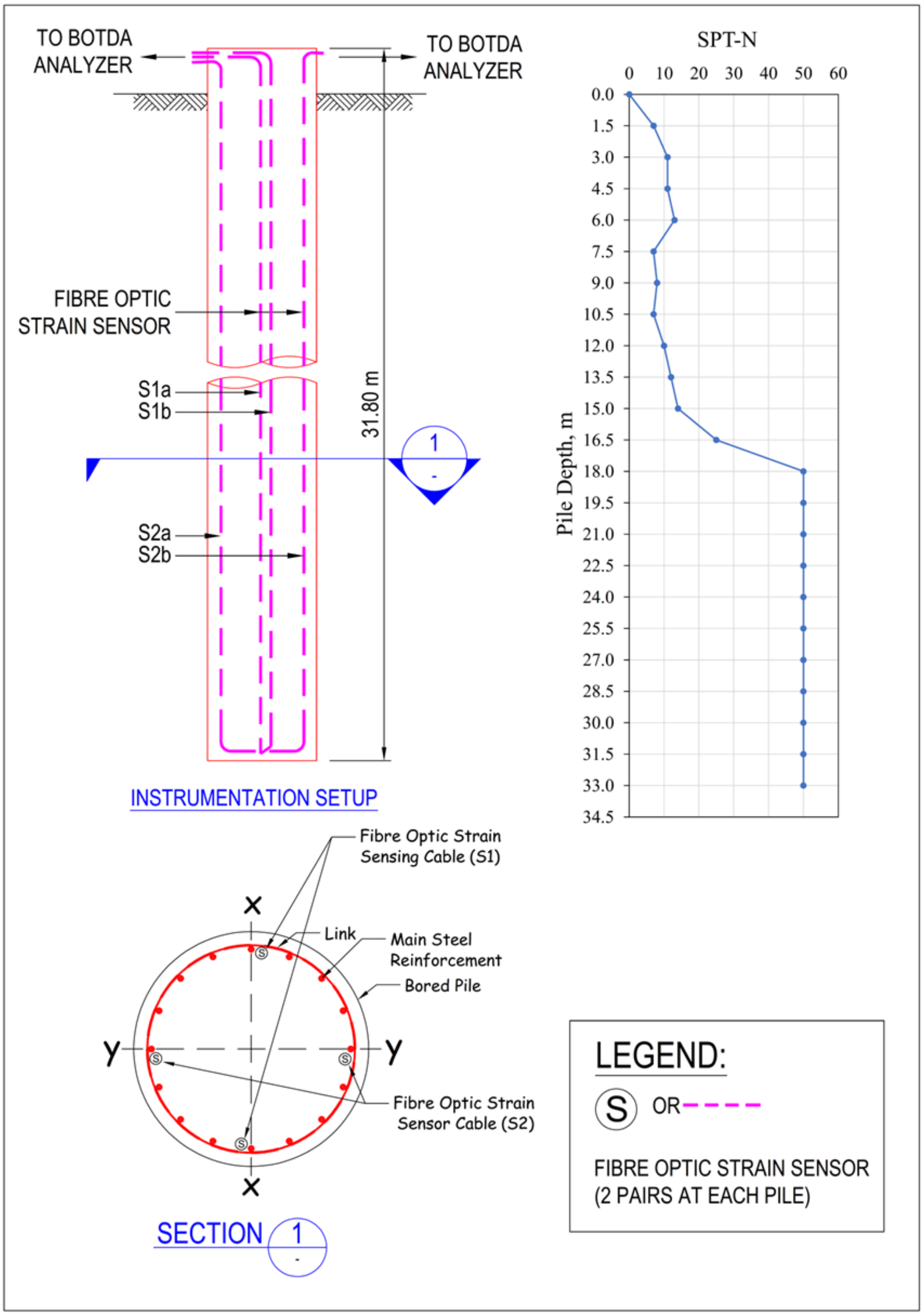

Fig. 3. Instrumentation setup in test pile (TL1)

3.1. Top Loaded Static Load Test on Cast-in-situ Bored Pile for TL1

The TL1 was equipped with DFOS. Concrete coring and an unconfined compression test validated the pile's integrity and anomalous. The diameter of the pile was 1200 mm. The details of the test pile are presented in **Table 1**. This test pile has a length of 31.8 m. According to the soil investigation report, the first 15.0 m of the soil was not hard, with SPT-N values ranging from 20 to 30. Beyond 18.0 m of depth, there was a hard layer with SPT-N > 50. The test pile was constructed using grade 30 concrete and a 12T25 primary reinforcing cage. Polymer was the stabilising fluid that was utilised to drill the hole. This test pile was installed with the DFOS to measure the strain along the pile during the loading stages. The optical cables were brought to the top of the pile with all the cables tied to the steel cage. From the top to the bottom of the pile, two pairs of distributed fibre optic strain sensing cables (S1a-S1b & S2a-S2b) were fixed to the major reinforcing bars (see **Fig. 3**). The continuous strain profile provided by these two pairs of distributed fibre optic sensors along the pile can be used to calculate the continuous shortening profile of the pile.

Table 1. Detail of instrumented test pile (bored pile – TL1)

Type of Test Pile	Bored Pile (TL1)
Pile Diameter	1200 mm
Working Load	7200 kN
Test Load	14400 kN
Types of Instrumentation	Fibre Optic Strain Cable
Test Equipment	Linear Voltage Displacement Transducers (LVDTs) Load cells Hydraulic jacks
Location	Bangi, Selangor
Pile length	31.8 m

3.1.1. TL1 Testing Procedure

This test used two hydraulic jacks to deliver axial loads to the pile's top. Two load cells were placed between the pile top and the hydraulic jacks to quantify the actual force imposed on the pile. Linear Variable Differential Transformers (LVDTs) were also used to measure the settlement of the pile's top.

The methods used to carry out the static load test were following ASTM D 1143/D 1143/M - 20 (2020). A predetermined load cycle and program were followed throughout the static load test. Two loading cycles totalling 14400 kN, or a maximum load of two times the Working Load (WL), or 7200 kN, were applied to the test pile. With five incremental load steps, the first cycle's maximum test load was set at 1 WL. The maximum test load was doubled to 2 WL in the second cycle, with 10 load increment steps.

The spatial resolution of the BOTDA analyser was set to 5 nanoseconds, which corresponds to a gauge length of 50 cm. It should be noted that readings could be taken at 5 cm intervals along the cable's length. At each loading stage, measurements were taken. The data collected from numerous instruments was evaluated to find any problems or anomalies with pile integrity. Additionally, the pile's integrity and any anomalies were cross-validated using test methods such as concrete coring and unconfined compression testing.

3.2. Top Loaded Static Load Test on Cast-in-situ Bored Pile for TL2

The TL2 was outfitted with DFOS. The integrity and anomaly of the pile were checked by exposing the pile structure for visual inspection. The pile had a diameter of 900 mm. **Table 2** contains information about the test pile.

This test pile has a length of 43.3 m. According to the soil investigation report, the first 31.5 meters of the foundation were not hard, with SPT-N values in the 20s. Beyond 31.5 m depth, there was a hard layer with SPT-N > 50. The test pile was built with grade 40 concrete and a 14T16 primary reinforcing cage. The polymer was employed as a stabilising fluid during the hole-drilling process.

The DFOS was installed with this test pile to measure the strain along the pile during the loading stages. **Fig. 4** depicts the instrumentation setup. All optical cables were carried to the top of the pile and fastened to the steel cage. Two pairs of distributed fibre optic strain sensing cables were attached to the major reinforcing bars from pile top to pile toe. These two distributed fibre optic sensing cables offer a continuous strain profile along the pile, which was utilised to calculate the pile's continual shortening profile and detect any pile integrity issues or anomalies. At each loading and unloading stage, LVDT readings were taken.

Table 2. Detail of instrumented test pile (bored pile – TL2)

Type of Test Pile	Bored Pile (TL2)
Pile Diameter	900 mm
Working Load	5500 kN
Test Load	11000 kN
Types of Instrumentation	Fiber Optic Strain Cable
Test Equipment	Linear Voltage Displacement Transducers (LVDTs) Load cells Hydraulic jacks
Location	Kuala Lumpur Town Centre
Pile length	43.3 m

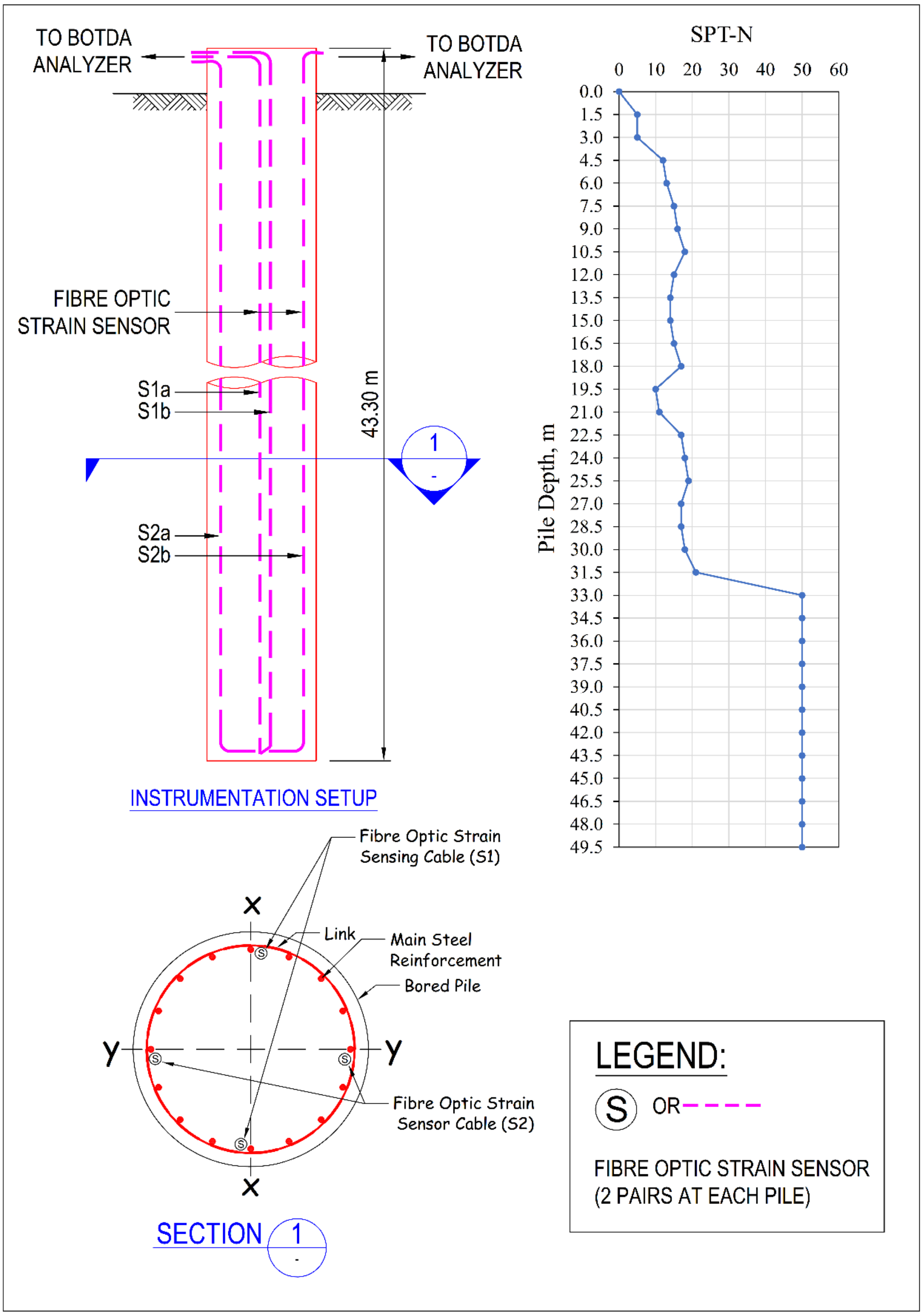

Fig. 4. Instrumentation setup in test pile (TL2)

3.2.1. TL2 Testing Procedure

In this experiment, two hydraulic jacks were utilised to apply axial loads at the top of the pile. Two load cells were positioned between the pile's top and the hydraulic jacks to measure the actual load applied to the pile accurately. LVDTs (Linear Variable Differential Transformers) were employed to monitor the settlement of the pile's top.

The static load test procedures followed the guidelines outlined in ASTM D 1143/D 1143/M – 20 (2020). The static load test was carried out according to the prescribed load cycle and program. The test pile was subjected to a maximum load of 2 times the Working Load (WL), equal to 5500 kN, or a total of 11100 kN distributed over two loading cycles. The maximum test load was set at 1 × WL in the first cycle, with four incremental load steps. In the second cycle, the maximum test load was increased to 2 × WL, with eight load increment steps.

The BOTDA analysers were configured with a spatial resolution of 5 nanoseconds, which corresponds to a gauge length of 50 cm. Notably, readings could be recorded at 5 cm intervals along the cable's length. Measurements were taken at each loading step. The data from various instruments were analysed to identify any issues related to pile integrity or anomalies. Furthermore, the pile's integrity and any anomalies were confirmed by visually inspecting the pile structure.

4. Measurement Results

4.1. Top Loaded Static Load Test on Cast-in-situ Bored Pile -TL1

With the continuous strain profile, DFOS is able to detect anomaly measurements in some of the test piles and subsequently increase the reliability of pile performance interpretation. For TL1, a DFOS sensor was installed in the test pile. Anomalies measurement was detected near the pile head. A coring test was carried out on the test piles to verify the problem physically. The mentioned test pile diameter is 1200 mm in diameter and 32 m in length. The whole length of the pile is constructed in soil strata with the top 10m in a soft layer with SPT N value ≈ 10. As shown in **Fig. 5**, the continuous strain profile was measured during the load test.

With the low SPT N value near the pile top, the pile top was not expected to have high soil friction. The strain profile near the pile top was expected to be nearly vertical with a gentle gradient. As the anomalies were near the pile head, a core test can be carried out to verify the concrete quality relatively easily. A 3 m length of the concrete sample had been cored out from the pile at the pile head, and the photo of the core sample is shown in **Fig. 6**. The core length shows that the concrete quality near the pile top is bad, and some of the length is empty. The core samples were tested with the unconfined compressive strength test. Some core samples could only achieve 10.4 MPa instead of the designated strength of the pile, which should be 35 MPa.

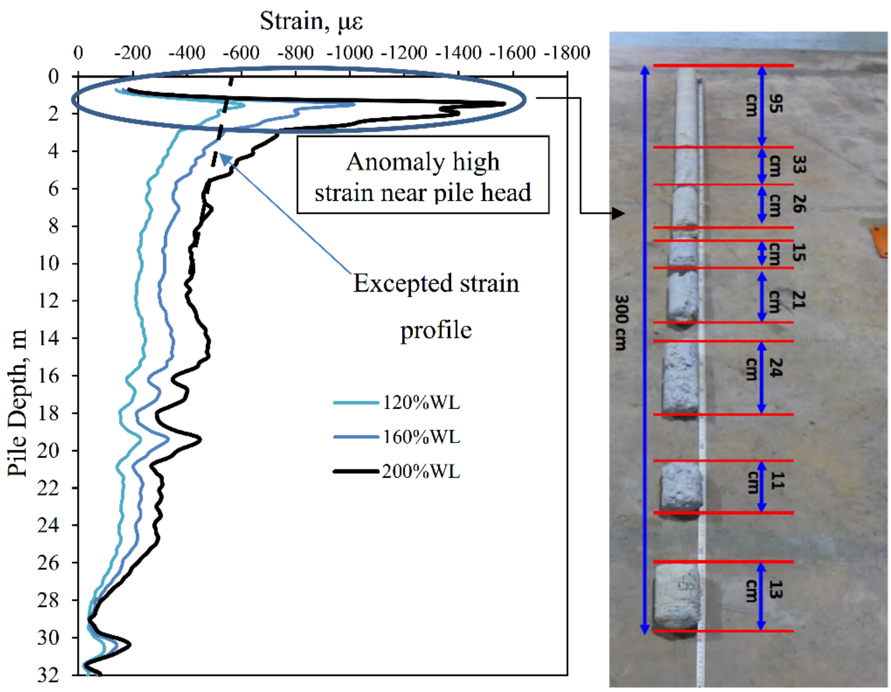

Fig. 5. Anomalies high strain measured near pile head

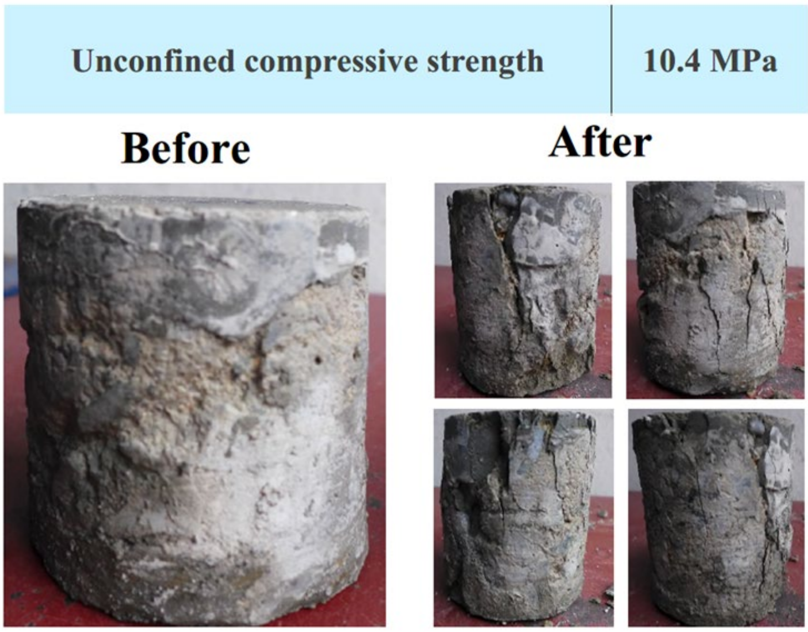

Fig. 6. Unconfined Compressive Strength of core sample

4.2. Top Loaded Static Load Test on Cast-in-situ Bored Pile- TL2

DFOS sensors were also installed in the test pile in another load test. Anomalies measurements were detected near the pile head. The anomaly measurement Kanwas detected at about 5 m depth from the pile head. The pile diameter was 1200 mm and 12 m in length with grade 40 N/mm2 concrete. The top 5.5 m length of the pile was in soft soil, and the friction was negligible. The pile was constructed with a 4.5 m length permanent steel casing. With the 4.5 m length steel casing and negligible soil friction near the pile top, the vertical straight line strain profile was expected to be recorded up to 5 m depth (**Fig. 7**). The pile was tested up to 220%WL. In the progress of increasing the test load to 230%WL, the sound of strong concrete crushing can be heard at the site, and the pile head settlement increased drastically from 20 mm to 53 mm. The DFOS sensing cable is broken, and the measurement is not able to continue at 230%WL. The pile was excavated to the suspected broken level to verify the test result. The test pile was confirmed broken at approximately 5 m depth just below the permanent steel casing, as shown in **Fig. 7**.

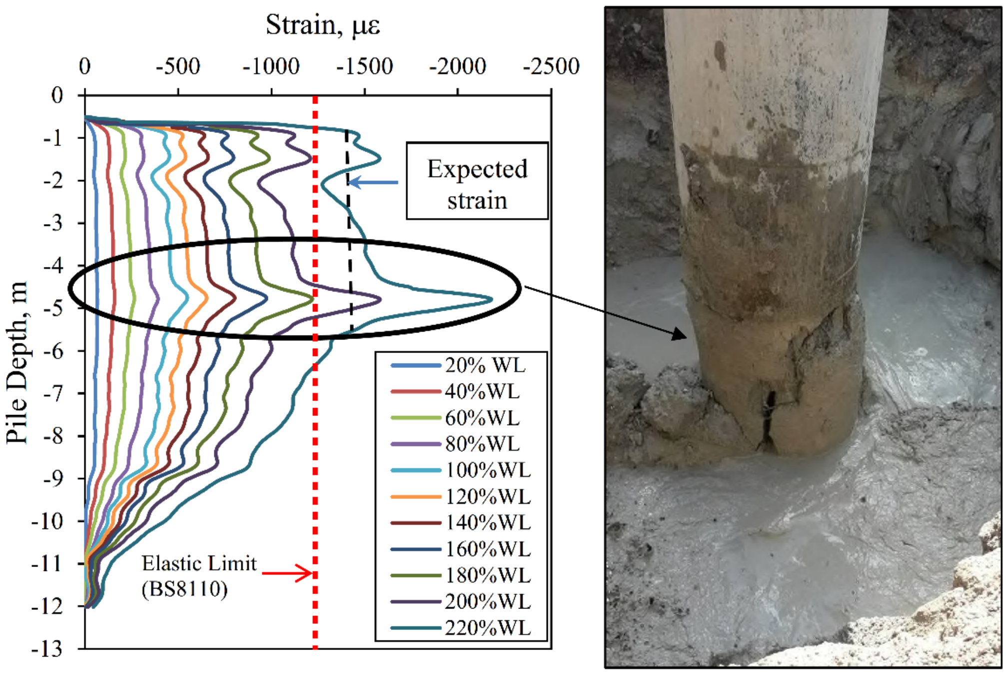

Fig. 7. Anomaly measurement of strain profile and visual validation

5. Discussion

The primary advantage of employing a Distributed Fiber Optic Sensing (DFOS) system for measurements lies in its ability to easily capture the complete strain profile rather than discrete data points obtained from traditional strain gauges. This continuous strain profile provides a more accurate understanding of overall pile performance and facilitates the detection of any abnormal pile behaviour. Such insights were previously challenging or uneconomical to obtain using conventional measurement systems.

BS8110-1:1997 (2007) has proposed a stress-strain curve for concrete, as depicted in **Fig. 8**, for adoption in reinforced concrete design. According to this suggested stress-strain curve, concrete with characteristic strength (fcu) values of 35 N/mm2 and 40 N/mm2 should reach their elastic limits at strain values of 1159 με and 1239 με, respectively, considering a material safety factor (γm) of 1.5. An important assumption in interpreting the results of instrumented test piles is that the concrete remains within its elastic range. The pile load transfer analysis uses the concrete's Young's modulus (Ec). If the concrete exceeds its elastic limit while still using Young's modulus for elastic concrete, it can introduce uncertainty and errors into the pile load transfer analysis.

DFOS enables the effective identification of pile sections with abnormally high strain. These high-strain sections often comprise subpar-quality concrete, as **Fig. 6** and **7** illustrate. Pile sections with inferior concrete quality have reduced structural stiffness and deform more than other sections with good-quality concrete. They tend to reach or exceed the elastic limit earlier, as shown in **Fig. 5** and **6**. Inferior concrete quality contributes to a lower and more uncertain Ec value. To obtain reliable results regarding pile performance, pile sections with poor-quality concrete should be excluded from the pile load transfer analysis.

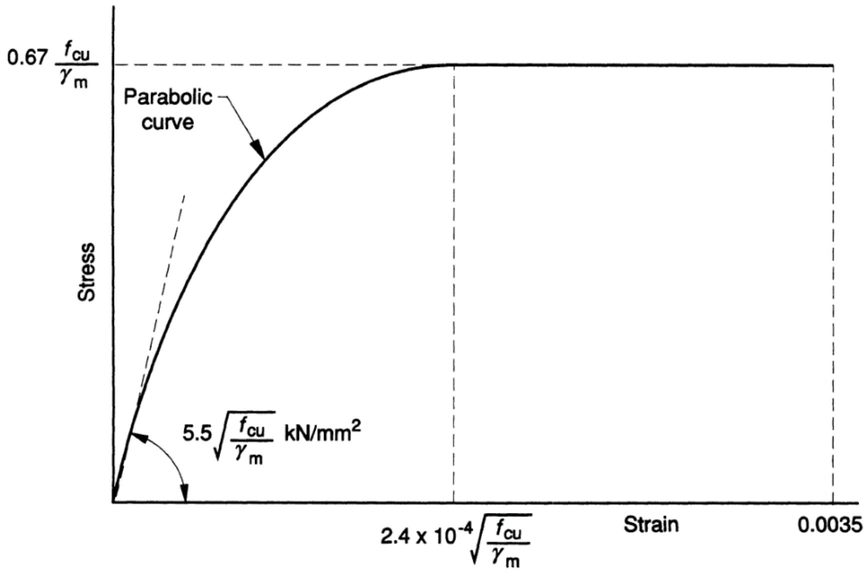

Fig. 8. Design Stress-Strain Curve for Normal Weight Concrete (adopted from BS8110: Part 1:1997)

6. Conclusion

It has been successfully executed to use a novel approach for instrumenting bored piles with distributed optical fibre strain sensors. The findings of field tests have generally shown that there is excellent agreement between fibre optic (FO) sensors and conventional sensors. When compared to the discrete data produced from conventional strain gauges, the main benefit of adopting dispersed measurements is the simplicity with which the entire strain profile can be easily captured. Traditional strain gauges frequently require data extrapolation between a few sensing locations, require time-consuming installation, and are prone to data problems caused by localised measurement inaccuracies.

When assessing a pile's load transfer and shaft friction and locating any anomalies in the strain pattern, having access to a comprehensive, continuous strain profile is crucial. In the case studies, this innovative approach successfully located characteristics of concrete contamination in problematic piles. Existing non-destructive testing (NDT) techniques may benefit from the Distributed Fiber Optic Strain Sensing (DFOS) technology. Until recently, conventional measurement devices were unable to provide such comprehensive information.

Credit authorship contribution statement

Bun Pin Tee: Conceptualization, Methodology, Writing – original draft, Preparation, Validation, Formal analysis, Investigation, Writing – review & editing, Visualisation. **Rini Asnida Abdullah**: Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualisation. **Hisham Muhammad**: Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualisation. **Ahmad Safuan A Rashid**: Writing – review & editing, Validation, Project administration, Methodology, Investigation, Formal analysis, Conceptualisation. **Afiqah binti Ismail**: Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualisation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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