Instrumented Laterally Loaded Pile Test using Distributed Fibre Optic Sensor

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ABSTRACT: Instrumented horizontal pile load test is widely used to evaluate lateral soil resistances/parameters and to verify design assumptions. Recent technological advancement of optical fibre sensing has led new ways in measuring the lateral load-deflection profile. The distributed sensing, namely Brillouin Optical Time Domain Analysis (BOTDA) is a novel technique of measuring strains in a spatially continuous manner. By installing distributed fibre optic strain sensing cables, continuous strain profile and deflection curve throughout the pile can be obtained. The objective of this article is to present one of the earliest deployment of BOTDA optical fibre sensors in lateral pile load test in Malaysia under offshore environment and share invaluable lessons learned from the instrumentation process. Installation method, lateral load test setup and data interpretation are also discussed. The computed lateral pile load-deflection profile was in excellent agreement with the measured pile top deflection using displacement sensors. The location of cracks detected based on continuous strain profile was also in good agreement with result of Low Strain Integrity Testing.

KEYWORDS: BOTDA, Pile instrumentation, Lateral load, Marine structure

1. INTRODUCTION

Marine structures like wharves, jetties, breasting dolphins along with other offshore structures are designed with specific considerations of large amount of horizontal forces and overturning moment generally arise from wave, current, seismic, wind, and sometimes earth and water pressures. Operational forces like mooring and berthing forces from vessels are horizontal forces in nature. These loads are often resisted by foundation such as piles and diaphragm walls. As part of verifying the horizontal load capacity of foundations, pulling and lateral load tests are often specified in piling construction project (e.g. Broadhead, 1970).

This paper presents an offshore lateral load test on a Contiguous Bored Pile (CBP) as part of a project involving widening of a cargo jetty in Langkawi Island, Malaysia. The CBP wall comprised of 112 piles with a diameter of 1500mm with rock socketed into 11m of limestone formation. The objective of this article is to present one of the earliest deployment of distributed optical fibre sensors in lateral pile load test in Malaysia that was performed under complex marine environment. Installation method, lateral load test setup and data interpretation are discussed together with data interpretation from conventional instrumentation.

1.1 Brillouin Optical Time Domain Analysis (BOTDA)

Passive optical fibre sensors have been used in various offshore applications for quite some time due to inherent capabilities such as small, lightweight, the ability to generate large amounts of data, low attenuation, and immunity to electromagnetic interference (EMI). Applications include ocean bottom seismic system (Thompson et al., 2007), offshore platform (Ren et al., 2006), downwell monitoring (Kersey, 2000) and Parafil ropes (Ludden et al. 1995). The technology application can be extended to offshore foundations to monitor the axial deformation and flexural rigidity of piled foundations.

Brillouin Optical Time Domain Analysis (BOTDA) is a novel technique of measuring strains in a continuous manner. The novelty of this technology is that a single fibre optic cable is capable of sensing over the entire length of the cable (potentially up to 100km length) for any strain and temperature changes. Applications of BOTDA in piled foundations have been reported by many researchers in the past years (*e.g.* Mohamad *et al*., 2011 and Piao *et al.*, 2015). The technology has been proven to have superior measurement capabilities compared to conventional geotechnical instrumentation. These include cracking or deformities detection (Mohamad *et al*., 2016) and ability to measure continuous strain profile as compared to spatially discrete data obtained when using the Vibrating Wire Strain Gauges (VWSG). This paper describes the first ever implementation of distributed optical fibre sensor based on BOTDA at nearshore environment in Malaysia (Figure 1). Details of the instrumentation is reported in Section 2.2.

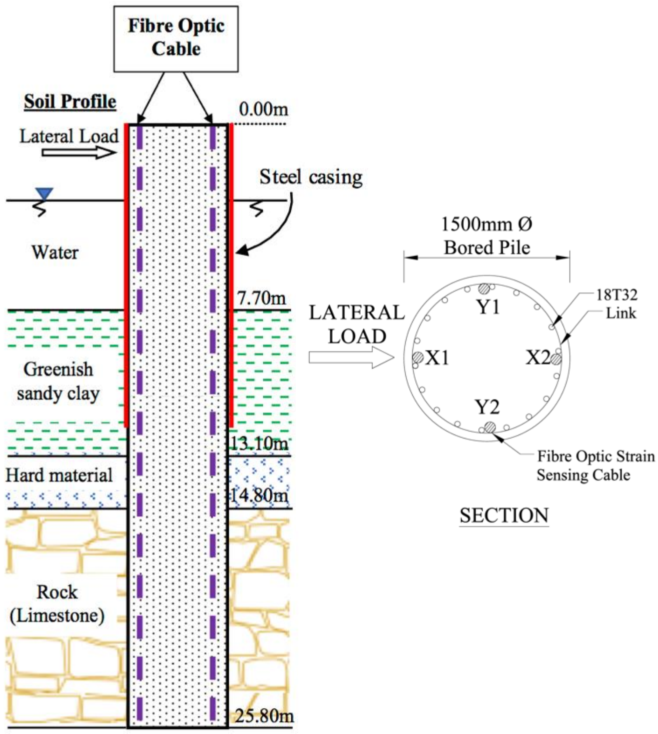

Figure 1 Instrumentation setup in test pile and soil profile

2. LATERAL LOAD TEST ON INSTRUMENTED BORED PILE

2.1 Subsurface conditions and pile construction

In this project, the bored piles were designed to form a contiguous bored pile (CBP) wall as a retaining structure for a jetty widening. After completion, the CBP wall needs to retain an average of 7-8 m depth of backfilling sand (reinforced with layers of high strength woven geotextiles). The proposed CBP location which was nearshore was not accessible by boring machine from onshore. During construction, the boring machine had to be placed on a barge to carry out drilling work. Permanent steel casings embedded down to a meter below the seabed were required to create a nominal diameter bored pile of 1500mm. These bored piles were specified with concrete Grade 40 and 18T32 of main steel reinforcement as shown in Figure 1.

One of the bored piles (CBP 55) located at the mid-span of wall was selected for lateral load test to verify the design parameter. The test pile was designed to resist up to 200 kN lateral working load (WL). The soil profile consists of 5.4m thick of greenish sandy clay below the sea level and overlying on slightly fractured limestone formation (Figure 1). The length of the test pile was 25.8m with 11m socketed into limestone rock. Procedures of drilling, hole cleaning, tremie installation, and concrete pouring were carefully monitored to ensure quality of pile construction.

2.2 Lateral load test and instrumentation

A specifically designed strain sensing optical fibre cable for embedment in concrete piles is shown in Figure 2. The strain cable is reinforced with six strands of steel wires and tightly buffered with polyethylene coating (Mohamad and Tee, 2015; Mohamad *et al*., 2016). Two pairs (two loops) of sensing cable were fixed to the main reinforcement bars from top to toe of the pile in two axes. Strain sensing cables X1 and X2 were installed in line to lateral load on plane while strain sensing cables Y1 and Y2 were installed at an angle normal to lateral load which were at neutral axis of the pile (refer Figure 1). These two pairs of distributed fibre optic sensor (X1-X2 and Y1-Y2) provide a continuous strain profile along the four sides of the pile. The data are then further converted to lateral displacement profile along the entire length of pile (see Section 3.2).

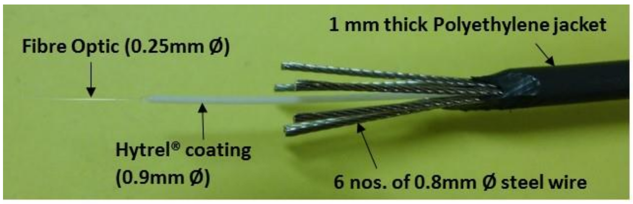

Figure 2 Strain sensing cable (5mm dia.) for bored pile application

It is worth mentioning that a temperature compensation cable was not needed in this project. Under the assumption of temperature between each faces of the pile are equal, the derivation curvature strain (the difference of strain at X1 minus X2) will cancel the thermal strain effect (see later Eq. 2). Moreover, temperature fluctuation below the sea and ground is usually minimal to affect the strain readings during the relatively short period of load test.

An optical fibre interrogator (OZ Optics' Foresight™) with spatial resolution of 0.5m (pulse width of 5ns) and strain accuracy (repeatability at standard deviation, σ) of 6$\mu\varepsilon$ is used in this study. An averaging number of 65,000 and spatial step of 0.05m was set in the interrogator which completed a set of strain reading within 5 minutes.

One set of hydraulic jack was used to load the pile up to the designated lateral load (Figure 3). A reaction pile (CBP 57) with similar design as the test pile was used as a support/counter force to load against the test pile. A load cell was used to measure the amount of lateral force transferred to the pile. Linear Voltage Displacement Transducers (LVDTs) were installed on an independent reference frame to measure the lateral displacement at the pile top of both the reaction pile and the test pile. The lateral load test was conducted in accordance with the load cycle and load programme supplied by the design engineer. The pile Lateral Working Load (WL) was 200 kN. The test pile was loaded to a maximum of 150% WL or 300 kN in a single cycle with six steps of load increment. Each load increment was 25% WL. The pile was maintained at a load of 150% WL for 60 minutes. Then, the lateral load was released in three steps; each step at 50% WL.

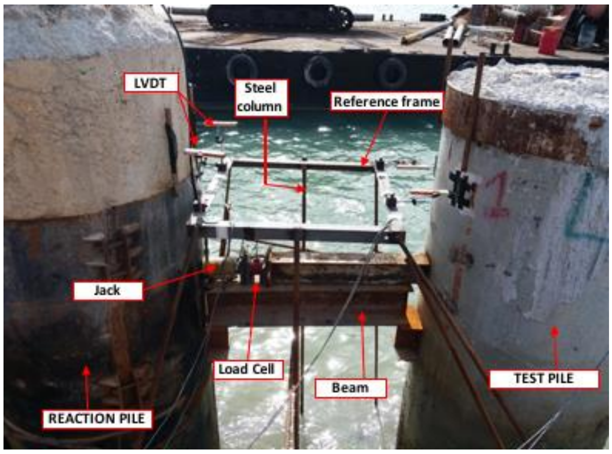

Figure 3 Lateral load test setup

3. RESULTS OF LATERAL LOAD TEST

3.1 Pile top lateral displacement from LVDT measurements

Figure 4 shows the lateral displacement for both the reaction pile and the test pile based on the LVDT measurements at approximately 1m below the pile top. The reaction pile lateral displacement increased almost linearly up to a maximum of 5.28 mm at 150% WL and decreased to 1.75 mm after the lateral load was fully released.

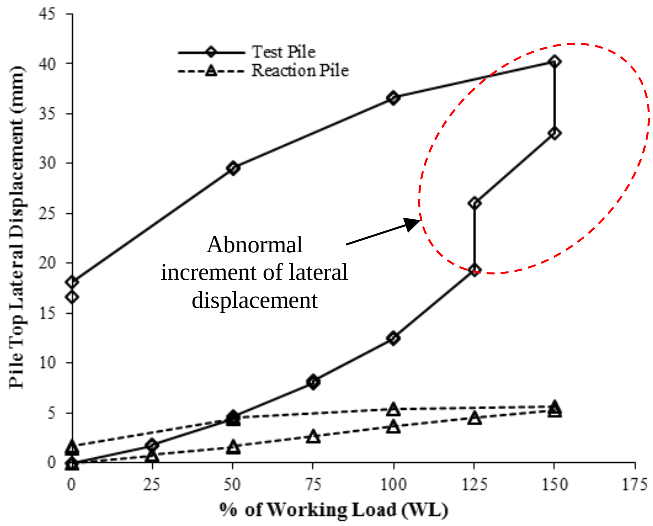

Figure 4 Pile top lateral displacement based on LDVT measurements for the test pile and the reaction pile

For the test pile, the magnitude of the lateral displacement was significantly higher compared to the reaction pile despite having similar structural and geotechnical designs. The variation of flexural behaviour between the two piles is not uncommon considering the challenges in controlling the construction quality of bored cast-in-situ piles underwater (*e.g.* concrete stiffness, diameter and depth of piles, and variable ground reactions along the shaft). At 125% WL, the lateral displacement at the pile top increased from 19.32 mm to 26.09 mm after maintaining constant load for 20 minutes.

The maximum lateral displacement for the test pile was 33.02 mm at 150% WL and increased to 40.19 mm after maintaining constant load at 150% WL for 60 minutes. After the load was fully released, the residual lateral displacement was 16.62 mm which was high (nearly half of the maximum lateral displacement). This abnormal result indicated that the test pile can only resist less than 125% WL. The test pile may have failed structurally (e.g. pile crack or broken) or geotechnically (soil or rock socketed length not sufficient). Based on only the LVDT measurements, the causes of excessive lateral displacement would be unknown without additional information from other instrumentation.

3.2 Strain profile based on measurement from Distributed Fibre Optic Sensor (F.O.)

Figure 5(a) shows the strain profile of strain sensing cables X1 and X2 along the full length of the test pile from 25% WL to 150% WL. The strain profiles of X1 and X2 at 25% WL to 100% WL almost mirror each other with X1 having positive magnitude (elongation/tension) and X2 having negative magnitude (shortening/compression). However, at 125% WL and 150% WL, the tensile strain of X1 at depth 11.5m to 15.5m was significantly higher and not proportional to the compressive strain at X2. This observation is further explained in Section 3.3.

From the strain profile along two fibres placed symmetrically with respect to the axis (X1 and X2), quantities of the lateral component can be derived from Eqs. (1) to (3) with ε_a and ε_b are strain measurement at two opposite fibres, and *D* is the distance between two fibres and by adopting trapezoidal integration rule. In case of rock socketing pile, where the pile's toe tends not to move and rotate, the constants *A* and *B* can be assumed as zero.

$$\textit{Curvature},\ \kappa(z) = 1/D\ (\varepsilon_a - \varepsilon_b) \qquad (1)$$

$$\textit{Gradient},\ \varphi = \int \kappa\, dz + A \qquad (2)$$

$$\textit{Lateral Displacement},\ u = \int \varphi\, dz + B \qquad (3)$$

By using Eqs. (1) to (3), the strain profile from Figure 5(a) was converted into curvature profile, gradient profile and lateral displacement profile as shown in Figures 5(b), 5(c) and 5(d) respectively. Lateral displacements at the pile top measured by the LVDTs were also plotted in Figure 5(d) to compare with the lateral displacement curves derived from the measured F.O. sensor. Both results show excellent agreement between them, which reflected the double integration method and assumption of boundary conditions (parameter *A* and *B*) are correct with no measurement error observed. Based on Figures 5(a) and 5(d), no significant lateral load effect was transferred to the pile at depths below 15.5m to pile toe. This means at this level, the lateral resistance provided by the limestone layer is very good.

3.3 Anomalies detection based on Distributed Fibre Optic Sensor (F.O.) measurement

Strain sensing cables X1 and X2 positioned to the same axis line of lateral loading setting were installed with intension to convert measured strain profile to lateral displacement profile. Strain sensing cables Y1 and Y2 on the other hand were installed at the neutral axis with intension to detect any lateral displacement incurred at the direction normal to lateral load.

Figures 6(a), 6(b), 6(c) and 6(d) show the strain profile of strain sensing cables X1, X2, Y1 and Y2 respectively from 50% WL to 150% WL. At 50% WL and 100% WL, the strain profiles of cable X1 almost mirrored the strain profiles of cable X2 while the strain profile for cables Y1 & Y2 did not detect any significant strain reading. This indicates that the lateral load transfer was near perfect to the major axis (X1-X2) without much deviation of load to minor axis (Y1-Y2). No anomalies were detected at 50% WL and 100% WL. This matched with measurements of the pile top lateral displacement by LVDT whereby the displacement increased almost linearly up to 100% WL.

At 125% WL and 150% WL, the strain sensing cable X1 showed an abnormal tensile strain reading at depths of 11.5 m to 15.5 m which was not detected at strain sensing cable X2 (refer to Figures 6(a) and 6(b)). In normal circumstances, the tensile strain reading at X1 should mirror the compression strain reading at X2. This abnormal tensile strain indicated that tensile crack may have occurred at depths of 11.5 m to 15.5m at the pile face along cable X1. This result corresponds with the pile top lateral displacement curve which shows non-linear line or abnormal increment at 125% WL and 150% WL.

Figure 7 shows strain increment of cables X1 and X2 at depth of 13.6 m which was the depth with maximum tensile strain. It is clear from the results that there is a rapid increase of strain at 125% WL and 150% WL for cable X1. The test pile had not cracked below 100% WL. Beyond 100% WL, the pile yielded and incurred excessive lateral displacement. A similar finding was also reported in Zhu *et al.* (2012) which utilised the conventional sensor (strain gauges) as the main instrumentation in four piles under lateral load test, and Glisic *et al.* (2002) using long-gauge fibre optic sensors for pile flexural test.

Further anomalies were detected on cables Y1 and Y2 (Figures 6(c) and 6(d)) at a similar depth with 125% WL and 150% WL. Liew and Choo (2004) had highlighted the significant effects of crack to the moment inertia of the reinforced concrete. For a cracked section, the effective moment inertia of the section is less than the gross moment inertia and varies with the extent of cracking at the section. Sinnreich and Ayithi (2014) also highlighted how concrete pile fracture on the tensile side can change the neutral axis location and affect the pile bending stiffness. Therefore, the tensile strain observed on cables Y1 and Y2 at load 125% WL and 150% WL, was the consequence of pile fracture/crack on the tensile side. The neutral axis shifted towards the compressive face which caused cables Y1 and Y2 to fall in the tensile region, and hence detected the tensile strain.

4. DYNAMIC PILE INTEGRITY TESTING

Following the results obtained from the bending test, the integrity of the test pile (CBP 55) was further investigated using Low Strain Pile Integrity Testing (PIT). The PIT method uses a hand-held hammer struck the pile top, to generate stress wave that travels down the shaft to the pile bottom, where it is reflected and measured. If this reflection occurs at the correct time and if no earlier reflection waves are received at the pile top, the pile shaft is considered free of major defects. Under the condition of a sound pile (no cross-sectional and stiffness changes), the toe signal would have been recorded at the corresponding depth of 25.8m.

Figure 8 shows the velocity curve result of PIT that is compared with F.O. strain data plotted on the same vertical scale (depth). It should be noted that the integrity testing for CBP 55 was performed after the pile head was trimmed (broken down) to a specified level (cut-off at -3.5m). As shown in Figure 7, the wave propagation signal indicated a reflection at a distance 8.3m below the cut-off level which corresponds exactly to the first strain peak or crack observed from F.O. at depth of -12m. This confirms a pile defect where such gap induced by the crack does not allow compressive impact wave to propagate down below and indicate actual toe level.

PIT test results from reaction pile (CBP 57) on the other hand detected a minor shaft enlargement/high friction at about 12m. However, the pile integrity was acceptable. Other 18 piles were also inspected with generally no significant irregularities detected.

High Strain Dynamic Pile Testing were also performed on four neighbouring bored piles using Pile Driving Analyzer (PDA) to evaluate activated static capacity and assess the structural integrity of the piles. Subsequent Case Pile Wave Analyses Program (CAPWAP) was used to calculate the dynamic characteristics of the soils and resistance distribution along the shaft and toe of the pile. The PDA and the subsequent CAPWAP analyses indicated the piles had achieved activated static capacities of 800 to 900 tonnes with no apparent pile damage.

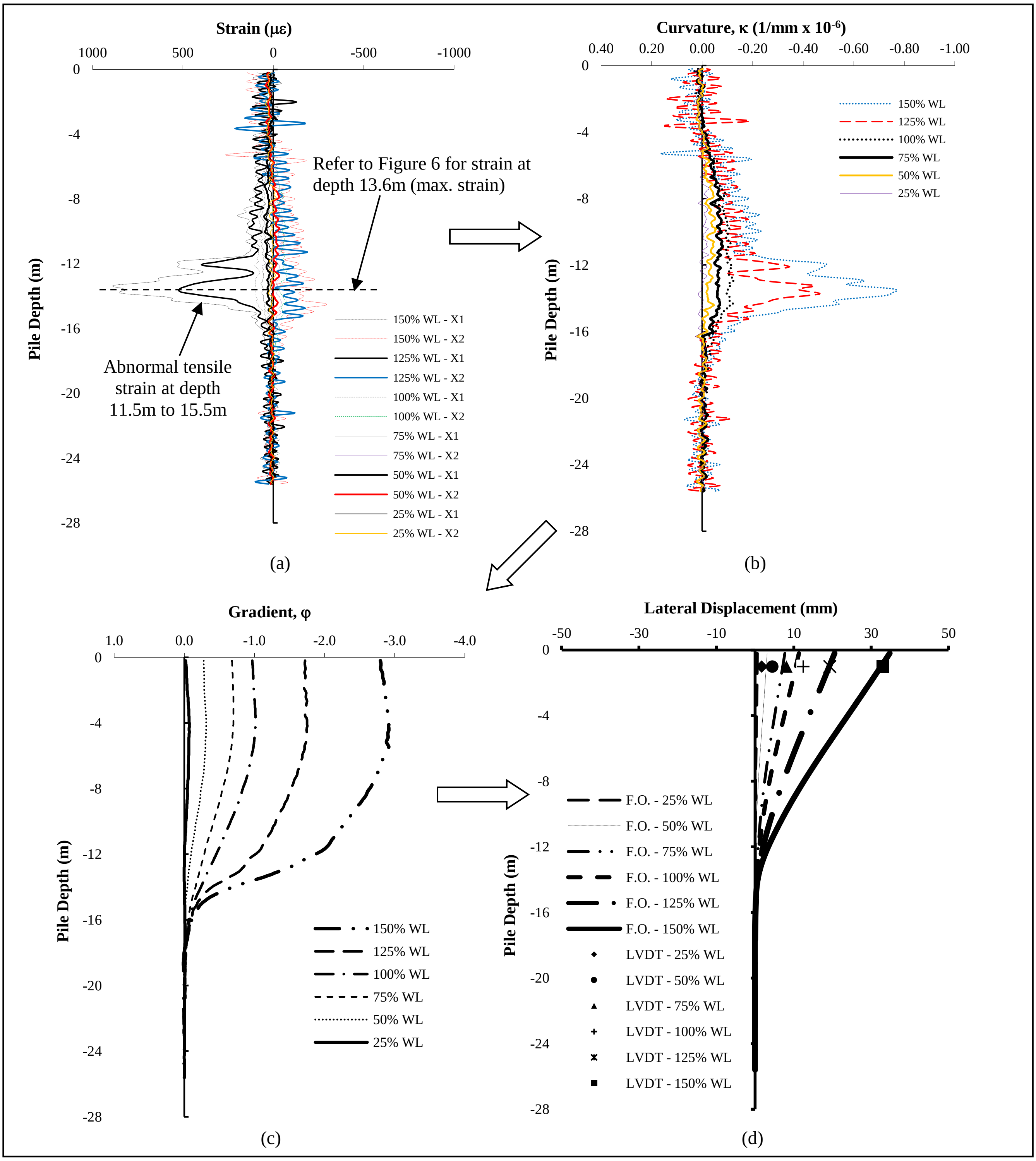

Figure 5 Distributed fibre optic sensor results based on strain sensing cables X1 and X2 (a) Continuous strain profile (b) Curvature profile (c) Gradient profile (d) Lateral displacement profile and pile top lateral displacement measured from LVDT

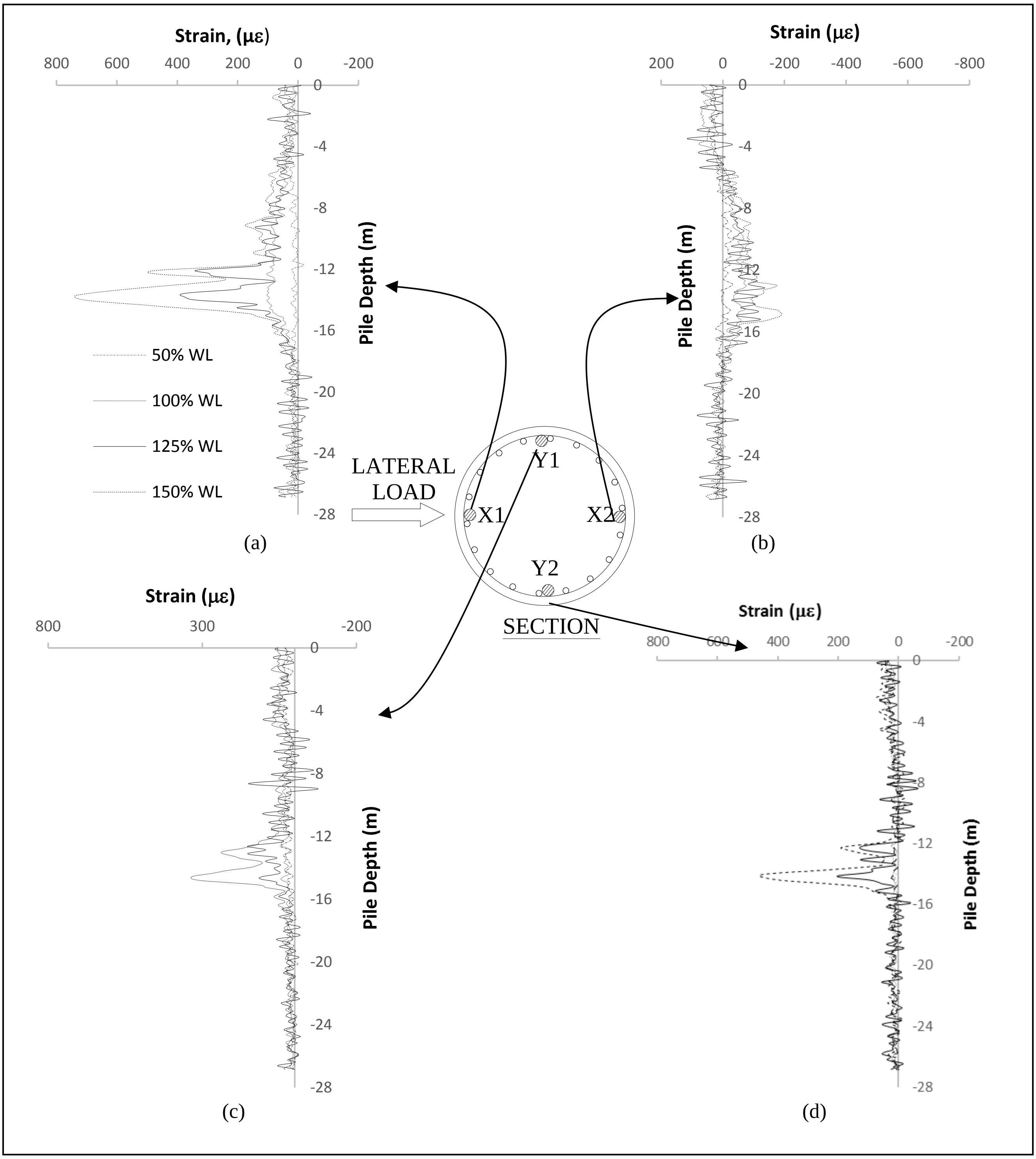

Figure 6 Continuous strain profile of distributed fibre optic sensor (a) Sensing cable X1 (b) Sensing cable X2 (c) Sensing cable Y1 (d) Sensing cable Y2

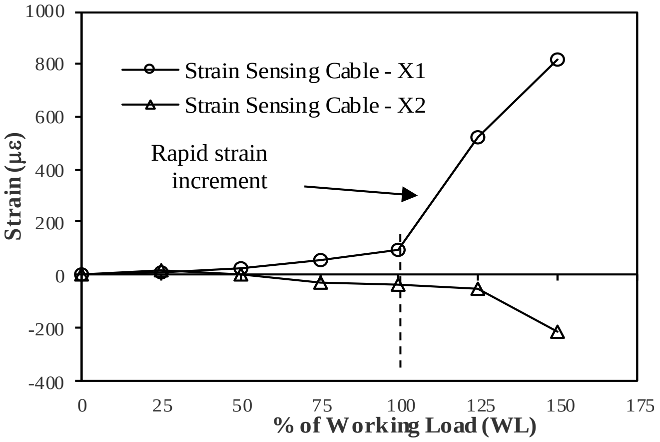

Figure 7 Strain of sensing cables X1 and X2 at depth 13.6m (depth with maximum strain)

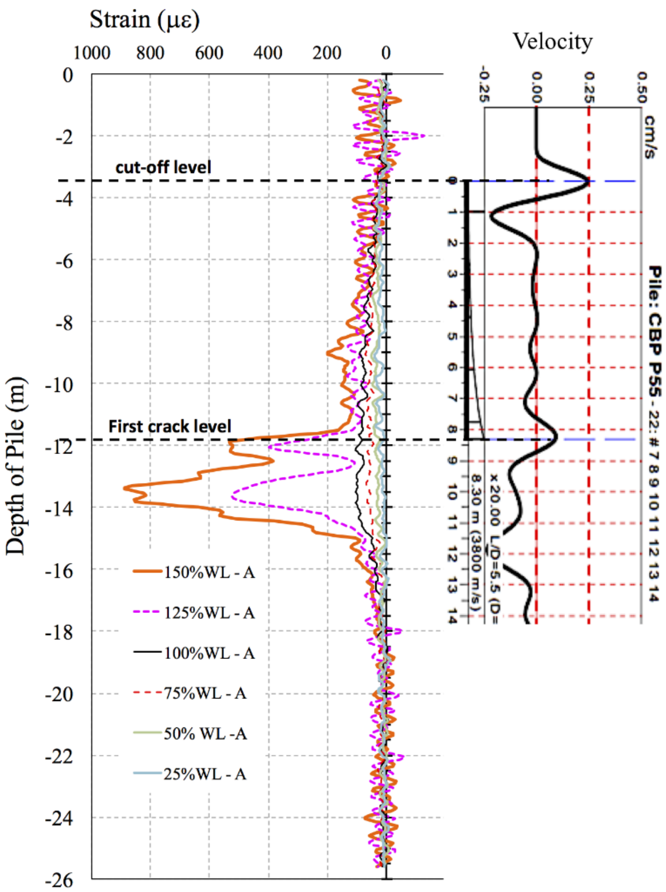

Figure 8 Strains measured by sensing cable X1 (left) and PIT trace record (right)

5. CONCLUSION

A novel way of instrumenting bored piles using distributed fibre optic sensor in nearshore environment has been successfully implemented. Pile lateral deformations can be detected from a pair of strain cables measured along the tensile face and the compressive face over the entire length of the pile. This enables direct measurement of curvature or bending strains which can be further analysed to obtain bending moments, and shear force diagrams (Mohamad *et al*., 2011). Lateral resistance of the marine soils and limestones formation below the sea bed can be inferred by correctly assigning the pile's flexural rigidity parameter during the load deflection (*p*-*y*) curve analysis. In this case, the uncracked and cracked bending stiffness of the pile under working load and exceeding working load can be analysed for estimation of the modulus of subgrade reaction. This will be reported in future study.

The field-test results generally showed very good agreement between the LVDT measurement (conventional sensor) and results from F.O. sensors. Anomalies (signs of pile yielding) were detected and consistent between four strain sensing cables and later corroborated with PIT measurement. In this project, minor shaft enlargement or high friction resistance was interpreted by PIT on several cases of CBP piles at a depth of roughly below the permanent steel casing. Although the integrity of the piles was assessed to be acceptable, a better design specification would be to install the steel casing until reaches the rock layer. This is to ensure uniform lateral resistances along the CBP wall as prescribed previously by the project designer.

It is important to note that the distributed F.O. technology not only capture the overall deformation of the structure but also able to pin-point precisely the location of anomalies. Moreover, the technology able to replace many commonly used instruments of pile testing, such as inclinometer, VWSG, LVDT, tell-tale extensometer which are notoriously difficult to install and all together costlier. The cable installation technique for BOTDA measurement is fairly quick, and under the offshore environment, this attribute is extremely useful.

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