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11TH INTERNATIONAL SYMPOSIUM FIELD MONITORING IN GEOMECHANICS

Bored pile integrity assessment using Distributed Fibre Optic Sensor (DFOS)

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Abstract

Strain measurements along a bored pile under different applied static loads, are very important for the analysis of load-transfer and pile's capacity. The Distributed Fiber Optic Strain Sensing (DFOSS) system consists of Brillouin Optical Time Domain Analysis (BOTDA) interrogator and optical strain cables, enable the measurement of continuous strain profile along the deep foundations. The DFOSS system provides significantly more information as compared to the conventional discrete strain gauges. Features such as defective pile, concrete contamination, improper toe formation, etc, can be identified using DFOSS system; however, cannot be achieved using the conventional discrete sensors. This article presents the integrity assessment of deep foundation using the DFOSS system. The distributed optical strain cables were installed in two concrete bored piles in order to measure geotechnical capacity and structural deformation, if any. Maintained load tests using kentledge system were carried out on two test piles, where continuous strain profiles were recorded at every loading stage. The advantages and limitation of the DFOSS system are introduced, and the ability of DFOSS system in pile's integrity assessment are also demonstrated in this paper. The DFOSS can be a very good complementary test for static pile load test, to assess the integrity of deep foundations.

Keywords: Pile Integrity, Distributed Fibre Optic Strain Sensor (DFOSS), Brillouin Optical Time Domain Analysis (BOTDA).

1. Introduction

Instrumented static pile load tests provide important information about the pile design parameters, construction methods and information on soil-structure interaction (Fellenius, 2001). Static load tests are often being specified as a requirement in construction projects in order to confirm the geotechnical capacity of the constructed piles.

Traditionally, discrete sensors such as Vibrating Wire Strain Gauge (VWSG), are used to monitor the change in strain along the bored piles during static pile load tests, to compute the load transfer behaviour of the pile. These sensors are installed at pre-determined levels along the pile during installation. However, due to the inhomogeneous nature of the soil, it is difficult to predetermine the level of sensors accurately. In order to obtain better accuracy in load transfer measurement, VWSG are normally placed at closer intervals, which will increase cost to the test. In addition, VWSG are very prone to damage during the installation.

In Malaysia, before or after the static pile load tests, it is common to carry out non-destructive tests (NDT) to assess the pile's integrity. These NDTs include the High Strain Dynamic Pile Load Test, Cross-hole Sonic Logging Test (Chernauskas & Paikowsky, 2000) and Low Strain Integrity Test (Turner, 1997; White et al., 2008). These conventional NDTs are able to indicate anomalies along a pile, before and after static pile load tests. However, these NDTs are unable to quantify the seriousness of the anomalies. In many cases, further tests are required to assess the extent of pile integrity issue and to determine if the pile can still be used under working load (Amir & Amir, 2009).

The fibre optic sensing system such as the Distributed Fiber Optic Strain Sensing (DFOSS) system gradually receive more demands in pile test applications due to their superior advantages. The advantages of DFOSS as compare to the conventional sensors are the ease in installation, long term stability, durability, immunity against electromagnetic interference, corrosion resistance, etc. The DFOSS system is unique as it can provide continuous data along the pile lengths, unlike discrete sensors which can only measure localised data. Besides, pile shortening can be computed from the continuous strain profile, hence eliminate the needs to install extensometers. The DFOSS cables embedded in concrete piles are durable and can be used for long-term measurement. The use of DFOSS system in measuring continuous strain data has been reported in many literatures (Klar et al., 2006; Lu et al, 2012; Mohamad & Tee, 2015; Pelecanos et al, 2017). There are various

DFOSS systems such as BOTDA, BOTDR, BOFDA, etc. In this paper, BOTDA systems are used. This paper aims to present the capability and performance of DFOSS system in pile integrity assessment, by analysing the continuous strain profile obtained during the static pile load tests.

2. Literature Review

2.1 Brillouin Optical Time Domain Analysis (BOTDA)

There are three main categories of fibre optic sensing system used for civil engineering applications, i.e., the Fabry-Perot interferometers (discreet sensing points), Fibre Bragg sensors (quasi-distributed sensor system), and Distributed Fibre Optics Sensing system, DFOSS (continuous sensor system). In this paper, the Brillouin Optical Time Domain Analysis (BOTDA) interrogator (DFOSS system) was used to measure the continuous strain profiles during the static pile load tests.

For instrumented pile tests, the DFOSS systems are adopted to measure the continuous strain profile, which is then used to compute the mobilised pile shaft resistance and end bearing. The DFOSS functions are based on the properties of spectrum of the backscattered light within the optical fibre, using the Brillouin Optical Time Domain Analysis (BOTDA) system. Many literatures explained the principals of BOTDA and the analysis method to obtain the full strain profile (Iten, 2012; Pelecanos et.al, 2018).

2.2 Theoretical Strain Profile in Piles

Pile integrity issues may impact the bored pile performance. There are many reasons that can cause pile integrity issues including inadequate ground investigation, inappropriate construction approaches, mishandling of concrete casting procedures, etc. Some examples of typical problems found in bored pile construction are found in Mohamad et al. (2016). In this study, anomalies of the pile as measured by BOTDA were verified by construction records and field inspection.

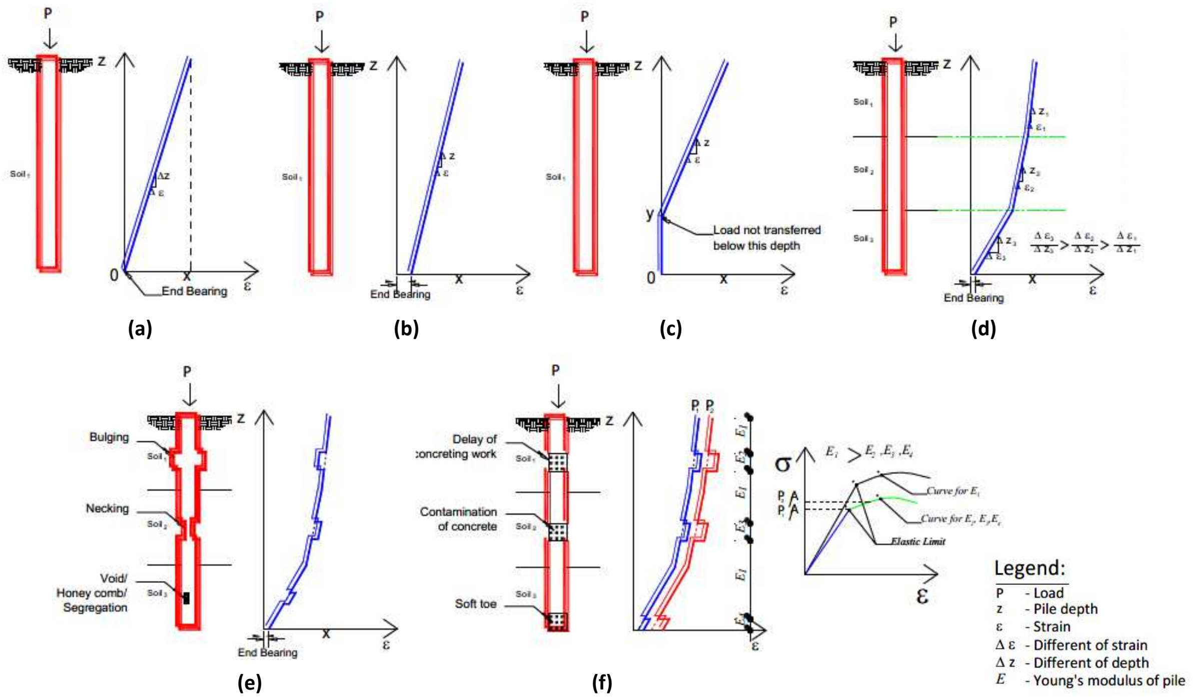

Figure 1: Strain profile along pile under various conditions

Figure 1 illustrates the various theoretical strain profiles along the pile (without anomalies) under different conditions. Figure 1a to Figure 1d are four piles with same stiffness, EA, where E is young's modulus and A is cross sectional area of pile. Figure 1a and 1b show pile in uniform soil material. Both cases show gradual reduction in strain magnitude along the pile length as load, P is applied at pile top. However, Figure 1a indicates there is no end bearing mobilised at pile toe (zero strain at the pile toe level); while Figure 1b shows that there are some end bearing mobilized at pile toe, i.e., non-zero strain at pile toe. Figure 1c shows that the pile friction is not fully mobilised as the load at pile top doesn't transfer beyond depth *y* (Zero strain below depth *y*). Figure 1d is the example closest to actual pile behaviour, where the pile is embedded in three different soil types (inhomogeneous subgrade). Stiffer soil layer experiences relatively less deformation when load is applied onto the pile. This will also provide relatively more restraints to the pile section at the stiff soil layer (hence smaller deformation). Therefore, the change in the gradient of strain profile, measured in pile section at stiff soil layer will be relatively more. Steeper strain profile indicates stiffer soil which provide more restraints or friction to the pile. Shaft friction for soil *3* > soil *2* > soil *1*, hence the gradient of strain curves varies, where $\Delta\varepsilon_3/\Delta z_3 > \Delta\varepsilon_2/\Delta z_2 > \Delta\varepsilon_1/\Delta z_1$.

Figure 1e and 1f illustrate the theoretical strain profile with integrity issue (anomaly). In Figure 1e, anomaly strain occurs where localise pile cross-sectional area, A is not consistent. When the cross-sectional area, A is smaller (eg., necking), the strain at that level is relatively higher and where cross-sectional area, A is larger (eg., bulging), the strain at that level is relatively lower. In Figure 1f, anomaly strain occurred at depth where concrete strength or concrete Young's modulus, E is not consistent. When concrete Young's modulus is lower (eg., concrete contamination, soft toe, etc), localised higher strain will be detected.

3. Case Studies

This article presents two integrity assessments of concrete bored piles. Both test piles were installed with two loops (four sides) of DFOSS cables along the pile (Figure 2 & Figure 5). The main purpose of this DFOSS cable is to measure the change in strain during the static pile load tests, which carried out in accordance to ASTM D1143 Deep Foundation Elements Under Axial Compressive Load. In these two case studies, the DFOSS captured several localised anomalies along the pile during the tests. The capability of DFOSS system in detecting pile's anomalies is the focus of this paper.

Table 1 summarizes the details of the two test piles. Discussion on installation approaches, geological formation, test methods, results and discussions are presented in the following sections.

Case Study	Test Pile ID	Pile Diameter (mm)	Test Load (kN)	Reinforcement bar	Concrete Grade	Subgrade Type
1	TP-1	600	5600	8T25	40	Sandy Silt
2	TP-2	900	18475	16T16	45	Kuala Lumpur Limestone

Table 1: Summary of case studies

3.1 Case Study 1

Test Descriptions

Located in Klang Valley, Malaysia, TP-1 is a 600 mm bored pile with a penetration depth of 27.8 m from the piling platform level. The subsoil information is as shown in Figure 2, where the first 11.0 m are very soft greenish grey marine clay and then follows by hard brownish grey sandy silt with SPT-N value exceeding 50.

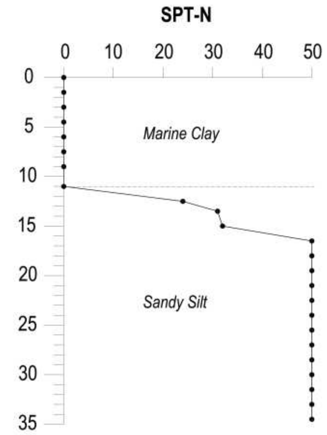

Figure 2: Geological information of test pile location (TP-1).

Figure 3 shows the setup arrangement of TP-1. Two pairs of DFOSS cables were fixed at four sides along the reinforcing cage from top to the toe of the pile to verify the geotechnical design parameters of TP-1 under various static load conditions. Two abnormal incidents were recorded during the concrete casting process which may potentially cause pile integrity issues. The first incident was that the prefabricated steel cage according to borehole depth was not fully lowered down into the borehole. Some soil was suspected to have collapsed and dropped into the bored hole. The second incident was a the late arrival of final concreting truck (> 4 hours), which may potentially cause disturbance to setting process of casted concrete and subsequently affect the concrete quality or strength.

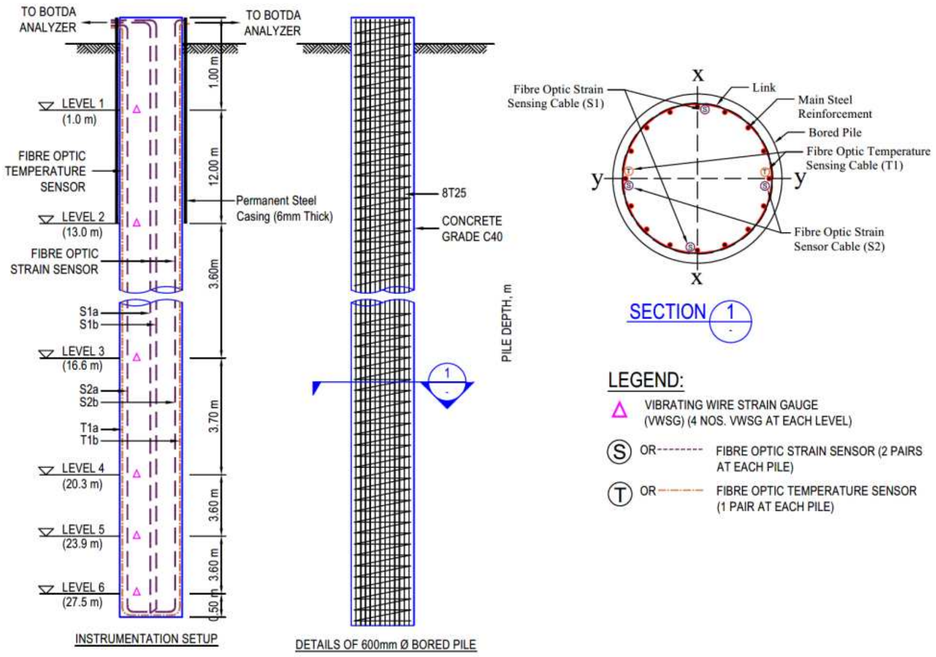

Figure 3: Schematic diagram of TP-1 set up.

TP-1 is an instrumented working test pile, designed to a safety factor of 2. The allowable pile capacity is 2800 kN and the test load is 5600 kN. The test was conducted in two cycles, in accordance to the loading schedule provided by the engineer. First cycle was tested to maximum load of 2800 kN in seven steps of load increment; and second cycle was tested to 5600 kN in fourteen steps of load increment.

The static load test was carried out using the reaction pile method. A hydraulic jack was used to apply axial load onto the test pile and a load cell was used to measure the actual load applied. The pile top settlement was measured using the Linear Voltage Displacement Transducers (LVDTs).

Results and Discussion

During the static axial load test, continuous strain profile of TP-1 was collected using BOTDA, at each loading stage. The measured strain profiles were then compared to the theoretical strain profile generated using RATZ programme (a non-linear load transfer analysis programme). Parametric studies were carried out using RATZ program to obtain the stiffness of soils and shaft friction of the pile. Several assumptions made are as follows:

(1) Ultimate shaft friction was correlated using SPT-N values (Figure 1). Estimation of actual "N" values were extrapolated based on the soil investigation reports (i.e., 50*300/x ; where x is the penetration depth in mm achieved after 50 blow counts).
(2) Correlation equation between SPT-N value and ultimate shaft friction is $\tau = pnN$, where p is reference pressure of 100kPa, n is the empirical soil coefficient (adopted 0.025 for clayey sand with silt) and $\tau/N = 2.5$ as suggested by (Chang and Broms, 1991) for weathered rocks.
(3) Concrete modulus of 41 GPa was adopted.
(4) End bearing pressure at the pile base was limited to 4.5 MPa (O'Neil & Reese, 1999).

From Figure 4, it is observed that there are three major differences in measured strain magnitudes along the pile depth, compared to the numerical analysis results. Higher strain values were measured at 4.0 m to 8.0 m depth during the load test. At this depth, the pile was confined by the permanent steel casing, meaning, the pile's cross-sectional area was uniform. Hence, the higher measured strain values at this level indicates that the Young's Modulus of concrete at this section is comparatively lower. This is in agreement with the field record which recorded a four hours late arrival of the final concrete truck. Continuous vibration with tremie pipe (to prevent concrete from hardening) while waiting for the arrival of more concrete had possibly affected the setting process of the concrete and the concrete strength.

The pile has 13.0 m length permanent steel casing installed to prevent the collapse of the soft subgrade. The measured strain results at 13.0 m to 16.5 m show relatively lower magnitude as compared to the theoretical strain, approximately by 20%. This section of the pile is right below the permanent casing, where the SPT-N value of the subgrade ranges between 20 to 40. The repeated process of drilling, cleaning and removing soil materials from the bored hole had likely caused the soil to collapse at this zone (interface with permanent casing). It is highly possible to have a localised larger cross-sectional area (or bulging) which resulted in higher pile stiffness and localised lower strain values.

Figure 4 shows a localised high strain at pile toe level. This localised higher strain value is possibly due to "soft toe" i.e., concrete contamination at toe level. The contaminated concrete results in a lower concrete Young's Modulus and hence relatively higher strain (deformation) values were obtained during load test. During the pile casting procedure, the reinforcing steel cage was not able to be lowered down normally at the final 0.7 m length. This is likely due to soil collapse at the pile toe or due to the verticality issue of bored hole. It is possible that the concrete was contaminated at pile toe and contributed to the "soft toe" problem.

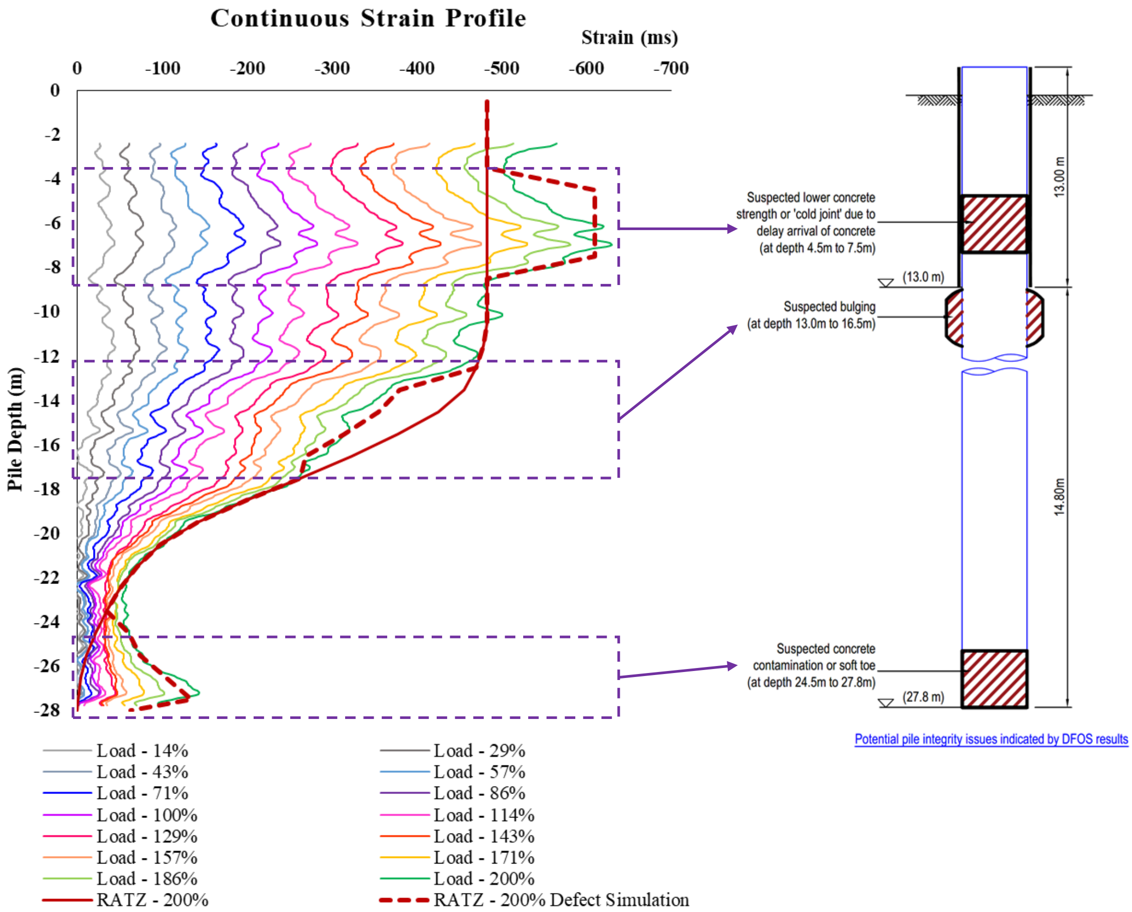

Figure 4: Continuous stain profile of TP-1 under different loads.

3.2 Case 2

Test Descriptions

Case 2 demonstrates an instrumented axial static pile load test for a 900 mm diameter bored pile. The test pile TP-2, is installed in Kuala Lumpur Limestone formation and the soil profile is as shown in Figure 5. The first 8.0 m from the ground consists of sandy silt clay with SPT-N values lower than 10. Limestone was found at 8.0 m below the ground and has total core recovery ranging from 80% to 100%, and rock quality designation ranging from 10% to 93% as shown in Figure 4.

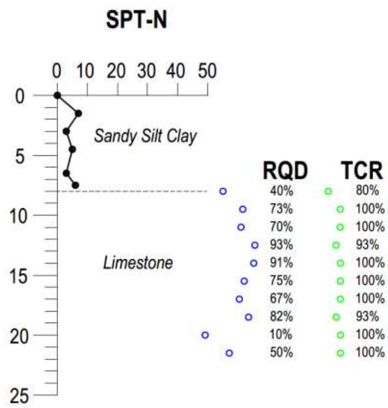

Figure 5: Geological information of test pile location (TP-2).

TP-2 has a pile length of 11.6 m, inclusive of 3.2m rock socket (competent flat rock layer was found at 8.4 m from platform level). Similar to Case Study 1, TP-2 was also instrumented with two loops (four sides) of DFOSS cables along the pile, from pile top to pile toe.

The static axial pile load test on TP-2 was carried out in accordance to designated load programme. The static load test was carried out in 3 cycles where in each cycle, the loads were increased by 20% working load until the maximum test load of that cycle. Then unloading by 20% working load decreasing until 0 kN. Four hydraulic jacks were used to apply the loads onto the test pile. While, four load cells and four LVDTs were used to measure the actual total load applied and pile top settlement, respectively.

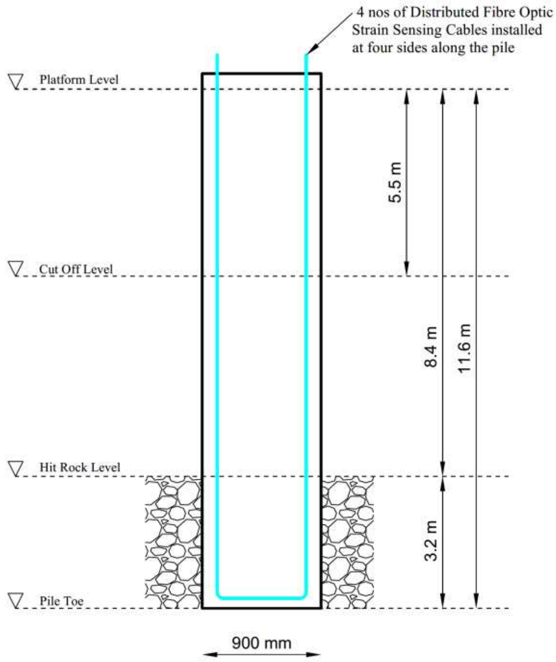

Figure 6: Test pile details of TP-2.

Results and Discussion

The axial static load test achieved 230% instead of 250% working load as planned. This is due to the concrete being crushed at approximately 5.0m depth. From the strain profile, relatively higher strain values were recorded at approximately 5.0 m, which exceeded 2000 με at 220%WL. This high strain recorded indicated the pile had a structural integrity issue.

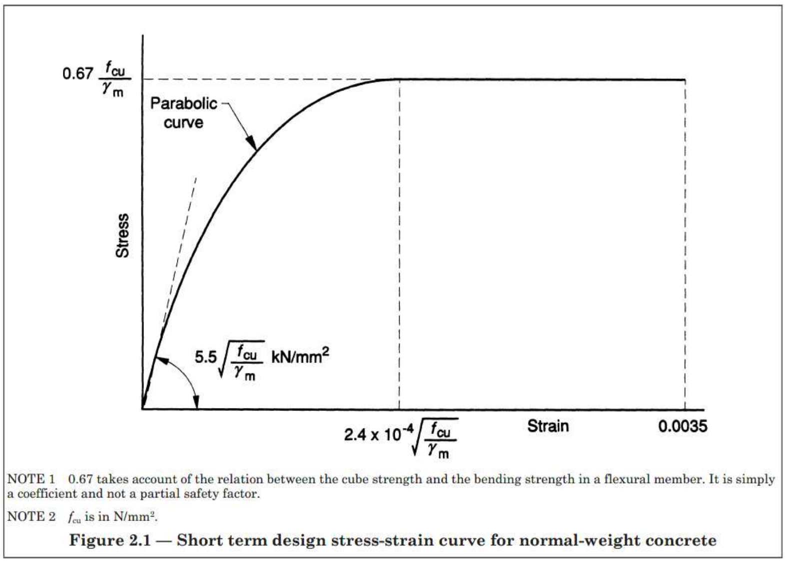

Figure 7: Short term design stress-strain curve for normal-weight concrete (adopted from BS8110)

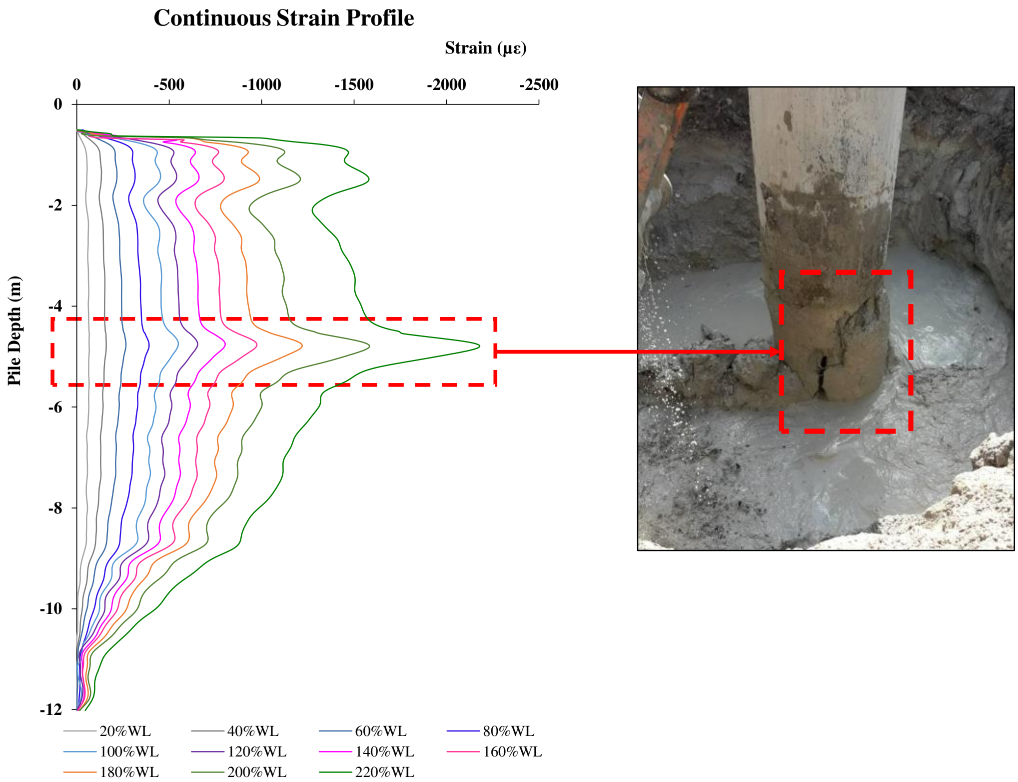

Figure 8: Comparison of measured continuous strain profile to actual pile's condition.

Figure 7 shows the short-term design stress strain curve for normal weight (adopted from Figure 2.1 of BS8110-1:1997). From the graph, it can be calculated that the grade G45 concrete has elastic limit of 1315 με. With the measured strain at 5.0 m depth (>2000 με), which significantly exceeded the elastic limit, indicated localized concrete crushed issue.

Excavation and visual inspection were carried out at TP-2 in order to verify the cause of the pile failure. Figure 8 shows the actual condition of TP-2 at approximately 5.0m, significant structural integrity problem and concrete crushed were observed.

This case study shows the superior performance of DFOSS system in detecting the deep foundation's integrity under static loads. From the assessment of the magnitude of measured strain, it is possible to accurately reveal the concrete behaviour or pile integrity under various applied loads.

4. Conclusions

Based on the two case studies, we know that DFOSS is able to obtain more precise continuous strain profile to better compute mobilised shaft friction and end bearing. The continuous strain profile can indicate the rigidity of soil and the pile shaft resistance obtained, i.e., steeper gradient indicates higher friction and stiffer soil/rock material. This continuous strain measurements enable detection of abnormal behaviours or anomalies along the piles, i.e., soft toe, concrete contamination, necking and bulging, pile integrity issue, etc. DFOSS system is a good complement for static load test, as the distributed strain measurement can provide pile integrity information which is hard to be achieved using conventional discrete strain gauges.

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