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CHARACTERIZING ANOMALIES IN DISTRIBUTED STRAIN MEASUREMENTS OF CAST-IN-SITU BORED PILES

Hisham Mohamad[a*], Bun Pin Tee[b], Koh An Ang[c], Mun Fai Chong[d]

[a]Civil and Environmental Engineering Department, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak.
[b]Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[c]GDS Instruments Sdn. Bhd., 40400 Shah Alam, Selangor, Malaysia
[d]Dynamic Pile Testing Sdn. Bhd., 40150 Shah Alam, Selangor, Malaysia

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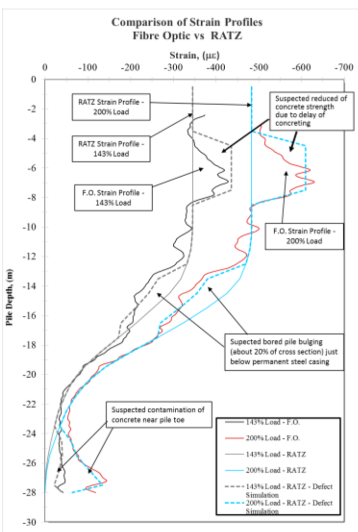
*Corresponding author
hisham.mohamad@
petronas.com.my

Graphical abstract



Abstract

This paper describes the method of identifying typical defects of bored cast-in-situ piles when instrumenting using Distributed Optical Fiber Strain Sensing (DOFSS). The DOFSS technology is based on Brillouin Optical Time Domain Analyses (BOTDA), which has the advantage of recording continuous strain profile as opposed to the conventional discrete based sensors such as Vibrating Wire strain gauges. In 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 cause the pile to fail. In this study, a new technique of detecting such defects is proposed using DOFSS technology which can potentially supplement the existing non-destructive test (NDT) methods. Discussion on the performance of instrumented piles by means of maintained load test are also presented.

Keywords: Bored pile; fiber-optic sensing; BOTDA ; maintained load test

Abstrak

Kertas kerja ini menerangkan kaedah untuk mengenalpasti kecacatan tipikal pada cerucuk terjara tuang di-situ apabila dipasang dengan instrumen sensor Gentian Optik Terikan Tersebar (DOFSS). Teknologi DOFSS adalah berdasarkan Brillouin Optical Time Domain Analyses (BOTDA), yang mempunyai kelebihan untuk mengesan profil terikan berterusan berbanding dengan sensor konvensional berasaskan diskret seperti tolok terikan dawai bergetar. Pada instumentasi cerucuk khususnya, mendapatkan profil terikan berterusan adalah penting apabila menganalisis pemindahan beban dan rintangan aci cerucuk, serta mengesan sebarang kejanggalan dalam rejim terikan. Ciri-ciri seperti kecacatan perleheran di aci, ketakselanjaran konkrit, gangguan bahan asing dan formasi dasar cerucuk yang tidak betul akibat kontaminasi konkrit pada dasar dengan partikel tanah, yang mungkin menyebabkan cerucuk gagal. Dalam kajian ini, satu teknik baru untuk mengesan kecacatan telah dicadangkan dengan menggunakan teknologi DOFSS yang berpotensi menambahbaik kaedah ujian tanpa musnah (NDT) yang sedia ada. Perbincangan mengenai prestasi instrumentasi cerucuk melalui ujian beban tetap juga turut dibentangkan.

Kata kunci: Cerucuk terjara; sensor gentian optik; BOTDA; ujian beban tetap

1.0 INTRODUCTION

Pile load testing provides key information about pile design for a specific geological ground structure. These tests are required to guarantee that the piles will meet long-term stability requirements for the foundation of the building.

There are many types of sensor that can be used to monitor strain along the pile during pile load testing. The most commonly used sensor is the Vibrating Wire Strain Gauge (VWSG) installed at certain intervals along the steel cage of a pile before the concrete or grout pouring stage. It is normal that at each instrumented level, a total number of four sets of VWSGs are needed to measure the deformation of the pile in two planes and infer averaged unit shaft frictions between each level. However, VWSG has several limitations and problems which include read-out drifts, prone to damages, tedious installation process, and requires many instrumented levels (smaller vertical spacing and very costly) in order to achieve higher accuracy of load transfer measurement [1,2].

In an effort to improve the situation, fiber optic sensors are introduced in this study to perform the same function as VWSG. Fiber optic sensors are becoming a well established technology for a variety of geophysical and civil engineering applications [3-5]. The advantages of fiber optic sensors compared to VWSG are long-term performance, resistance to corrosive environments, immunity against electromagnetic interferences, array-capability by wavelength-demultiplexing, and miniaturize in size [6].

There are different techniques that can be used to monitor the fiber optic signal. Fiber Bragg Grating (FBG) sensors are a type of distributed Bragg reflector constructed in a short segment of optical fiber that reflects particular wavelengths of light and transmits all others. They are made by laterally exposing the core of a single-mode fiber to a periodic pattern of intense ultraviolet light and FBG of different wavelengths can be multiplexed in an optical fiber (Figure 1). Unfortunately, the survival rate of embedded FBG system in pile instrumentation is lower than conventional sensors because the exposed grating points are very fragile and requiring further cable protection [6-8].

A more superior method of measuring the strain profile in a continuous manner along the pile shaft has been reported in the literature [3,9]. The technology is based on Brillouin scattering sensing (Figure 1) known as Brillouin Optical Time Domain Reflectometry (BOTDR) or Brillouin Optical Time Domain Analysis (BOTDA). This is described further in the next section.

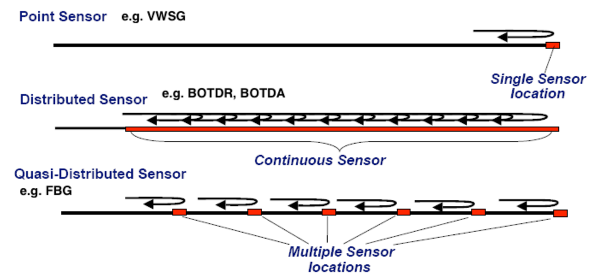


Figure 1 Basic architecture of strain sensors

2.0 DISTRIBUTED OPTICAL FIBER 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 fiber and propagates in the fiber, while the continuous wave (CW) light is launched at the opposite end of the fiber and propagates in the opposite direction (Figure 2). 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 singlemode fiber 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).

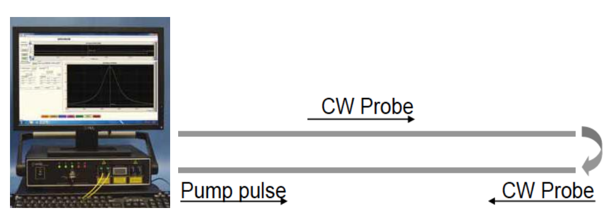


Figure 2 Principle measurement of a BOTDA system

2.2 Optical Cable

Figure 3 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 singlemode fiber 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.

The cables are attached along two opposite sides of the steel cage as described in the authors' previous publications [3,9,10]. The instrumentation method developed for deployment in concrete structures has been tested and validated in the laboratory and field environment [11].

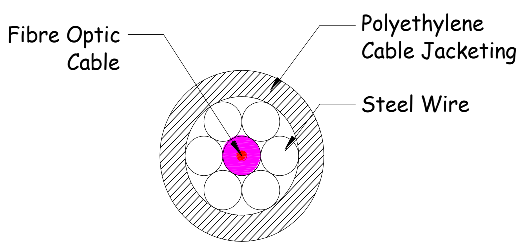


Figure 3 Configuration of strain sensing optical cable

3.0 PROBLEMS IN CAST-IN-SITU PILE CONSTRUCTION AND IDEALIZED STRAIN PROFILE

3.1 Problems in Cast-in-Situ Pile Construction

The imperfections of pile construction that may impact on its foundation performance may arise from a number of sources, including natural sources, inadequate ground investigation, construction, pile load testing and loading during operation [12]. However, only the construction related issue is discussed in this paper as it may results in abnormal strain distribution profile when measured using BOTDA. Examples of such construction problems, either from inadequate construction control or from inevitable consequences of construction activities include [12]:

- A soft toe on bored piles due to inadequate base cleaning
- Defects within the shaft of bored piles
- Inadequate founding conditions
- Ground movements developed due to drilling during the construction process, and
- Excavation and dewatering effects, especially with remedial piling projects.

In general, the types of pile defects contributed by construction-related imperfections in piles are structural defects and geotechnical defects. Structural defects can result in the size, strength, and/or stiffness of the pile being less than assumed in design (Figure 4). Such defects have been discussed extensively in the literature, particularly with respect to cast-in situ concrete piles [12,13]. Examples of structural defects include the following: "necking" of the shaft of bored piles, leading to a reduced cross-sectional area along part of the pile, poor quality control during the construction of bored piles, leading to some parts of the shaft having lower strength than assumed in design and tensile cracking of large diameter bored piles under the influence of thermal strains. Bulging is defined as a kind of pile shape imperfection; bulging increases the pile cross-section in certain areas along the pile length but increases the pile skin friction force [14].

Geotechnical defects usually arise from either a misassessment of the in situ conditions during design, or else from construction related problems, and may include reduced shaft friction and end bearing resistance arising from construction operations such as the use of bentonite without due caution, and a "soft base" arising from inadequate cleaning of the base of bored piles. The latter is one of the most common concerns in bored pile construction and is likely to lead to a reduction in the stiffness of the soil below the base of the pile.

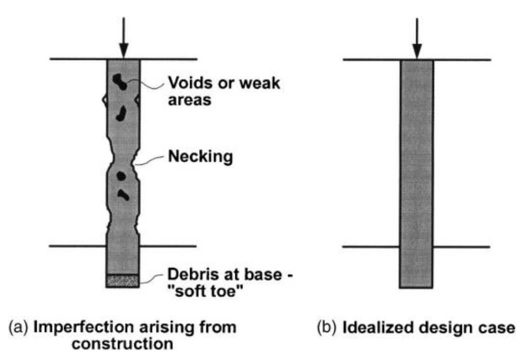


Figure 4 Imperfection relation to construction technique [12]

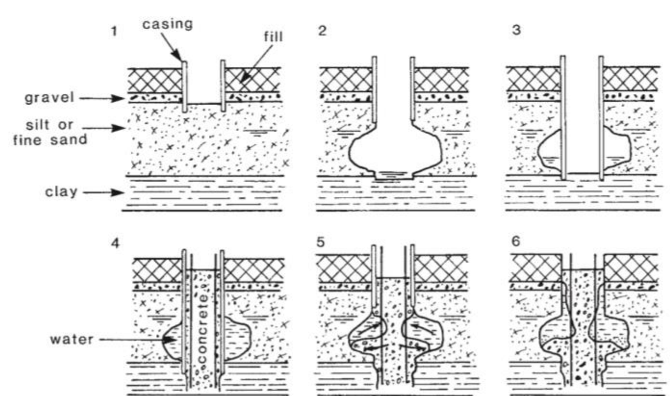


Figure 5 Schematic presentation of formation of water-filled cavities [15]

For placing concrete under a bentonite drilling mud, the tremie method is used and it is important that a suitably designed mix is adopted. Fine sand and silt suspended in the bentonite slurry will gradually settle to the base of the pile, hence final cleaning of the hole should be carried out shortly before concreting. However, if the bore is left filled with slurry for long periods, or if the bentonite suspension is heavily contaminated with soil particles, an appreciable thickness of filter-cake may accumulate. The filter-cake may be strong enough to resist abrasion during the placing of concrete, giving rise to a significant reduction in shaft friction on the completed pile. In clay soils the concrete becomes contaminated with debris and intermixed with slurry [15].

After concreting, extraction of the temporary casing can create problems particularly if delays occur and partial separation of the pile shaft may result (Figure 5). Friction between the concrete and the casing is obviously aggravated by the use of dirty or dented casings. With unsuitable mix designs, it is not unknown for the casing to be withdrawn still filled with concrete. Difficulties arise in pulling the casing if a low-slump concrete is used, or if the aggregate is particularly angular [15].

3.2 Idealized Strain Profile

With pile load test, idealized strain profile in pile such as Figure 6 can be obtained. Figures 6a shows a strain profile of a pile free of soil loaded with load, P. The strain profile is vertical straight line. All the load from top of the pile fully transferred to toe of pile. When the pile placed in uniform soil and pile length optimized according to shaft friction (Figure 6b), the strain profile shall have only single slope, $\Delta\varepsilon/\Delta z$ and zero strain at pile toe (without end bearing). If end bearing mobilised, strain at pile toe is more than zero (Figure 6c). Figure 6d shows the load from top of pile doesn't transferred beyond depth, y.

Actual soil profile is not consistent along pile depth. When shaft friction for $soil_3 > soil_2 > soil_1$ (Figure 6e), strain profile slope is varies with $\Delta\varepsilon_3/\Delta z_3 > \Delta\varepsilon_2/\Delta z_2 > \Delta\varepsilon_1/\Delta z_1$. Figures 6a to 6e are strain profile for pile with consistent stiffness, *EA*, where *E* is young's modulus and *A* is cross sectional area of pile.

As discussed in section 3.1, cast-in-situ pile is often with some imperfections. Figure 6f shows pile with inconsistent cross sectional pile area, *A*. Bulging causing additional cross section pile area and subsequently reduce relative strain; necking causing reduction of cross sectional pile area and subsequently increase relative strain. When pile with void/honeycomb/segregation, effective cross sectional pile area decreased and causing increase of relative strain.

When concrete quality of pile in doubt, young's modulus, *E* of pile directly affected. Problems like delay of concreting work (exceeded concrete setting time), contamination of concrete and "soft toe" causing reduction of concrete strength and young's modulus, *E* of pile will decreased. Figure 6g shows strain profile of pile with load P_1 and P_2. E_1 represent young's modulus at area where concrete quality not affected and E_2, E_3, and E_4 represent level with lower young's modulus. Depth with lower young's modulus have relatively higher strain and tend to achieve elastic limit earlier.

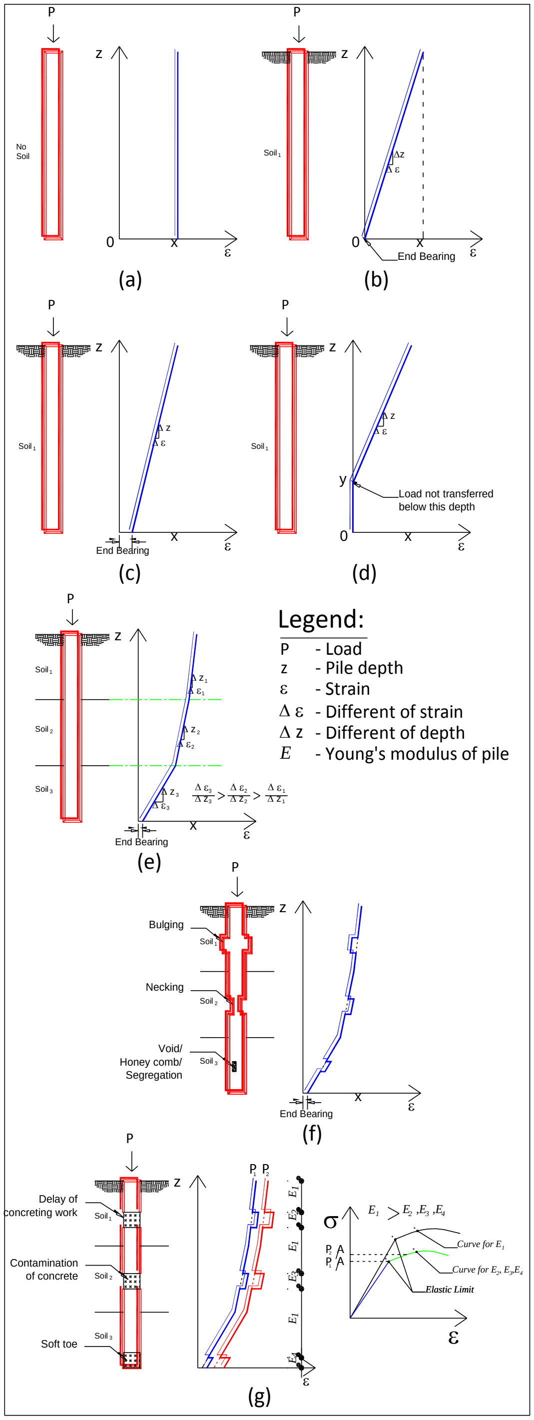


Figure 6 Idealized strain profile in pile during pile load test

4.0 BACKGROUND OF FIELD SITE

Static Load Test on instrumented test pile was carried out on a 600 mm diameter bored cast-in-situ pile at Klang. Subsurface investigation shows that first 12.5 m of the ground is very soft marine clay with SPT-N value are zero. From 12.5 m to 37 m depth, it consists of sandy silt with SPT-N value range from 24 to 50. The pile was designed to undertake shaft friction only (ignored the contribution of base resistance). Due to very soft ground at top, 13 m length of permanent steel casing was provided for this test pile. Total pile length is 27.8 m. Concrete grade for the pile is grade 40 with 8 nos. T25 main steel reinforcement from top to toe of pile. Polymer had been used to stabilise the borehole during drilling process. Figure 7 shows the detail of the test pile.

4.1 Instrumentation

This test pile is instrumented with distributed fiber optic sensor and conventional sensor, i.e. vibrating wire strain gauges (VWSG), tell-tale extensometer and Linear Voltage Displacement Transducers (LVDTs).

Two pairs of distributed fiber optic strain sensing (S1a-S1b & S2a-S2b) cable were fixed to the main reinforcement bars from top to toe of pile (Figure 7). This two pairs of distributed fiber optic sensor provide continuous strain profile along the pile which can be derived to continuous shortening profile of the pile. Six levels of VWSG with each layer 4 numbers and 2 numbers of tell-tale extensometer were also installed in the test pile as indicated in Figure 7.

4.2 Load Test Procedures

Single hydraulic jack was used to load the pile to the designated load. Load cell were used to measure the amount of load transferred to pile. Linear Voltage Displacement Transducers (LVDTs) was used to measure pile top settlement.

The static load test was conducted in accordance to load cycle and load programme given by consultant. The pile was tested up to maximum 2 times working load with the working load of 2800kN. Load test was conducted in 2 cycles. For 1st cycle, maximum test load was 1 time working load with 7 steps of load increment. For the 2nd cycle, maximum test load was 2 times working load and 14 steps of load increment.

5.0 MEASUREMENT RESULTS

Figure 8 compares the strain measurements from Fiber-Optic (FO) sensors and VWSG, 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 was transferred below depth of 21 m. For the top 13 m of the pile, where ground condition is very soft and with permanent steel casing, strain profile is almost a vertical straight line (except the spike at level 4 m to 8 m) which shows that shaft friction was very minimum.

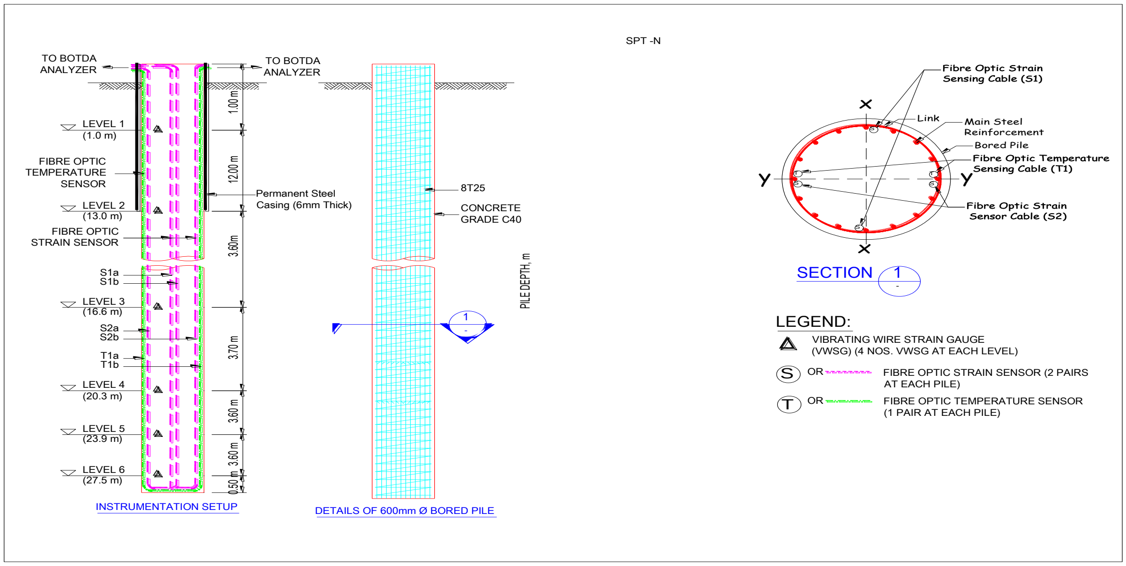


Figure 7 Instrumentation setup and SPT-N value

6.0 THEORETICAL CALCULATION

A theoretical study was performed in order to quantify the pile performance and to establish the load-transfer curve base on the measurement results. This was examined using RATZ program (Randolph [16]), a non-linear load transfer analysis of axially loaded piles. Several parametric studies were performed in order to obtain the likely strengths and stiffness of soils and shaft resistance of the pile so as to match the measured load–displacement response. Certain assumptions and modification of empirical parameters had to be adopted in the RATZ program as explained below:

i. The peak shaft resistance is correlated using the SPT-N values. However because the "N" values are limited to maximum blow count of 50 as in accordance to the code BS EN ISO 22476-3:2005+A1:2011, an estimation of the actual "*N*" higher than 50 had to be extrapolated from the penetration record (*i.e.* 50*300/*x*, where *x* = penetration depth in mm achieved after 50 blow counts). Note that this assumption may result in very large "*N*" values, but is deemed necessary in order to obtain a more realistic shaft resistance profile for the bottommost elevations.

ii. The correlation between SPT and peak shaft is given as:

$$\tau_{peak} = p_A\, n_\tau\, N \qquad (1)$$

where p_A is a reference pressure = 100kPa ≅ 1 tsf ≅ 1 kgf/ cm^2 and n_τ is empirical coefficient that depends on soil type and pile type, here assumed as 0.025 for clayey sand with silt (e.g. Aoki *et al*. [17]; Viggiani *et al.*, [18]) or τ_{peak}/N = 2.5. This is consistent with the reported ratio of τ_{peak}/N ranging from about 0.7 to 4 (kPa) for bored piles in residual soils and weathered rocks (Chang and Broms [19]).

iii. Various correlations between SPT N and shear modulus, G are available in the literature particularly for the mixed sandy-clayey soils (Seed *et al.* [20]; Anbazhagan *et al.* [21]; Imai *et al.* [22]; Ohsaki *et al*. [23]). From RATZ curve-matching exercise (load-displacement) profile, Anbazhagan *et al*. [21] regression equation was found to give the best fit to the observed deformation as shown in Figure 9. The empirical equation is given (in kPa) as:

$$G = 24280N^{0.55} \qquad (2)$$

iv. A constant concrete modulus *E* = 41 GPa is adopted. The end bearing pressure at pile base is limited to 4.5MPa as suggested by Reese and O'Neill [24] after adopting SPT-*N* empirical factor at the pile's base (n_{base} = 1.15 for sandy silt as reported by Decourt, [25]).

7.0 INTERPRETATION OF PILE DEFECT

For soil-structure interaction problems, the interaction forces, P(z) acting on a pile shaft (Eq. (3)) 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. (4)) and integrating (Eq. (5)) the distributed strain data, which in turn results in transfer load functions.

$$P(z) = \varepsilon EA \qquad (3)$$

where EA is the pile's axial stiffness.

$$\tau(z) = \frac{1}{\pi D}\frac{\partial P}{\partial z} = \frac{EA}{\pi D}\frac{\partial \varepsilon}{\partial z} \qquad (4)$$

$$u(z) = \int \varepsilon dz \qquad (5)$$

where $\tau(z)$ is the skin stress and $u(z)$ is the axial displacement or elastic compression

i. With the continuous strain profile, imperfections/defect in the bored pile can be detected by comparing relative stiffness (*EA*) along the pile. In Figure 9, fiber optic (FO) continuous strain profile at 143 % and 200 % of working load are compared to theoretical result generated from RATZ. 3 majors imperfection in this field test can be observed from the comparison. At 4 m to 8 m depth of the pile, localize higher strain can be observed. For this area, the cross sectional area of pile is consistent as it is within permanent steel casing. During concreting, the last pouring was delayed about 4 hours. With the tremie pipe still continuously compact the concrete within that 4 hours, it is highly possible that integrity of concrete was affected. Young's modulus at that particular depth tend to became relatively low. Lower Young's modulus contributed to relatively higher strain.

ii. At 13 m to 16.5 m depth of the pile, localize lower strain (about 20%) can be observed. This is the depth just below the permanent casing where the soil is still weak (refer to SPT-N value). With repeating process of drilling and discharge earth from bored hole, highly possible that some of the soil from this relatively weaker area collapsed into bored hole. Consequently, it created bigger cross sectional area to pile and contributed to lower strain measurement.

iii. At pile toe, strain measurement is relatively higher compare to level above. It could be the effect of "soft toe" with contamination of concrete which directly lower the Young's modulus of concrete. During construction, the steel cage was forced to be pushed down into bored hole for the last 0.7 m length. This observation shows that some soil may had collapsed into pile toe and created "soft toe" condition and contaminated concrete at pile toe. Other possibility is "incomplete cleaning" of the base of the bored pile.

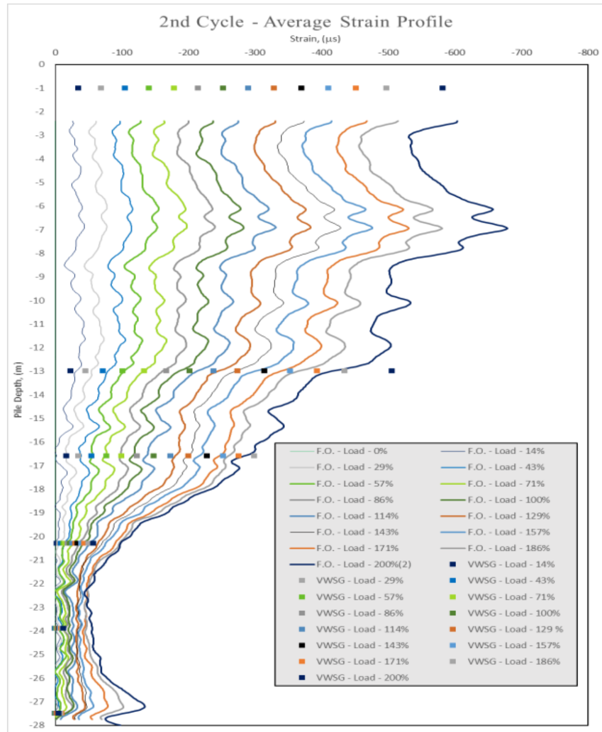


Figure 8 Strain Profile of distributed fiber optic strain sensor (BOTDA) vs VWSG

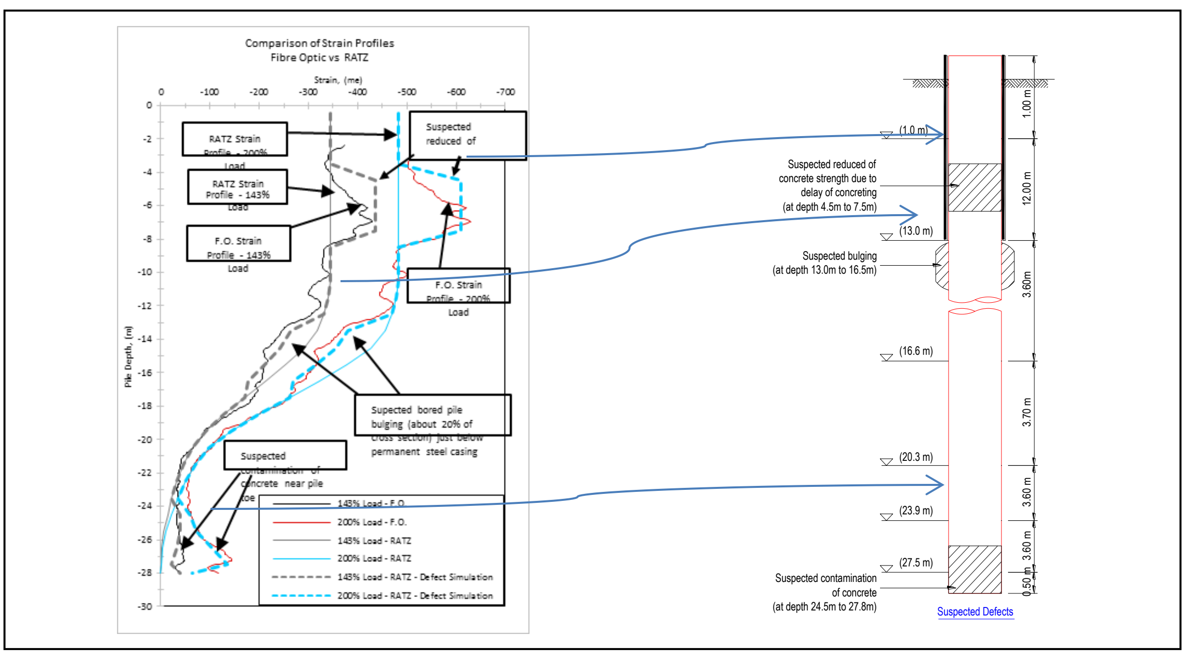


Figure 9 Imperfections/defect simulation

8.0 CONCLUSION

A novel way of instrumenting bored pile using distributed optical fiber strain sensing has been successfully implemented. The field-test results generally showed very good agreement between the conventional and fiber 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. Full continuous 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 "soft toe", contamination of concrete, defective pile bulging had been successfully detected for this case study. DOFSS technology can potentially supplement the existing non-destructive test (NDT) methods. Such information was not possible to obtain from conventional measurement system.

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