

PILE STRUCTURAL DEFORMATION USING INSTRUMENTED TEST PILE  
WITH DISTRIBUTED FIBRE OPTIC SENSOR

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## **DEDICATION**

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is those which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time. This thesis is also dedicated to my wife and children for their unyielding love and supports which have inspired me to complete this research.

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## ABSTRACT

The distributed fibre optic sensor (DFOS) technology adopted in this study is based on Brillouin scattering sensing technology known as Brillouin Optical Time Domain Analysis (BOTDA). BOTDA is a well-established technology for various civil engineering applications, but the study of its application in the instrumented pile load test is still very limited. Here, the study considers the instrumental static axial top-loaded, bi-directional loaded, and laterally loaded in bored pile and static axial top-loaded in the precast reinforced concrete pile. The study also focuses on the pile structural deformation measurement technique, anomaly detection, and interpretation of instrumented test piles with DFOS. The DFOS strain sensing system was first calibrated in the laboratory and then installed in the full-scale on-site control specimen to compare and verify the instrumented data with conventional instrumentation such as Vibrating Wire Strain Gauge (VWSG) and Telltale Extensometer. Subsequently, the DFOS was used in seven (7) full-scale instrumented pile load tests. DFOS via BOTDA technology had successfully measured continuous strain profile. With the continuous strain profile in the axially loaded instrumented test pile, DFOS is capable of measuring the pile structural deformation of the entire pile length. If there are any imperfections in bored piles, such as shaft bulging, cold joints in concrete, intrusion of foreign matter, and improper toe formation due to contamination of concrete, it can be detected through anomaly measurement along the continuous strain profile. By eliminating those measurement anomalies, misinterpreting load transfer curves and pile geotechnical behaviour through continuous strain profiles can be minimised. The measurements were further verified by numerical analysis in RATA software, the pile integrity test (proof coring test and unconfined compression strength test), and visual inspection. A new installation technique and configuration of DFOS had been established in instrumented precast reinforced concrete (RC) piles and laterally loaded instrumented bored piles. The entire pile length deformation in long slender RC piles, including pile joints, was successfully measured and interpreted with DFOS measurement. In the laterally load instrumented test piles, the interpreted lateral movement via DFOS was found to be in good agreement with conventional sensor measurement. In addition, the pile defect detected through anomaly measurement was further verified with a low-strain pile integrity test. In conclusion, the DFOS via BOTDA technology is successfully implemented in various instrumented test piles. Continuous pile structural deformation measurement and anomaly detection improve the reliability of instrumented test pile analysis. This technology will reform the current practice on various types of instrumented test piles and provide a better understanding or comprehensive interpretation of pile structural and geotechnical behaviour.

## ABSTRAK

Teknologi sensor gentian optik teragih (DFOS) yang diguna pakai dalam kajian ini adalah berdasarkan teknologi penginderaan hamburan Brillouin yang dikenali sebagai Analisis Domain Masa Optik Brillouin (BOTDA). BOTDA ialah teknologi yang telah digunapakai untuk pelbagai aplikasi kejuruteraan awam, tetapi kajian penggunaannya dalam ujian beban cerucuk berinstrumen masih sangat terhad. Di sini, kajian mempertimbangkan ujian beban statik instrumental atas-paksi, beban dwi-arah dan beban-sisi dalam cerucuk gerak, dan beban statik atas paksi dalam cerucuk konkrit bertetulang pratuang. Kajian ini juga menumpukan teknik pengukuran ubah bentuk struktur cerucuk, pengesanan anomali, dan tafsiran cerucuk ujian berinstrumen dengan DFOS. Sistem pengesan terikan DFOS pada mulanya ditentukan di makmal dan kemudiannya dipasang pada spesimen kawalan di tapak berskala penuh bagi membandingkan dan mengesahkan data dengan instrumentasi konvensional seperti Tolok Terikan Wayar Bergetar (VWSG) dan *Telltale Extensometer*. Selepas itu, DFOS telah digunakan pada tujuh (7) ujian beban cerucuk berinstrumen skala penuh. DFOS melalui teknologi BOTDA telah berjaya mengukur regangan secara berterusan. Dengan profil terikan berterusan dalam cerucuk ujian berinstrumen atas paksi, DFOS dapat mengukur ubah bentuk struktur keseluruhan panjang cerucuk. Jika terdapat sebarang ketidaksempurnaan dalam cerucuk gerak seperti aci membonjol, sambungan sejuk dalam konkrit, pencerobohan bendasing, dan pembentukan tapak kaki cerucuk yang tidak betul akibat pencemaran konkrit, ia boleh dikesan melalui pengukuran anomali di sepanjang profil terikan berterusan. Dengan menyingkirkan anomali pengukuran tersebut, salah tafsir lengkung pemindahan beban dan sifat geoteknik cerucuk melalui profil terikan berterusan boleh diminimumkan. Pengukuran selanjutnya disahkan secara analisis berangka dalam perisian RATAZ, ujian integriti cerucuk (ujian teras bukti dan ujian mampanan tidak terkurung) dan pemeriksaan visual. Satu teknik pemasangan dan konfigurasi DFOS baharu telah diwujudkan dalam cerucuk konkrit bertetulang pratuang (RC) berinstrumen dan cerucuk gerak berinstrumen beban sisi. Keseluruhan ubah bentuk panjang cerucuk dalam cerucuk RC langsing yang panjang, termasuk sambungan cerucuk, telah berjaya diukur dan ditafsirkan dengan pengukuran DFOS. Dalam cerucuk ujian berinstrumen beban-sisi, pergerakan sisi yang ditafsirkan melalui DFOS didapati dalam persetujuan yang baik dengan pengukuran sensor konvensional. Di samping itu, ujian integriti cerucuk terikan rendah turut mengesahkan kecacatan cerucuk yang dikesan melalui pengukuran anomali. Kesimpulannya, DFOS melalui teknologi BOTDA telah berjaya digunapakai dalam pelbagai jenis ujian cerucuk berinstrumen. Pengukuran ubah bentuk struktur cerucuk berterusan dan pengesanan anomali telah meningkatkan kebolehpercayaan analisis cerucuk ujian berinstrumen dengan ketara. Teknologi ini pasti akan membawa pembaharuan kepada amalan semasa bagi pelbagai ujian cerucuk berinstrumen dan memberikan pemahaman yang lebih baik atau tafsiran secara menyeluruh tentang kelakuan struktur dan geoteknikal cerucuk.

## TABLE OF CONTENTS

	TITLE	PAGE
	<b>DECLARATION</b>	<b>iii</b>
	<b>DEDICATION</b>	<b>iv</b>
	<b>ACKNOWLEDGEMENT</b>	<b>v</b>
	<b>ABSTRACT</b>	<b>vi</b>
	<b>ABSTRAK</b>	<b>vii</b>
	<b>TABLE OF CONTENTS</b>	<b>viii</b>
	<b>LIST OF TABLES</b>	<b>xiv</b>
	<b>LIST OF ABBREVIATIONS</b>	<b>xxi</b>
	<b>LIST OF SYMBOLS</b>	<b>xxii</b>
<b>CHAPTER 1</b>	<b>INTRODUCTION</b>	<b>1</b>
1.1	Background	1
1.2	Statements of Problem	3
1.3	Objectives of Research	5
1.4	Scope of Research	5
1.5	Significance of Research	7
1.6	Outline of Thesis	8
<b>CHAPTER 2</b>	<b>LITERATURE REVIEW</b>	<b>9</b>
2.1	Pile Foundations	9
2.2	Type of Pile	10
2.2.1	Cast-in-situ Bored Pile	11
2.2.1.1	Problem in Cast-in-situ Bored Pile	11
2.2.1.2	Design of Geotechnical Capacity in Soil for Bored Pile	14
2.2.1.3	Design of Geotechnical Capacity in Rock for Bored Pile	16
2.2.2	Precast Reinforced Concrete (RC) Pile	20

2.2.2.1	Problem in Precast Reinforced Concrete Pile	21
2.2.2.2	Design of Geotechnical Capacity for Precast Reinforced Concrete Pile	23
2.3	Pile Load – Settlement Modelling Using RATZ	25
2.4	Pile Integrity Test	28
2.4.1	Low-Strain Integrity Test	28
2.4.2	Proof Coring of Pile Shafts	32
2.5	Background of Instrumented Test Pile	33
2.6	Type of Instrumented Test Pile	34
2.6.1	Axially Loaded	34
2.6.2	Laterally Load Test	38
2.7	Conventional Instrumentation for Instrumented Pile Load Test	39
2.7.1	Tell-tale Extensometer	39
2.7.2	Strain Gauge	41
2.7.3	Load Pressure Cell	44
2.7.4	Dial Gauge or Linear Voltage Displacement Transducer (LVDT)	44
2.7.5	Inclinometer	46
2.8	Analysis and Interpretation of Conventional Instrumented Test Pile Result	49
2.8.1	Axially Loaded	49
2.8.1.1	Top Loaded	49
2.8.1.2	Bi-Directional Loaded	57
2.9	Fibre Optic Sensing Technology	60
2.9.1	Introduction	60
2.9.2	Type of Fibre Optic Sensor	62
2.9.2.1	Point Sensor or Quasi-Distributed Sensor	63
2.9.2.2	Distributed Sensor	64
2.10	Instrumented Test Pile with Distributed Fibre Optic Sensing Technology	65
2.10.1	Introduction	65

2.10.2	Distributed Fibre Optic Strain (DFOS) Sensing Cable	66
2.10.3	Applications of DFOS in Civil Engineering	67
2.10.4	Issues that Affected Instrumented Pile Load Test Interpretation	69
2.10.5	Instrumented Pile Load Test with Fibre Optic Sensor	75
2.10.5.1	Application of Point-wise Fibre Optic Sensor (Fibre Bragg Grating)	75
2.10.5.2	Application of Distributed Fibre Optic Sensor in Instrumented Test Pile	79
2.11	Area of Improvement Required / Research Gap	90
<b>CHAPTER 3</b>	<b>RESEARCH METHODOLOGY</b>	<b>93</b>
3.1	Introduction	93
3.2	DFOS System and Sensing Cable Calibration	95
3.2.1	DFOS System and Sensing Cable Calibration in Laboratory	95
3.2.2	Full Scale On-site Calibration on Instrumented Pile Load Test (Control Specimen)	98
3.2.2.1	Detail of Instrumented Pile (Control Specimen)	98
3.2.2.2	Instrumentation Installation	100
3.2.2.3	Testing Procedure	102
3.2.2.4	Interpretation of DFOS Strain Measurement	103
3.3	Full Scale On-site Application on Instrumented Pile Load Test	104
3.3.1	Top Loaded Static Load Test on Cast-in-situ Bored Pile (Partially Control Specimen – TL1)	106
3.3.1.1	Instrumentation Installation	107
3.3.1.2	Testing Procedure	109
3.3.1.3	Numerical Analysis	110



3.3.2	Top Loaded Static Load Test on Cast-in-situ Bored Pile (Case with pile integrity and anomaly issue – TL2)	113
3.3.2.1	Instrumentation Installation	115
3.3.2.2	Testing Procedure	115
3.3.3	Top Loaded Static Load Test on Cast-in-situ Bored Pile (Case with pile integrity and anomaly issue – TL3)	116
3.3.3.1	Instrumentation Installation	118
3.3.3.2	Testing Procedure	118
3.3.4	Top Loaded Static Load Test on Precast RC Pile (RCP1 & RCP2)	119
3.3.4.1	Testing Procedures	122
3.3.4.2	Soil Interaction and Pile Shortening	123
3.3.5	Bi-Directional Static Load Test on Cast-in-situ Bored Pile (BL1)	124
3.3.5.1	Instrumentation Installation	127
3.3.5.2	Testing Procedures	127
3.3.6	Lateral Static Load Test on Cast-in-situ Bored Pile (LL1)	129
3.3.6.1	Instrumentation Installation	131
3.3.6.2	Testing Procedures	131
<b>CHAPTER 4</b>	<b>RESULTS AND DISCUSSION</b>	<b>133</b>
4.1	Introduction	133
4.2	DFOS System and Sensing Cable Calibration	133
4.2.1	Calibration of DFOS System in the Laboratory	133
4.2.2	Instrumented Static Axial Load Test on Cast-in-situ Bored Pile (Control Specimen - In Rock Formation with Debonding Near Pile Top)	135
4.2.2.1	Results	136
4.2.2.2	Discussion	140
4.3	Full Scale On-site Instrumented Load Test	143
4.3.1	Top Loaded Static Load Test on Cast-in-situ Bored Pile (Partially Control Specimen with	

Permanent Casing in Soft Ground Layer – TL1)	143
4.3.1.1 Results	143
4.3.1.2 Discussion	144
4.3.2 Top Loaded Static Load Test on Cast-in-situ Bored Pile (Case Study with pile integrity and anomaly issue – TL2)	147
4.3.2.1 Result and Discussion	147
4.3.3 Top Loaded Static Load Test on Cast-in-situ Bored Pile (Case Study with pile integrity and anomaly issue – TL3)	149
4.3.3.1 Discussion	150
4.3.4 Top Loaded Static Load Test on Precast RC Pile (RCP1 and RCP2)	152
4.3.4.1 Result and Interpretation of RCP1	152
4.3.4.2 Result and Interpretation of RCP2	160
4.3.4.3 Discussion	165
4.3.5 Bi-Directional Static Load Test on Cast-in-situ Bored Pile (BL1)	168
4.3.5.1 Strain Profile	168
4.3.5.2 Pile Shaft Friction	172
4.3.5.3 Pile Movement	176
4.3.5.4 Potential Causes of Low Shaft Friction	180
4.3.5.5 Karstic Limestone Feature	180
4.3.5.6 Construction Method	181
4.3.5.7 Discussion	181
4.3.6 Lateral Static Load Test on Cast-in-situ Bored Pile (LL1)	182
4.3.6.1 Pile top lateral displacement from LVDT measurements	183
4.3.6.2 Strain Profile Based on Measurement from Distributed Fibre Optic Sensor	185

4.3.6.3	Anomalies Detection based on Distributed Fibre Optic Sensor (DFOS) Measurement	186
4.3.6.4	Discussion	190
<b>CHAPTER 5</b>	<b>CONCLUSION AND RECOMMENDATIONS</b>	<b>193</b>
5.1	Research Outcomes and Conclusion	193
5.2	Recommendations	194
	<b>REFERENCES</b>	<b>197</b>
	<b>LIST OF PUBLICATIONS</b>	<b>209</b>

## LIST OF TABLES

TABLE NO.	TITLE	PAGE
Table 2.1	Suggested ultimate shaft resistance factor, $K_{su}$ for bored pile	15
Table 2.2	Suggested ultimate base resistance factor, $K_{bu}$ for bored pile	16
Table 2.3	Summary of Rock Socket Friction Design Values (Gue et al., 2003)	19
Table 2.4	Suggested ultimate shaft resistance factor, $K_{su}$ for precast reinforced concrete pile	24
Table 2.5	Suggested ultimate base resistance factor, $K_{bu}$ for precast reinforced concrete pile	24
Table 3.1	Summary of the specification for analyser (OZ, 2018)	95
Table 3.2	Setting on BOTDA Interrogator during Calibration	97
Table 3.3	Elongation Interval for DFOS System Laboratory Calibration	98
Table 3.4	Detail of instrumented test pile (bored pile)	99
Table 3.5	Summary of full scale case studies detail	105
Table 3.6	Detail of instrumented test pile (bored pile – TL1)	106
Table 3.7	Detail of instrumented test pile (bored pile – TL2)	113
Table 3.8	Detail of instrumented test pile (bored pile – TL3)	116
Table 3.9	Detail of two instrumented test piles (RC square piles)	120
Table 3.10	Loading sequences of the two test piles	122
Table 3.11	Detail of instrumented test pile (BL1)	125
Table 3.12	Loading cycle of BDSLT	128
Table 3.13	Detail of instrumented test pile (LL1)	129
Table 4.1	Calibration Data DFOS System	134
Table 4.2	Loading sequences of the two test piles	152
Table 4.3	Detail of instrumented test pile (BL1)	168
Table 4.4	Detail of instrumented test pile LL1	182

## LIST OF FIGURES

<b>FIGURE NO.</b>	<b>TITLE</b>	<b>PAGE</b>
Figure 2.1	Necking in bored piles when the casing is removed (John et al., 2012)	12
Figure 2.2	The effect of scour on borehole using drilling buckets (John et al., 2012)	12
Figure 2.3	Procedure for measurement and calculation of rock quality designation, RQD (Deere & Deere, 1989)	18
Figure 2.4	Distribution of Socket Resistance with regards to Socket Length and Modulus Ratio (Pells & Tuner, 1979)	19
Figure 2.5	Idealisation of pile in load transfer analysis (Randolph, 2003)	26
Figure 2.6	Analysis of a short pile element – axial response (Randolph & Gourvenec, 2017)	27
Figure 2.7	Schematic of a typical time-base ‘sonic echo’ test layout (John et al., 2012)	29
Figure 2.8	Graphical representation of hammer blow and ‘echo’ reflection observed at the pile head from a ‘free’ end at the pile toe (John et al., 2012)	30
Figure 2.9	Pile head response in multiple soil strata (John et al., 2012)	31
Figure 2.10	Examples of clear toe response and additional secondary response of Pile Integrity Test (John et al., 2012)	31
Figure 2.11	Typical arrangement for static load test – Kentledge System (ASTM, 2020)	35
Figure 2.12	Typical arrangement for static load test – Reaction System (ASTM, 2020)	36
Figure 2.13	Typical arrangement for static load test – Bi-directional System (ASTM, 2018)	37
Figure 2.14	Typical arrangement for static load test – Tension load test (ASTM, 2022a)	37
Figure 2.15	Typical arrangement for static load test – Lateral load test (ASTM, 2022a)	38
Figure 2.16	Tell-tale extensometer installation in a bored pile	40

Figure 2.17	Various vibrating wire strain gauges, VWSG (Geokon, 2021)	42
Figure 2.18	54 numbers of cables connecting VWSG on steel cage and to datalogger.	43
Figure 2.19	Load cell used during the static load test	44
Figure 2.20	Dial gauge	45
Figure 2.21	Linear Voltage Displacement Transducer	46
Figure 2.22	Cross sectional view of inclinometer casing with grooves	47
Figure 2.23	The total error of inclinometers are contributed by random and systematic errors (Mikkelsen, 2003)	48
Figure 2.24	Inclinometer probe and logger	48
Figure 2.25	Error induced due to bending effect when including all strain gauge that are not positioned opposite to each other (Fellenius & Tan, 2012)	54
Figure 2.26	Typical load distribution curve (SEAGS & AGSSEA, 2019)	54
Figure 2.27	Typical load-movement curve and resistance-movement curve (SEAGS & AGSSEA, 2019)	55
Figure 2.28	Pile with residual force (left) and pile without residual force (right) (SEAGS & AGSSEA, 2019)	56
Figure 2.29	Hysteresis loop for shaft resistance mobilized in a static load test (SEAGS & AGSSEA, 2019)	56
Figure 2.30	Influence of strain gauge location and installation technique (Hayes & Simmonds, 2002)	59
Figure 2.31	Bi-directional Load Test and strain gauges installation (Loadtest, 2021)	60
Figure 2.32	Structure of single mode fibre optic sensing cable (Kechavarzi, 2016)	61
Figure 2.33	Classification of Fibre Optic Technology	62
Figure 2.34	Principle of measurement of a BOTDA system	66
Figure 2.35	Configuration of fibre optic strain sensing cable	67
Figure 2.36	Imperfection relation to construction technique (Poulos, 2005)	70
Figure 2.37	Schematic presentation of formation of water-filled cavities	71

Figure 2.38	(a) to (g) Idealized strain profile in pile during pile load test	73
Figure 2.39	Lateral Load Test Setup	76
Figure 2.40	FBG strain reading during lateral load test	76
Figure 2.41	Applied Bending Moment versus calculated bending moment from FBG Strain Gauges Output	77
Figure 2.42	FBG sensor installation position	78
Figure 2.43	End resistance versus penetration depth	78
Figure 2.44	Axial force profiles along the piles at different penetration depths: axial forces of (a) P1 and (b) P2	79
Figure 2.45	Axial strains in the micropile	80
Figure 2.46	Example of BOTDR strain measurement	80
Figure 2.47	Comparison of VWSG and BOTDR measurement in O-Cell Load Test	82
Figure 2.48	Axial pile strain due to excavation	83
Figure 2.49	Monitored data profiles: (a) axial strain; (b) axial force; (c) vertical displacement	84
Figure 2.50	Strain measured by the three fibres at the maximum load. A sketch of the reinforcement cage is reported on the left, correctly aligned with the y-axis.	85
Figure 2.51	An example of raw and smoothed strain data obtained from an individual strain DFOS cable.	86
Figure 2.52	Strain distributions obtained from distributed fibre optic sensor (all load increment) and VWSG (the last load increment).	87
Figure 2.53	Strain profiles measured by the DFOS system along various ductile piles in different soils during pull-out tests and corresponding results of dynamic probing (DPH): a. fine sand and gravel; b. silt and clay; c. clay and gravels	88
Figure 2.54	Analysis of crack evolution in the grout material - small part of grout material excavated after the test	89
Figure 2.55	Comparison between internal electrical and fibre optic strain measurements along the pile: a. position of sensors; b. mean strain profiles derived from DFOS sensing cables; c. strain profiles measured by strain gages along the installed rebar	89
Figure 3.1	Flow of Methodology	94

Figure 3.2	Calibration of the DFOS Strain Sensing Cable	97
Figure 3.3	Instrumentation setup in test pile (Control Specimen)	101
Figure 3.4	Section view of the DFOS setup	102
Figure 3.5	Instrumentation setup in test pile (TL1)	107
Figure 3.6	Instrumentation devices mounted on the steel cage	108
Figure 3.7	Plan View of Instrumentation Setup at Pile Top	109
Figure 3.8	Instrumentation setup in test pile (TL1)	110
Figure 3.9	Soil investigation near to test pile location.	111
Figure 3.10	Instrumentation setup in test pile (TL2)	114
Figure 3.11	Instrumentation setup in test pile (TL3)	117
Figure 3.12	Soil profile and mobilized shaft friction - RCP1 & RCP2	120
Figure 3.13	Configuration of DFOS cables in MS tubes of RC piles	121
Figure 3.14	Instrumented RC Pile Segment	123
Figure 3.15	Geological Information of pile location	126
Figure 3.16	Schematic diagram of the BDSLT set up	126
Figure 3.17	Instrumentation setup in test pile and soil profile	130
Figure 3.18	Lateral load test setup	132
Figure 4.1	Calibration Result of 1m length DFOS Sensing Cable	134
Figure 4.2	DFOS Strain Sensing Cable Coefficient	135
Figure 4.3	Strain distribution of test pile measured during (a) Loading, and (b) Unloading cycles	138
Figure 4.4	Mobilised shaft friction.	139
Figure 4.5	Back-calculated secant modulus of concrete	139
Figure 4.6	Summary of measurement points between FO and VWSG at five different depths measured during the three loading cycles.	140
Figure 4.7	Creeping behaviour observed during data acquisition from few sets of data under constant loading	142
Figure 4.8	DFOS Versus VWSG Strain Measurement (TL1)	144
Figure 4.9	Imperfection/defect Simulation with RATZ	145
Figure 4.10	Anomalies High Strain Measured Near Pile Head	148



Figure.4.11	Unconfined Compressive Strength of Core Sample	149
Figure 4.12	Anomaly Measurement of Strain Profile and Visual Validation	150
Figure 4.13	Design Stress-Strain Curve for Normal Weight Concrete (adopted from BS8110: Part 1:1997)	151
Figure 4.14	Soil profile and mobilized shaft friction - RCP1	153
Figure 4.15	Load versus pile head settlement curve – RCP1	154
Figure 4.16	Continuous strain profile versus pile depth – RCP1	155
Figure 4.17	Pile Head Movement versus Pile Shortening Calculation from DFOS for RCP1	156
Figure 4.18	Pile shortening – RCP1	157
Figure 4.19	Load distribution along test pile RCP1	158
Figure 4.20	Mobilised Shaft Friction Versus Average Strain of RCP1	159
Figure 4.21	Soil profile and mobilized shaft friction – RCP2	160
Figure 4.22	Load versus pile top settlement curve – RCP2	161
Figure 4.23	Continuous strain profile versus pile depth – RCP2	162
Figure 4.24	Pile shortening – RCP2	163
Figure 4.25	Load distribution along test pile RCP2	164
Figure.4.26	Pile Head Movement versus Pile Shortening Calculation from DFOS for RCP2	165
Figure.4.27	Overall load versus settlement curve of RCP1 & RCP2	166
Figure 4.28	Change in strain along the pile during BDSLT	170
Figure 4.29	Change in strain (4 separate sensing cables) along the pile at depth above the jack during BDSLT at 150%WL	171
Figure 4.30	Back-Calculated Concrete Modulus	172
Figure 4.31	Load distribution along test pile	174
Figure 4.32	Mobilized Shaft Friction (Upper Pile Section) against Average Strain	174
Figure 4.33	Mobilized Unit Shaft Friction (Lower Pile Section) against Average Strain	175
Figure 4.34	Mobilised Unit End Bearing against Toe Movement	175
Figure 4.35	Upward and downward movement against applied load	176

Figure.4.36	Equivalent top settlement curve	177
Figure 4.37	Upward and downward movement vs load curves	179
Figure 4.38	Conversion curve of top load versus movement	180
Figure 4.39	Setup of Test Pile and Subgrade Condition	183
Figure 4.40	Pile top lateral displacement based on LDVT measurements for the test pile and the reaction pile	184
Figure 4.41	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	186
Figure 4.42	Continuous strain profile of distributed fibre optic sensor (a) Sensing cable X1 (b) Sensing cable X2 (c) Sensing cable Y1 (d) Sensing cable Y2	188
Figure 4.43	Maximum Strain of sensing cables X1 and X2 at depth 13.6m (depth with maximum strain)	189
Figure 4.44	Pile Integrity Test result on Test Pile	190

## LIST OF ABBREVIATIONS

BOFDA	-	Brillouin Frequency Domain Analysis
BOTDA	-	Brillouin Optical Time Domain Analysis
BOTDR	-	Brillouin Optical Time Domain Reflectometer
CBP	-	Contiguous Bored Pile
CFA	-	Continuous Flight Auger
DFOS	-	Distributed Fibre Optic Sensor
EPFI	-	Extrinsic Fabry-Perot Interferometers
FBG	-	Fibre Bragg Grating
FEA	-	Finite Element Analysis
LVDT	-	Linear Voltage Displacement Transducer
MS	-	Mild Steel
OBR	-	Optical Backscattered Reflectometer
ODiSI-B	-	Optical Distributed Sensor Interrogator
OFDR	-	Optical Frequency Domain Reflectometry
OTDR	-	Optical Time Domain Reflectometer
RC	-	Reinforced Concrete
RQD	-	Rock Quality Designation
SPT	-	Standard Penetration Test
TCR	-	Total Core Recovery
VWSG	-	Vibrating Wire Strain Gauge

## LIST OF SYMBOLS

$A$	-	Pile Cross Sectional Area
$E$	-	Elastic Modulus of Pile
$E_c$	-	Back-Calculated Concrete Modulus
$\Delta L$	-	Change in length / pile shortening
$P$	-	Load transferred
$\sigma$	-	Stress
$\varepsilon$	-	Strain
$A$	-	Pile Cross Sectional Area

# CHAPTER 1

## INTRODUCTION

### 1.1 Background

Due to the global growth in population and the advancement in construction technology, more high-rise buildings and mega infrastructures are built in recent decades. Capacity required for pile foundation is getting higher and higher. The foundation for these structures must be well designed in order to withstand the significant loads, yet at the same time optimizing the design parameters and cost (Mirsayapov & Koroleva, 2014). Advancement in technology allows the use of Finite Element Analysis (Liu et al., 2012; Pressley & Poulos, 1986) or machine learning approaches (Kardani et al., 2020; Nguyen et al., 2020; Prayogo & Susanto, 2018) to predict the foundation behaviour under high loads. However, the inhomogeneous nature of the soil strata creates various uncertainties in determining the geotechnical design parameters for the pile foundation. Pile load tests are necessary to verify that these piles will comply long-term capacity requirements for the building foundation (Tomlinson & Woodward, 2014). With the Instrumented Pile Load technique, the pile geotechnical design parameter can be verified and various useful information of pile behaviour under static load can be obtained.

Various types of sensors had been used in instrumented test pile in order to monitor the pile behaviour under loading condition. The commonly used measuring sensors in instrumented test pile are strain gauge and tell-tale extensometer for axially loaded test pile and inclinometer for lateral load test pile (Buttling, 1976; Krasinski & Wiszniewski, 2017; Liew et al., 2010; Moayedí et al., 2015; Russo, 2013; Wang et al., 2015).

Strain gauge and tell-tale extensometer is point-wise sensor used to measure pile axial deformation. Both type of sensor is installed at certain intervals along the

pile or at selected depth according to soil or rock profile to obtain load transferred/distribution at targeted soil or rock layer during load test. Due to the nature of the sensors are point-wise sensors, it only able to provide piece of the puzzle information regarding the pile behaviour during load test. Factors such as uncertainty of soil strata, non-uniform concrete material and pile section, imperfection of sensor installation, etc., can contribute more than 40% of error which will further jeopardize the result of instrumented test pile analysis (Hayes & Simmonds, 2002).

For lateral load test, inclinometer is used to measure tilt angle along the pile at certain fixed interval and subsequently convert the tilt angle into lateral deformation profile. The tilt angle measurements normally are taken manually and at interval of every 500 mm. Typical inclinometer system accuracy is  $\pm 0.25$  mm per reading, or  $\pm 6$  mm accumulated over 50 readings (25 m length) which include errors introduced by casing, probe, cable, readout, and operator (Durhamgeo, 2020). The typical accuracy of inclinometer system caused the system to be less reliable and will contribute significant error to pile lateral deflection measurement. Strain gauge can be used to evaluate the distribution of load transfer from the pile to the surrounding soil during lateral load test. Strain gauge should be installed in pairs to measure axial strain, with the gauges in each pair located at same depth, symmetrically opposite each other, equal distant and parallel to the pile axis, and in line with the applied load (ASTM, 2022c). Lateral deflection can be interpreted by integrate the different in strain for each pair of strain gauge along the pile depth. With the strain gauge as point-wise sensor at selected depth/interval, the pile lateral deformation analysis is less reliable due to unavailable of data in between the point-wise sensor interval.

Instrumented test pile forms a crucial part to verify pile performance and geotechnical capacity. A more comprehensive and reliable system is required to improve the implementation of instrumented test pile in order to obtain more accurate geotechnical parameter through load-transfer analysis. In this study, a new technique is established using DFOS via BOTDA technology to improve the performance of varies instrumented test pile. It able to improve accuracy of pile load transfer analysis and supplement the existing pile integrity testing. Pile deformation

at varies geological ground stratum is also discussed based on measurement from DFOS.

## 1.2 Statements of Problem

Instrumented pile load test provides important information regarding the performance of pile. These tests are necessary to verify that the piles will comply long-term capacity requirements for the building foundation. Although the strain gauge has been widely used for a long time, there are several limitations such as time-consuming to install and to connect to data acquisition system, prone to damages, tedious installation process (Ammar *et al.*, 2007), and requires at many instrumented levels (smaller vertical spacing and very costly) in order to achieve reliable load transfer measurement. Imperfection such as pile shaft necking, cold joint and concrete contamination especially at pile toe, among the factor that caused anomalies measurement and contribute to error in pile performance analysis.

Considering the shortcoming of conventional sensor in instrumented test pile application, a method using global strain extensometer (GloStrExt) was established to improve the survivor rate of sensor (Ali *et al.*, 2008; Hanifah & Lee, 2005). Global strain extensometer is a type of post-installation sensor. Steel pipe need to be pre-installed in the bored pile during concrete casting. The GloStrExt sensor can be installed inside the steel pipe after casting of bored pile. It had simplified the tedious installation process compare to conventional sensor and also minimises the risk of sensor damaged due to concreting process. Although survivor rate of sensor can be improved, the GloStrExt system is point-wise sensor and not able to provide full length pile information during load test. The issue of non-uniform concrete material and pile section, imperfection in bored pile during construction still not able to be fully measured or detected using GloStrExt system. Without full length pile information, it may jeopardize the result of instrumented test pile analysis.

The advancement in fibre optic sensing technology provides a better alternative to replace strain gauge in instrumented test piles. There are different techniques that can be used to monitor the fibre optic signal. Fibre Bragg Grating (FBG) sensors are a type of distributed Bragg reflector constructed in a short segment of optical fibre that reflects particular wavelengths of light and transmits all others. They are made by laterally exposing the core of a single-mode fibre to a periodic pattern of intense ultraviolet light and FBG of different wavelengths can be multiplexed in an optical fibre. With the multiplexed nature, multiple sensors can be interconnected in single cable and directly minimised the tedious work to handle large amount of cable. Even the tedious work to handle large amount of cable can be minimise, the FBG system is still point-wise sensor and not able to provide full length pile information during load test. If the pile is embedded in many types of different soil strata, the quantity of point-wise sensor required will be numerous in order to measure mobilised shaft friction in different soil strata during the load test.

In recent year, some DFOS technology with ability to measure continuous strain profile along the pile had been introduced as an alternative to improve and compliment the conventional point-wise instruments in the instrumented pile test. DFOS technology such as Brillouin Optical Time Domain Reflectometer (BOTDR) (Ouyang et al., 2015; Pelecanos et al., 2018), Optical Frequency Domain Reflectometry (OFDR) (Bersan et al., 2018), Luna Optical Distributed Sensor Interrogator (ODiSI-B) (Kania et al., 2020), Optical Backscattered Reflectometer (OBR) (Monsberger et al., 2020) and etc had been used in few full-scale case studies. Most of the case studies successfully prove that DFOS able to measure continuous strain profile and provide usefully information for the full length of pile. But those technology still have shortcoming such as low accuracy ( $> 20 \mu\epsilon$ ) compare to VWSG ( $2 \mu\epsilon$ ) and some can only measure in short length ( $< 70$  m) continuously. Therefore, those DFOS technology as mentioned above still not the perfect solution to improve instrument test pile significantly.

DFOS via BOTDA technology with accuracy of  $2 \mu\epsilon$  and measurement range of more than 2 km is adopted in this study in order to overcome those shortcomings in current instrumented test pile. With the continuous strain profile measurement via



BOTDA, the pile structure deformation, load-transfer and mobilised shaft friction of a pile can be analysed with better confidence level. Anomalies strain along the pile can be detected and directly improve the interpretation result of pile performance significantly.

### **1.3 Objectives of Research**

The objectives of this research are to develop the application technique of Distributed Fibre Optic Sensor (DFOS) based on BOTDA technology in varies type instrumented pile load test. The application technique shall include installation method/configuration, data collection, data processing and data interpretation relevant to both geotechnical and structural behaviour of the pile. The objectives shall include:

- (a) To study the feasibility of using distributed fibre optic sensor via BOTDA in instrumented test pile.
- (b) To develop method of instrumented test pile in varies types of test pile using distributed fibre optic sensor via BOTDA.
- (c) To establish method of pile structural deformation measurement and interpretation in instrumented test pile with distributed fibre optic sensor.
- (d) To establish method of anomaly detection in instrumented test pile and study the effect of anomaly to the interpretation of instrumented test pile result.

### **1.4 Scope of Research**

This study looks into the application of DFOS in different type of instrumented test piles including axially top loaded bored pile, Bi-Directional loaded bored pile, lateral loaded bored pile and axially top loaded precast reinforced concrete (RC) pile. The DFOS system used for this study is based on the Brillouin

Optical Time Domain Analysis (BOTDA) technology. The flow of study is shown in Figure 3.1.

The study started with the calibration of the measurement system (BOTDA) and the sensing cable. After the calibration, the sensing cable and the BOTDA system are used for full scale on-site calibration or verification on control specimen (pile with consistent structural properties). During full scale on-site measurement, the DFOS measurements are validated with comparison to other type of conventional sensor, i.e., strain gauge, tell-tale extensometer and LVDT.

After the laboratory and full scale on-site calibration, seven full scale on-site instrumented pile load tests were executed and the measurement were verified with conventional sensor measurement, numeric analysis dan pile integrity test. The type of instrumented pile load test involved including:

- (a) 3 full scale Top Loaded Load Test on Cast-in-situ Bored Pile
- (b) 1 full scale Bi-Directional Load Test on Cast-in-situ Bored Pile
- (c) 2 full scale Top Loaded Load Test on RC Pile
- (d) 1 full scale Lateral Load Test on Cast-in-situ Bored Pile

Pile load tests are carried out approximately 2 weeks to 1 month after the installation of test pile. The details of testing methods, equipment, loading sequences data collection and other parameters are described in Chapter 3. The detailed interpretation of result is discussed and demonstrated in Chapter 4. The final stage of this study is to interpret the data collected from DFOS of each pile tests. The pile behaviours, structural deformation, anomaly and the performance of the DFOS systems are assessed and evaluated.

## 1.5 Significance of Research

The distributed fibre optic sensing based on Brillouin Optical Time Domain Analysis (BOTDA) is an advanced technique of measuring continuous strain profile which has major advantages over conventional point-wise sensors. With the continuous strain profile, the behaviour of entire pile length can be assessed completely.

With the BOTDA system especially in instrumented bored pile, the load-transfer, mobilised shaft friction and end bearing of pile can be analysed from the continuous strain profile. Defect in pile shaft such as pile shaft necking, cold joint and concrete contamination can be detected based anomalies measurement on the continuous strain profile. By eliminate those anomalies, the interpretation of pile structural and geotechnical behaviour can be significantly improved.

In precast reinforced concrete pile especially long slender pile, continuous strain profile is useful for the computation of pile shortening (which is substantial in long slender piles) and provides a whole new insight to have better understanding on the behaviour of long precast reinforced concrete (RC) piles response under axial pile load test. Failure criterion of long slender pile can be reviewed not only based on the load-settlement curve, but also to assess the load-transfer curve (t-z curve), shortening profile of piles and the degree of mobilised pile friction and end bearing result from the interpretation of continuous strain profile.

Lateral behaviour of the pile can be interpreted from the continuous strain profiles measured along the tensile face and the compressive face over the entire length of the pile. It can easily replace inclinometer for lateral deformation measurement at relatively lower cost. It also able to detect any structural anomalies with direct measurement (compare to inclinometer) and reflect the true lateral structural behaviour.

## **1.6 Outline of Thesis**

There are five chapters in this thesis. Chapter 1 generally introduces the objectives of this study and the scopes of work. The fundamental studies and previous research were reviewed and summarized in Chapter 2. Topics reviewed are of wide range which cover the type of pile, pile load-settlement modelling using RATA, pile integrity test, instrumented pile test, conventional sensors, fibre optic sensors and the application in civil engineering, i.e., FBG, BOTDR and OBR. Chapter 3 thoroughly discusses the methodology of the study. The methodology was categorized into verification tests in laboratory, on site testing and result validation with conventional sensor, numeric analysis and pile integrity test. Chapter 4 presents the results, validation and discussions on all the case studies. The final chapter draws the conclusions and recommendation for future.

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## LIST OF PUBLICATIONS

### Indexed Journal

1. Mohamad, H., & Tee, B. P. (2015). Instrumented pile load testing with distributed optical fibre strain sensor. *Jurnal Teknologi*, 77(11).
2. Mohamad, H., Tee, B. P., Ang, K. A., & Chong, M. F. (2016). Characterizing Anomalies In Distributed Strain Measurements Of Cast-In-Situ Bored Piles. *Jurnal Teknologi*, 78(8-5).

### Non-Indexed Conference Proceedings

1. Lee, S. C., Tee, B. P., Chong, M. F., Ku Mahamud, K. M. S., & Mohamad, H. (2019). Structural Assessment for an old Steel Railway Bridge Under Static and Dynamic Loads Using Fibre Optic Sensors. In *International Conference on Smart Infrastructure and Construction 2019 (ICSIC) Driving data-informed decision-making* (pp. 729-736). ICE Publishing.
2. Mohamad, H., Tee, B. P., Chong, M. F., & Ang, K. A. (2017). Investigation of shaft friction mechanisms of bored piles through distributed optical fibre strain sensing. In *19th International Conference on Soil Mechanics and Geotechnical Engineering*.
3. Mohamad, H., Tee, B. P., Chong, M. F., Ang, K. A., Rashid, A. S. A., & Abdullah, R. A. (2019). Instrumented laterally loaded pile test using distributed fibre optic sensor. *Geotech. Engineering*, 50(2), 36-42.
4. Tee, B. P., Abdullah, R. A., Rashid, A. S. A., Mohamad, H., Chong, M. F., Ang, K. A. (2017). Underground Structure Behaviour and Deformation Monitoring with Distributed Fibre Optic Sensor. *SEACETUS2017*, 201-205.



5. Tee, B. P., Lee, S. C., & Chong, M. F. (2019). Assessment of Long Reinforced Concrete Piles Response under Axial Load Test using Distributed Fibre Optic Strain Sensor. *1<sup>st</sup> MGS & GeoSS Conference 2019*.