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

TEE BUN PIN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Civil Engineering)

Faculty of Civil Engineering
Universiti Teknologi Malaysia

DECEMBER 2022

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.

ACKNOWLEDGEMENT

In preparing this thesis, I was in contact with many people, researchers, academicians, and practitioners. They have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to all my thesis supervisors, Associate Professor Ir. Dr. Rini Asnida Abdullah, Associate Professor Dr. Ahmad Safuan A Rashid, Associate Professor Ir. Dr. Hisham Mohamad, for encouragement, guidance, critics and friendship. Without their continued support and interest, this thesis would not have been the same as presented here.

I am also indebted to Universiti Teknologi Malaysia (UTM) for provide necessary facility and equipment for my Ph.D study. Librarians at UTM, also deserve special thanks for their assistance in supplying the relevant literatures.

I am also very thankful to Mr. Chong Mun Fai and Mr. Ang Koh An for giving me opportunity to carry out my research work in their project sites with all necessary guidance and support.

My fellow postgraduate student should also be recognised for their supports. My sincere appreciation also extends to all my colleagues, especially Dr. Regine Lee Siew Cheng and others who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space. I am grateful to all my family member.

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 RATZ 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 gerek, 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 ditentukur 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 gerek seperti aci membonjol, sambungan sejuk dalam konkrit, pencerobohan bendasing, dan pembentukan tapak kaki ceruruk 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 RATZ, ujian integriti cerucuk (ujian teras bukti dan ujian mampatan tidak terkurung) dan pemeriksaan visual. Satu teknik pemasangan dan konfigurasi DFOS baharu telah diwujudkan dalam cerucuk konkrit bertetulang pratuang (RC) berinstrumen dan cerucuk gerek 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

LIST OF TABLES

LIST OF FIGURES

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
ΔL	-	Change in length / pile shortening
P	-	Load transferred
σ	-	Stress
ε	-	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 varies 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 varies 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; Krasiński & Wiszniewski, 2017; Liew et al., 2010; Moayedi 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 ±0.25 mm per reading, or ±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 $\mu\varepsilon$) compare to VWSG (2 $\mu\varepsilon$) 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 $\mu\varepsilon$ 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 RATZ, 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.

REFERENCES

Ali, F. H., Huat, B. B. K., & Lee, S. K. (2008). Pile Instrumentation Using Retrievable Sensors. *American Journal of Applied Sciences*, *5*(5), 597-604.

Amatya, B. L., Soga, K., Bennett, P. J., Uchimura, T., Ball, P., & Lung, R. (2008). Installation of optical fibre strain sensors on soil nails used for stabilising a steep highway cut slope. Advances in Transportation Geotechnics: Proceedings of the 1st International Conference on Transportation Geotechnics, Nottingham, UK.

Ammar, Z., Meganathan, V., Yehia, S., Abudayyeh, O., & Abdel-Qader, I. (2007). *Evaluating sensors for bridge health monitoring* 2007 IEEE International Conference on Electro/Information Technology.

Anbazhagan, P., & Sitharam, T. G. (2010). Relationship between low strain shear modulus and standard penetration test N values. *Geotechnical Testing Journal*, *33*(2), 150-164.

Aoki, N., & Velloso, D. A. (1975). An approximate method to estimate the bearing capacity of piles. Proceedings of the Fifth Pan- American Conference of Soil Mechanics and Foundation Engineering, Buenos Aires.

Aoki, N., Velloso, D. A., & Salamoni, J. A. (1978). Fundações para o Silo Vertical de 100000 t no Porto de Paranaguá. 6th Brazilian Conference of Soil Mechanics and Foundation Engineering,

ASTM. (2018). *ASTM D8169/D8169M-18: Standard Test Methods for Deep Foundations Under Bi-Directional Static Axial Compressive Load*. ASTM International.

ASTM. (2020). *ASTM D 1143/D 1143M-20 Standard Test Methods for Deep Foundations Under Static Axial Tensile Load*. ASTM International.

ASTM. (2022a). *ASTM D3689/D3689M-22: Standard Test Methods for Deep Foundation Elements Under Static Axial Tensile Load*. ASTM International.

ASTM. (2022b). *ASTM D3966/D3966M-22: Standard Test Methods for Deep Foundation Elements Under Static Lateral Load*. ASTM International.

ASTM. (2022c). *D3966M-22: Standard Test Methods for Deep Foundations Under Lateral Load*. ASTM.

Baldwin, C. S., Poloso, T., Chen, P. C., Niemczuk, J. B., Kiddy, J. S., & Ealy, C. (2001). Structural monitoring of composite marine piles using fiber optic sensors. Smart structures and materials 2001: smart systems for bridges, structures, and highways,

Bersan, S., Bergamo, O., Palmieri, L., Schenato, L., & Simonini, P. (2018). Distributed strain measurements in a CFA pile using high spatial resolution fibre optic sensors. *Engineering Structures*, *160*, 554-565.

Bordes, J. L., & Debreuille, P. J. (1984). Some facts about long-term reliability of vibrating wire instruments. *Reliability of geotechnical instrumentation*, 20-27.

Bourland, M. C., & Yuan, R. L. (2008). Vibrating wire strain gages and civil structures. 11th Biennial ASCE Aerospace Division International Conference on Engineering, Science, Construction, and Operations in Challenging Environments, Long Beach, California.

Broms, B. B. (1966). *Methods of Calculating the Ultimate Bearing Capacity of Piles- A Summary*. Sols-Soil.

Brown, M. J., Hyde, A. F. L., & Anderson, W. F. (2006). Analysis of a rapid load test on an instrumented bored pile in clay. *Géotechnique*, *56*(9), 627-638.

BSI. (2007). *BS8110-1:1997: Structural use of concrete - Part 1 : Code of practice for design and construction, Incorporating Amendments Nos 1,2,3 and 4*. BSI.

BSI. (2020). *BS 8004:2015+A1:2020: Code of practice for foundations*. British Standards Institution.

Buttling, S. (1976). Estimates of shaft and end loads in piles in chalk using strain gauge instrumentation. *Géotechnique*, *26*(1), 133-147.

CEN. (2011). *BS EN ISO 22476-3:2005+A1:2011: Geotechnical investigation and Testing - Field testing - Part 3: Standard penetration test*. CEN.

Chang, M. F., & Broms, B. B. (1991). Design of bored piles in residual soils based on field-performance data. *Canadian geotechnical journal*, *28*(2), 200-209.

Choquet, P., Juneau, F., Debreuille, P. J., & Bessette, J. (1999). Reliability, long-term stability and gage performance of vibrating wire sensors with reference to case histories. Proceedings of the 5th International Symposium on Field Measurements in Geomechanics, Chow, C. M., & Gue, S. S. (2015). Rationalised Settlement Criteria for Pile Load Test. *Jurutera*.

CHTS. (2009). *JT/T738: Static loading test of foundation pile. Self-balanced method*. China Highway and Transportation Society bridge and structural engineering branch.

Decourt, L. (1995). *Prediction of load settlement relationships for foundations on the basis of the SPT-T* Ciclo de Conferencias Inter."Leonardo Zeevaert", , UNAM, Mexico.

Deeks, A. D., White, D. J., & Bolton, M. D. (2005). A comparison of jacked, driven and bored piles in sand. Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering, Osaka, Japan.

Deere, D. U. (1968). Geological considerations. In K. G. Stagg & O. C. Zienkiewicz (Eds.), *Rock mechanics in engineering practice* (pp. 21). Wiley.

Deere, D. U., & Deere, D. W. (1989). *Rock quality designation (RQD) after twenty years* (Contract Report GL-89-1, Issue.

Doherty, P., Igoe, D., Murphy, G., Gavin, K., Preston, J., McAvoy, C., Byrne, B., Mcadam, R., Burd, H., & Houlsby, G. (2015). Field validation of fibre Bragg grating sensors for measuring strain on driven steel piles. *Géotechnique Letters*, *5*(2), 74-79.

Dunnicliff, J. (1993). *Geotechnical instrumentation for monitoring field performance*. John Wiley & Sons.

Durhamgeo. (2020). *Geotechnical instrumentation materials testing equipment*. https://durhamgeo.com/

Fellenius, B. H. (1989a). Tangent modulus of piles determined from strain data. *ASCE*, *1*, 500-510.

Fellenius, B. H. (1989b). Unified design of piles and pile groups. *Transportation Research Record*, *1169*, 75-82.

Fellenius, B. H. (2001). From strain measurements to load in an instrumented pile. *Geotechnocal News Magazine*, *19*(1), 35-38.

Fellenius, B. H., & Tan, S. (2012). Analysis of Bidirectional-cell tests for Icon Condominiums, Singapore. The 9th International Conference on Testing and Design Methods for Deep Foundations., Kanazawa, Japan.

Feng, X., Zhou, J., Sun, C., Zhang, X., & Ansari, F. (2013). Theoretical and experimental investigations into crack detection with BOTDR-distributed fiber optic sensors. *Journal of Engineering Mechanics*, *139*(12), 1797-1807.

FPrimeC. (2021). *Integrity Problems of Concrete Piles*. https://www.fprimec.com/integrity-problems-of-concrete-piles/

G&P. (2011). *Specification for testing of bored pile*. G&P Geotechnics Sdn Bhd.

Gao, L., Ji, B., Kong, G., Huang, X., Li, M., & Mahfouz, A. H. (2015). Distributed measurement of temperature for PCC energy pile using BOFDA. *Journal of Sensors*, *2015*.

Geoengineer.org. (2022). *Unconfined Compression Test*. https://www.geoengineer.org/education/laboratory-testing/unconfined-compression-test

Geokon. (2021). *Geokon Geotechnical + Structural Instrumentation*. https://www.geokon.com/

Glisic, B., & Inaudi, D. (2012). Development of method for in-service crack detection based on distributed fiber optic sensors. *Structural Health Monitoring*, *11*(2), 161-171.

Glisic, B., Inaudi, D., & Nan, C. (2002). Pile monitoring with fiber optic sensors during axial compression, pullout, and flexure tests. *Transportation Research Record*, *1808*(1), 11-20.

Gue, S. S., Tan, Y. C., & Liew, S. S. (2003). A Brief Guide to Design of Bored Piles under Axial Compression - A Malaysian Approach. Seminar on Bridge 2003, Kuala Lumpur.

Hanifah, A. A., & Lee, S. K. (2005). Innovation in instrumented test piles in Malaysia: application of global strain extensometer (GloStrExt) method for bored piles. Special lectures. Proceeding of Malaysian Geotechnical conference,

Hayes, J., & Simmonds, T. (2002). Interpreting strain measurements from load tests in bored piles. Proceedings of the Ninth International Conference on Piling and Deep Foundations,

Healy, P. R., & Weltman, A. J. (1980). *Survey of problems associated with the installation of displacement piles*. CIRIA.

Hiley, A. (1925). *A rational pile-driving formula and its application in piling practice explained* Engineering, London.

Hornby, I. W., & Noltingk, B. E. (1974). The application of the vibrating-wire principle for the measurement of strain in concrete. *Experimental Mechanics*, *14*(3), 123-128.

Hoult, N. A., Ekim, O., & Regier, R. (2014). Damage/deterioration detection for steel structures using distributed fiber optic strain sensors. *Journal of Engineering Mechanics*, *140*(12), 04014097.

Hunt, R. E. (2005). *Geotechnical engineering investigation handbook*. Crc Press.

Imai, T., & Tonouchi, K. (2021). Correlation of N value with S-wave velocity and shear modulus. In *Penetration Testing* (Vol. 67, pp. 72). Routledge.

Iten, M. (2012). *Novel applications of distributed fiber-optic sensing in geotechnical engineering* (Vol. 19632). vdf Hochschulverlag AG.

Janmonta, K., Uchimura, T., Amatya, B., Soga, K., Bennett, P., Lung, R., & Robertson, I. (2008). Fibre optics monitoring of clay cuttings and embankments along London's ring motorway. GeoCongress 2008: Characterization, Monitoring, and Modeling of GeoSystems,

JKR. (2017). *Guideline for piling works*. Jabatan Kerja Raya.

John, B., Tim, C., Hilary, S., Michael, B., William, B. J. B. P., Tim, B. J. B. C., David, P., Lidija, Z., Delwynne, R., & Tony, S. (2012). *ICE Manual of Geotechnical Engineering* (Vol. 1). ICE Publishing.

Kania, J. G., Sorensen, K. K., & Fellenius, B. H. (2020). Application of distributed fibre optic cables in piles. *Geotechnical Engineering*, *51*(3).

Kardani, N., Zhou, A., Nazem, M., & Shen, S.-L. (2020). Estimation of bearing capacity of piles in cohesionless soil using optimised machine learning approaches. *Geotechnical and Geological Engineering*, *38*(2), 2271-2291.

Kechavarzi, C. (2016). *Distributed fibre optic strain sensing for monitoring civil infrastructure: a practical guide*. Ice Publishing.

Klar, A., Bennett, P. J., Soga, K., Mair, R. J., Tester, P., Fernie, R., St John, H. D., & Torp-Peterson, G. (2006). Distributed strain measurement for pile foundations. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, *159*(3), 135-144.

Kontoni, D. P. N., & Farghaly, A. A. (2018). 3D FEM analysis of a pile-supported riverine platform under environmental loads incorporating soil-pile interaction. *Computation*, *6*(1), 8.

Krasiński, A., & Wiszniewski, M. (2017). Static load test on instrumented pile–field data and numerical simulations. *Studia Geotechnica et Mechanica*, *39*(3), 17-25.

Lam, C., & Jefferis, S. A. (2011). Critical assessment of pile modulus determination methods. *Canadian geotechnical journal*, *48*(10), 1433-1448.

Lam, C., Jefferis, S. A., Suckling, T. P., & Troughton, V. M. (2015). Effects of polymer and bentonite support fluids on the performance of bored piles. *Soils and Foundations*, *55*(6), 1487-1500.

Lee, H. M., & Park, H. S. (2013). Measurement of maximum strain of steel beam structures based on average strains from vibrating wire strain gages. *Experimental Techniques*, *37*(2), 23-29.

Lee, S. C., Tee, B. P., Chong, M. F., Ku Mahamud, K., & Mohamad, H. (2019). *Structural Assessment for an old Steel Railway Bridge Under Static and Dynamic Loads Using Fibre Optic Sensors* International Conference on Smart Infrastructure and Construction 2019 (ICSIC) Driving data-informed decision-making,

Lee, S. C., Tee, B. P., Chong, M. F., Mohamad, H., Ang, K. A., & Rahardjo, P. P. (2018). Application of Distributed Fibre Optic Sensor (DFOS) in Bi-directional Static Pile Load Tests. *Geotechnical Engineering Journal of the SEAGC 2018*.

Lee, W., Lee, W.-J., Lee, S.-B., & Salgado, R. (2004). Measurement of pile load transfer using the Fiber Bragg Grating sensor system. *Canadian geotechnical journal*, *41*(6), 1222-1232.

Leung, C. K. Y., Wan, K. T., Inaudi, D., Bao, X., Habel, W., Zhou, Z., Ou, J., Ghandehari, M., Wu, H. C., & Imai, M. (2015). Optical fiber sensors for civil engineering applications. *Materials and Structures*, *48*(4), 871-906.

Liew, S., & Choo, E. (2004). Bending moment interpretation of structural element with measured deflection profile. Malaysian Geotechnical Conference,

Liew, S. S., Khoo, C. M., Tan, S. T., & Loh, Y. E. (2010). *Review of Load Test Performance of Bored Pile Foundation in Weathered Meta-Sedimentary Formation and Kuala Lumpur Limestone,* The 17th Southeast Asian Geotechnical Conference,

Liu, J., Gao, H., & Liu, H. (2012). Finite element analyses of negative skin friction on a single pile. *Acta Geotechnica*, *7*(3), 239-252.

Loadtest. (2021). *Fugro Loadtest - Specialists in Foundation Testing* http://www.loadtest.com

Lopes, F. R., & Laprovitera, H. (1988). On the prediction of the bearing capacity of bored piles from dynamic penetration test. Proceedings of the First International Conference on Foundations on Bored and Auger Piles,

Massad, F. (2015). On the Interpretation of the Bidirectional Static Load Test. *Soils and Rocks*, 249-262.

Meyerhof, G. G. (1976). Bearing capacity and settlement of pile foundations. *Journal of Geotechnical Engineering, ASCE, 102*(3), 34.

Meyerhof, G. G. (1983). Scale Effects of Ultimate Pile Capacity. *Journal of geotechnical engineering*, *109*(6), 797.

Mikkelsen, P. E. (2003). Advances in inclinometer data analysis. Symposium on Field Measurements in Geomechanics. , Oslo.

Mirsayapov, I. T., & Koroleva, I. V. (2014, 25-27 August). Bearing capacity and deformation of the base of deep foundations' ground bases. Geotechnical Aspects of Underground Construction in Soft Ground: Proc. intern. symp. , Seoul, Korea.

Moayedi, H., Nazir, R., & Mosallanezhad, M. (2015). Determination of reliable stress and strain distributions along bored piles. *Soil Mechanics and Foundation Engineering*, *51*(6), 285-291.

Mohamad, H., Soga, K., Bennett, P. J., Mair, R. J., & Lim, C. S. (2012). Monitoring twin tunnel interaction using distributed optical fiber strain measurements. *Journal of geotechnical and geoenvironmental engineering*, *138*(8), 957-967.

Mohamad, H., Soga, K., Pellew, A., & Bennett, P. J. (2011). Performance monitoring of a secant-piled wall using distributed fiber optic strain sensing. *Journal of geotechnical and geoenvironmental engineering*, *137*(12), 1236-1243.

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).

Monsberger, C. M., Lienhart, W., & Hayden, M. (2020). Distributed fiber optic sensing along driven ductile piles: Design, sensor installation and monitoring benefits. *Journal of Civil Structural Health Monitoring*, *10*, 627-637.

Murphy, G., Igoe, D., Doherty, P., & Gavin, K. (2018). 3D FEM approach for laterally loaded monopile design. *Computers and Geotechnics*, *100*, 76-83.

Neely, W. J. (1991). Bearing capacity of augercast piles in sand. *Journal of Geotechnical Engineering, ASCE, 117*(2), 15.

Neoh, C. A. (1998). Design and construction of pile foundations in limestone formation. *Journal of Institution of Engineers, Malaysia, 59*(1), 23-29.

Nguyen, T. A., Ly, H. B., Jaafari, A., & Pham, T. B. (2020). Estimation of friction capacity of driven piles in clay using artificial Neural Network. *Vietnam Journal of Earth Sciences, 42*(3), 265-275.

Ohsaki, Y., & Iwasaki, R. (1973). On dynamic shear moduli and Poisson's ratios of soil deposits. *Soils and Foundations, 13*(4), 61-73.

Ouyang, Y., Broadbent, K., Bell, A., Pelecanos, L., & Soga, K. (2015). The use of fibre optic instrumentation to monitor the O-Cell load test on a single working pile in London. In. Ice Publishing.

OZ. (2018). *Fiber Optic Distributed Strain and Temperature Sensors (DSTS) Specification*. OZ Optics Ltd.

Paikowsky, S. G., & Hajduk, E. L. (2004). Design and construction of three instrumented test piles to examine time dependent pile capacity gain. *Geotechnical Testing Journal, 27*(6), 515-531.

Pelecanos, L., Soga, K., Elshafie, M. Z., de Battista, N., Kechavarzi, C., Gue, C. Y., Ouyang, Y., & Seo, H.-J. (2018). Distributed fiber optic sensing of axially loaded bored piles. *Journal of geotechnical and geoenvironmental engineering, 144*(3), 04017122.

Pelecanos, L., Soga, K., Hardy, S., Blair, A., Carter, K., & Patel, D. (2016). *Distributed fibre-optic monitoring of tension piles under a basement excavation at the V&A Museum in London.* Transforming the Future of Infrastructure through Smarter Information: Proceedings of the International Conference on Smart Infrastructure and ConstructionConstruction, 27–29 June 2016,

Pells, P. J. N., & Tuner, R. M. (1979). Elastic Solutions for Design and Analysis of Rock Socketed Piles. *Canadian geotechnical journal, 16*, 7.

Poulos, H. G. (1989). Pile behaviour—theory and application. *Géotechnique, 39*(3), 365-415.

Poulos, H. G. (2005). Pile behavior—Consequences of geological and construction imperfections. *Journal of geotechnical and geoenvironmental engineering, 131*(5), 538-563.

Prayogo, D., & Susanto, Y. T. T. (2018). Optimizing the prediction accuracy of friction capacity of driven piles in cohesive soil using a novel self-tuning least squares support vector machine. *Advances in Civil Engineering, 2018*.

Pressley, J. S., & Poulos, H. G. (1986). Finite element analysis of mechanisms of pile group behaviour. *International journal for numerical and analytical methods in geomechanics*, *10*(2), 213-221.

Randolph, M., & Gourvenec, S. (2017). *Offshore Geotechnical Engineering*. CRC Press.

Randolph, M. F. (2003). *RATZ manual version 4.2 - Load transfer analysis of axially loaded piles* In University of Western Australia.

Randolph, M. F., & Wroth, C. P. (1979). A simple approach to pile design and the evaluation of pile tests. In *Behavior of Deep Foundations*. ASTM International.

Reese, L. C., & O'Neil, M. W. (1988). *Drilled Shafts: Construction and Design*. FHWA-IF-99-025.

Reese, L. C., & O'Neill, M. W. (1989). *New design method for drilled shafts from common soil and rock tests* Foundation Engineering: Current Principles and Practices, Evanston, Illinois, United States.

Rieke, R. D., & Crowser, J. C. (1987). Interpretation of pile load test considering residual stresses. *Journal of geotechnical engineering*, *113*(4), 320-334.

RST. (2021). *Vibrating Wire Strain Gauge*. RST Instruments Ltd.

Russo, G. (2013). Experimental investigations and analysis on different pile load testing procedures. *Acta Geotechnica*, *8*(1), 17-31.

Savitzky, A., & Golay, M. J. E. (1964). Smoothing and differentiation of data by simplified least squares procedures. *Analytical chemistry*, *36*(8), 1627-1639.

Schwamb, T., Soga, K., Mair, R. J., Elshafie, M. Z., Sutherden, R., Boquet, C., & Greenwood, J. (2014). Fibre optic monitoring of a deep circular excavation. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, *167*(2), 144-154.

SEAGS, & AGSSEA. (2019). Honoring Dr. Bengt H. Fellenius. *Geotechnical Engineering Journal of the SEAGS & AGSSEA Journal*, *50*(3).

Seed, H. B., Idriss, I. M., & Arango, I. (1983). Evaluation of liquefaction potential using field performance data. *Journal of geotechnical engineering*, *109*(3), 458-482.

Siegel, T. C. (2010). Load Testing and Interpretation of Instrumented Augered Cast-in-Place Piles. *DFI Journal-The Journal of the Deep Foundations Institute*, *4*(2), 65-71.

Sinnreich, J., & Ayithi, A. (2014). Derivation of py curves from lateral pile load test instrument data. *Geotechnical Testing Journal*, *37*(6), 1025-1036.

Soga, K., Kwan, V., Pelecanos, L., Rui, Y., Schwamb, T., Seo, H., & Wilcock, M. (2015). The role of distributed sensing in understanding the engineering performance of geotechnical structures. In.

Soga, K., & Luo, L. (2018). Distributed fiber optics sensors for civil engineering infrastructure sensing. *Journal of Structural Integrity and Maintenance*, *3*(1), 1-21.

Sreeshylam, P., Ravisankar, K., Parivallal, S., Kesavan, K., & Sridhar, S. (2008). Condition monitoring of pre-stressed concrete structures using vibrating wire sensors. *International Journal of COMADEM*, *11*(3), 46.

Tan, G. H., Poh, Y. K., Osborne, N. H., Ng, C. C., & Brownjohn, J. M. (2008). Reducing false alerts by improving vibrating wire strain gauge data quality using fast fourier transform. International Conference on Deep Excavations,

Tan, Y. C., Chen, C. S., & Liew, S. S. (1998). Load Transfer Behaviour of Cast-in-place Bored Piles in Tropical Residuals Soils. Proceedings of the 13th Southeast Asian Geotechnical Conferences, Taipei.

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* 1st Malaysian Geotechnical Society (MGS) and Geotechnical Society of Singapore (GeoSS) Conference 2019, Petaling Jaya, Malaysia.

Thorburn, S., & MacVicar, R. S. L. (1971). *Pile load tests to failure in the Clyde alluvium*. Thomas Telford Publishing.

Thorburn, S., & Thorburn, J. Q. (1977). *Review of problems associated with the construction of cast-in-place concrete piles*. Directorate of Civil Engineering Services, Property Services Agency.

Toh, C. T., Ooi, T. A., Chiu, H. K., Chee, S. K., & Ting, W. N. (1989). Design Parameters for Bored Piles in a Weathered Sedimentary Formation. Proceedings of 12th International Conference on Soil Mechanics and Foundation Engineering, Rio de Janeiro.

Tomlinson, M., & Woodward, J. (2014). *Pile design and construction practice*. CRC Press.

Tremblay, J., El-Gamal, S., Wattanasanticharoen, E., & Benmokrane, B. (2009). Reinforced concrete pile load testing with fiber optic sensor. 4th International Conference on Structural Health Monitoring on Intelligent Infrastructure (SHMII-4),

Turner, M. J. (1997). *Integrity testing in piling practice* (R 144). CIRIA.

Udd, E. (1995). An overview of fiber‐optic sensors. *review of scientific instruments*, *66*(8), 4015-4030.

Udd, E., & Spillman Jr, W. B. (2011). *Fiber optic sensors: an introduction for engineers and scientists*. John Wiley & Sons.

Viggiani, C., Mandolini, A., & Russo, G. (2014). *Piles and pile foundations*. CRC Press.

Wang, X., Tweedie, R., & Clementino, R. (2015). Full-scale pile loading tests on instrumented concrete piles in clay till, in Edmonton, Alberta.

Wang, Y., Liu, X., Zhang, M., Sang, S., & Bai, X. (2020). Test and study of pipe pile penetration in cohesive soil using FBG sensing technology. *Sensors*, *20*(7), 1934.

Wright, L. (2000). Problems associated with the construction of bored cast-in-place concrete piles. Sixth Young Geotechnical Engineers Symposium,

Yu, C.-H. (2011). On design and construction of pile group foundation of Taipei 101. *Geotechnical Engineering Journal of the SEAGS & AGSSEA*, *42*(2), 56-69.

Zeni, L., Picarelli, L., Avolio, B., Coscetta, A., Papa, R., Zeni, G., Di Maio, C., Vassallo, R., & Minardo, A. (2015). Brillouin optical time-domain analysis for geotechnical monitoring. *Journal of Rock Mechanics and Geotechnical Engineering*, *7*(4), 458-462.

Zhu, L. J., Cheng, Y. M., & Yang, D. B. (2012). The analysis of instrumented pile under lateral load. *Journal of Geomechanics and Geoengineering*, *7*(1), 27-37.

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. *1st MGS & GeoSS Conference 2019.*