

FIBRE OPTIC SENSING MONITORING SYSTEM FOR PILE ON SLOPE

SAFINAZ BINTI KHAIRUL ANUAR

A project report submitted in partial fulfilment of the
requirements for the award of the degree of
Master of Civil Engineering (Geotechnics)

School of Civil Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

JANUARY 2019

DEDICATION

ALHAMDULILLAH...

Praise to Allah for His unlimited guidance and blessing

This thesis is dedicated to my beloved parents Khairul Anuar bin Kassim (father) and Nor Azrina binti Deris (mother), to my precious siblings, to my supervisor, lectures and all of my friends.

ACKNOWLEDGEMENT

First of all the, Alhamdulillah praise to Allah for His unlimited guidance and blessing, I would like to express my deepest appreciation to all those who provided me the possibility to complete this project. A special gratitude I give to my supervisor Assoc. Prof. Ir. Dr. Azman bin Kassim, whose contribution in stimulating suggestions and encouragement, helped me to coordinate my final year project especially in writing this report.

Furthermore I would also like to take this opportunity to express my gratitude to the lectures of Faculty of Civil Engineering who have taught me throughout my studies here in University Teknologi Malaysia. I would also like to thank my parents and siblings for always giving me encouragement and impetus to continue to succeed in this field of study. To my friends who have always been by my side, I am grateful for all the support.

I am also indebted to my fellow postgraduate student should also be recognised for their support. My sincere appreciation also extends to all my colleagues and others who have provided assistance at various occasions. Their views and tips are useful indeed.

Finally, I would also like to thanks to ane and all who directly or indirectly lent their helping hand in completing this project especially the member of faculty civil engineering UTM.

ABSTRACT

Monitoring system is very important in geotechnical works. In slope reinforced with pile, monitoring system is needed to monitor the displacement of the pile due to the slope instability. Therefore, this study will focus on a newly develop monitoring system using an optical fibre sensing technology to measure the strain of the pile install on the slope. The strain on the pile will be measure due to the slope instability and load increment on the slope crest. The advantage of using Optical fibre sensing technology is that it can give the strain measurement along the optical fibre length instead of from discrete points. This paper describes the experimental work conducted with the use of a distributed sensing technology called Brillouin Optical Time Domain Analysis (BOTDA). A small scale physical soil slope model was stimulated to measure the strain and calculate the displacement of the pile. The physical model result is then compared with numerical modeling using SLOPE/W and SIGMA/W. As a result, fibre optic is a good approach for geotechnical instrumentation and monitoring since they are sensitive toward the movement of geotechnical structure and soil. The optical fibre can measure the strain along the pile up to micro strain ($\mu\epsilon$).

ABSTRAK

Sistem pemantauan sangat penting dalam kerja-kerja geoteknik. Bagi cerun yang dikukuhkan dengan cerucuk, Sistem pemantauan diperlukan untuk memantau anjakan cerucuk disebabkan oleh ketidak stabilan cerun. Oleh itu, kajian ini akan tumpu kepada kaedah baru bagi sistem pemantauan yang menggunakan teknologi gentian optik untuk mengukur keterikan cerucuk di cerun. Keterikan cerucuk akan diukur berdasarkan oleh ketidak stabilan cerun dan penambahan beban pada puncak cerun. Kebaikan menggunakan teknologi gentian optik adalah ia dapat memberi bacaan sepanjang kabel gentian optik dan bukan hanya ukuran diskrit. Kajian ini menerangkan kerja-kerja eksperimen yang dijalankan dengan bantuan teknologi yang bernama Brillouin Optical Time Domain Analysis (BOTDA). Kerja fizikal cerun skala kecil diransangkan untuk mengukur keterikan and mengira anjakan cerucuk. Hasil kerja model physical cerun di bandingkan dengan model numerical menggunakan SLOPE/W dan SIGMA/W. Hasilnya, serat optik merupakan pendekatan yg baik bagi pemantauan geoteknik kerana serat optik sensitif terhadap struktur geteknik dan tanah. Serat optik boleh mengukur keterikan sepanjang cerucuk hingga keterikan micro ($\mu\epsilon$).

TABLE OF CONTENTS

	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENT	iv
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	vi
	LIST OF TABLES	x
	LIST OF FIGURES	xi
	LIST OF ABBREVIATIONS	xiii
	LIST OF SYMBOLS	xiv
	LIST OF APPENDICES	xv
CHAPTER 1	INTRODUCTION	1
1.1	Problem Background	1
1.2	Problem Statement	2
1.3	Aim and Objective	3
1.4	Scope of Study	3
1.5	Significant of Study	4
CHAPTER 2	LITERATURE REVIEW	5
2.1	Introduction	5
2.2	Slope Stability Analysis	5
2.2.1	Limit Equilibrium Method	6
2.2.2	Numerical Analysis Method	6
2.2.3	Limit Analysis Method	7
2.3	Pile Design	7
2.3.1	Ultimate Lateral Load	8
2.4	Modeling	12

2.5	Numerical Modeling	13
2.5.1	GeoStudio	14
2.5.2	GeoStudio Product Model	15
2.6	Optical Fibre and Cable	17
2.6.1	Basic Law of Optics	18
2.6.2	Types of Optical Fibre	19
2.6.3	Optical Fibre Sensing Technology	21
2.6.4	Principal of Distributed Optical Fibre Sensing	23
CHAPTER 3	RESEARCH METHODOLOGY	26
3.1	Introduction	26
3.2	Flowchart Research	26
3.3	Numerical Modeling – SLOPE/W	28
3.4	Physical Work	34
3.4.1	Preparation of Fibre Optic Cable	34
3.4.2	Fibre Optic Installation on Pipe	37
3.4.3	Physical Model Preparation and Pipe Installation	38
3.4.4	Testing on the Physical Model	41
3.5	SIGMA/W Numerical Modeling	42
3.6	Apparatus and Equipment	47
CHAPTER 4	RESULT AND DISCUSSION	48
4.1	Introduction	48
4.2	SLOPE/W Slip Surface Result.	48
4.3	Strain Distribution along Fibre Length	49
4.4	Strain to Displacement Conversion	52
4.5	Comparison with Numerical Modeling	53
4.6	Physical Model's Slip Surface Result.	55
4.7	Comparison of Strain, Displacement and Slope Surface Result	56
CHAPTER 5	CONCLUSION AND RECOMMENDATIONS	59
5.1	Introduction	59

5.2	Conclusions	59
5.3	Recommendations	60

REFERENCES	61
-------------------	-----------

LIST OF TABLES

TABLE NO.	TITLE	PAGE
Table 2.1	List of Limit Equilibrium Methods	6
Table 2.2	Shear force and bending moment offered by pile for three modes	11
Table 3.1	Gant chart of the research study	26
Table 3.2	Material properties of the soil	32
Table 3.3	Material properties of soil	43

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
Figure 2.1	Scheme of the problem	9
Figure 2.2	Problem under consideration (Di Laora et al., 2017)	10
Figure 2.3	Mode of failure (Viggiani, 1981)	10
Figure 2.4	Burland Triangle (Burland, 1987; Burland, 1996)	13
Figure 2.5	Illustration of numerical modelling	14
Figure 2.6	GeoStudio main page	14
Figure 2.7	Cross section of fibre (Mohamad, 2008)	17
Figure 2.8	Refracted light due to different index of refraction	18
Figure 2.9	Total internal reflection	19
Figure 2.10	Step-index and graded index multimode fibre illustration	21
Figure 2.11	Comparison of point, quasi-distributed and distributed strain sensing	22
Figure 2.12	Types of backscattering light (Hisham Mohamad, 2008)	24
Figure 3.1	Flowchart of the research study	27
Figure 3.2	The soil slope model chamber	28
Figure 3.3	Dimension of the chamber	28
Figure 3.4	KeyIn analysis tab in SLOPE/W	29
Figure 3.5	Set page window	30
Figure 3.6	Set units and scale window	30
Figure 3.7	Grid window	31
Figure 3.8	KeyIn points window	31
Figure 3.9	KeyIn materials window	32
Figure 3.10	Assign material menu	33
Figure 3.11	Soil slope model (no pile)	33
Figure 3.12	Optical Connector	35
Figure 3.13	Fibre Cleaver	36

Figure 3.14	Fibre optic fusion splicer	36
Figure 3.15	Splice Reinforcing	37
Figure 3.16	Fibre optic install along an axis	38
Figure 3.17	Slope formation process	39
Figure 3.18	Slope trimming process	39
Figure 3.19	Soil slope model	40
Figure 3.20	Pipe installation on slope	40
Figure 3.21	Load plate test on slope	41
Figure 3.22	Physical model testing setup	42
Figure 3.23	KeyIn analyses tab in SIGMA/W	42
Figure 3.24	SIGMA/W KeyIn material tab	43
Figure 3.25	KeyIn boundary condition tab	44
Figure 3.26	Soil slope model boundary conditions	44
Figure 3.27	Mesh for soil slope model	45
Figure 3.28	Soil slope model with pile	46
Figure 3.29	Load/defermentation analysis	46
Figure 3.30	KeyIn boundary conditions for surcharge load	47
Figure 4.1	Soil slope model without pile slip failure and FOS	48
Figure 4.2	Soil slope model with pile slip failure and FOS	49
Figure 4.3	Graph of strain vs fibre length at pipe	50
Figure 4.4	Illustration of pile and fibre optic position	50
Figure 4.5	Cros-section with axes X-X	51
Figure 4.6	Fibre length (m) vs strain	52
Figure 4.7	Graph of pipe length (m) vs displacement (mm) optical fibre	53
Figure 4.8	Graph of pipe length (m) vs displacement (m) SIGMA/W	54
Figure 4.9	Physical soil slope model slip surface	55
Figure 4.10	Slip surface illustration	56
Figure 4.11	Comparison strain and slip surface	57
Figure 4.12	Comparison displacement and slip surface	58

LIST OF ABBREVIATIONS

BOTDA	-	Brillouin Optical Time-Domain Analysis.
FDM	-	Finite Difference Method.
FEM	-	Finite Element Method.
BEM	-	Boundary Element Method.
DEM	-	Distinct Element Method.
DDA	-	Discontinuous Deformation Analysis.
BPM	-	Bonded Particle Model.
FBG	-	Fiber Bragg Grating.
UTM	-	Universiti Teknologi Malaysia
DSTS	-	Distributed Strain and Temperature Sensor.

LIST OF SYMBOLS

m	-	Metre
μm	-	Microns
c_1 and c_2	-	Shear Strength
k_1 and k_2	-	She
T	-	Shear Force
d	-	diameter
l	-	Length
n_I and n_R	-	Indices of refraction
I	-	Angle of incident
R	-	Angle of refraction
\emptyset	-	Friction Angle
c	-	Cohesion
γ_{bulk}	-	Unit Weight Bulk
$\mu\epsilon$	-	Micro- strain
ν	-	Poisson' Ratio

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
Appendix A	Ultimate Lateral Loading on Pile	63
Appendix B	Strain for Surcharge Load (at Pipe)	64
Appendix C	Displacement of Pipe Due to Surcharge Load	65
Appendix D	Data from SIGMA/W	66

CHAPTER 1

INTRODUCTION

1.1 Problem Background

Slope failure is one of the geotechnical failures that are widespread in many regions in the world. With the development of the economy and infrastructure constructing, more and more artificial slopes are encountered in practical engineering, such as embankment, road excavation, dike, surface mining and so on (Wang, Li, Shi, & Wei, 2009). A slope failure is a phenomenon that a slope collapses abruptly due to weakened self-retain ability of the earth under the influence of a rainfall or an earthquake. This failure directly threatens people lives and causes significant economic losses due to its sudden collapse. Therefore, countermeasures and early warning monitoring system plays a crucial role.

Different kinds of countermeasure have been developed in order to control the slope failure occurrence and to ensure the slope stability. One of the methods used to improve the slope stability is the installation of piles. The use of piles as a retaining element has been applied successfully in the past and proved to be an effective solution, since piles can be easily installed without disturbing the equilibrium of the slope (Hassiotis, Chamean, & Gunaratne, 1997). However, a proper stability analysis need to be carried out and monitoring system is still needed after the piles been installed at the slope to monitor the behavior of the structure due to the movement of slope.

In previous studies, instrumentation such as inclinometer was used to monitor the bending moment induced in the pile by slope movements (Smethurst et al, 2007). However, the data obtained need to be done at a few discrete points which consume more time and energy.

At present, monitoring techniques are changing from conventional methods which consist of point mode monitoring to a distributed monitoring system. In recent years, a distributed strain sensing used for monitoring structural health of building, bridges, dams, tunnels and others vital civil engineering infrastructures has been developed using light scattering based on Brillouin optical time- domain Analysis (BOTDA) technique. This technique is a nondestructive, compatible with distributed monitoring and on distance monitoring, anti-electromagnetic interference, corrosion resistance and durable. It is suitable for monitoring and early warning for structural and geotechnical engineering. It is also small, lightweight and can be easily installed into or on the surface of the monitored objects (Wang et al., 2009).

1.2 Problem Statement

The selection of monitoring instrumentation on slope is very critical. The instrumentation selected should be able to provide a reliable data. Most of the conventional strain sensing instrumentation can only produce data from a few discrete points. This only cause to consume more time and energy. This might also cause engineers to miss critical locations of soil movements. This problem can be solved by using the distributed fibre optic strain sensor which is incorporated using Brillouin Optical Time Domain Analysis (BOTDA) technique. The BOTDA will measure strain and temperature along the length of the optical fibre cable.

However, the accuracy and effectiveness of the optical fibre sensing technology is still a concern point since the application of the optical fibre sensing technology is not fully developed and established. Mohamad (2008) stated that the effectiveness of the fibre optic depends on the contact between the fibre optic and the geotechnical element or soil mass where the fibre optic can measure the correct amount of strain. Mohamad (2012) also stated that the accuracy of the strain measurement among others depends on the instrument laser setup.

Therefore, the effectiveness and accuracy of the optical fibre sensing technology is evaluated by considering the contact between the fibre optic and the

geotechnical element and the laser setup of the optical fibre sensing technology. By producing a physical model and assisted with a numerical model the effectiveness of the optical fibre sensing technology can be validated.

1.3 Aim and Objective

The aim of this study is to determine the deflection of the pile due to the instability of the slope as well as to validate the effectiveness of the optical fibre sensing technology and to fulfill the objective of this study. The objectives are set as follows:

- (a) To model a physical soil slope and estimate the slope failure.
- (b) To model pile on slope.
- (c) To monitor the pile behavior due to slope instability, and loading increment using BOTDA technique.
- (d) To validate the application of distributed optical fibre strain sensors using software application.

1.4 Scope of Study

The scope of this study will be based on the objectives that were stated. This study will start by producing a soil slope model with determined geometry. Then a pile prototype is selected to be installed on the soil slope model. The pile prototype install will be stimulated as an inclinometer which allowing the presence of lateral force on the pile to determine the strain on the pile faster. No axial force will be acted on the pile. Therefore, a PVC pipe was chosen as a prototype pile to be used on the soil slope model since it's more flexible. The pile will be monitored by using distributed optical fibre strain sensor using BOTDA technique. The monitoring of the pile will be based on the slope instability and loading increment on the slope. The

REFERENCES

- Ausilio, E., Conte, E., & Dente, G. (2001). Stability analysis of slopes reinforced with piles. *Computers and Geotechnics*, 28(8), 591–611. [https://doi.org/10.1016/S0266-352X\(01\)00013-1](https://doi.org/10.1016/S0266-352X(01)00013-1)
- Barrias, A., Casas, J., & Villalba, S. (2016). A Review of Distributed Optical Fiber Sensors for Civil Engineering Applications. *Sensors*, 16(5), 748. <https://doi.org/10.3390/s16050748>
- Di Laora, R., Maiorano, R. M. S., & Aversa, S. (2017). Ultimate lateral load of slope-stabilising piles. *Géotechnique Letters*, 7(3), 237–244. <https://doi.org/10.1680/jgele.17.00038>
- Habel, W. R., & Krebber, K. (2011). Fiber-optic sensor applications in civil and geotechnical engineering. *Photonic Sensors*. <https://doi.org/10.1007/s13320-011-0011-x>
- Hassiotis, S., Chamean, J. L., & Gunaratne, M. (1997). Design method for stablization of slope with piles. *Geotechnical and Geoenvironmental Engineering*, 123(April), 314–323.
- Ho, Y. Te, Huang, A. Bin, & Lee, J. T. (2006). Development of a fibre Bragg grating sensed ground movement monitoring system. *Measurement Science and Technology*, 17(7), 1733–1740. <https://doi.org/10.1088/0957-0233/17/7/011>
- Instruments, N. (2011). Overview of Fiber Optic Sensing Technologies. *Www.Ni.Com*, 1–7.
- 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. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000543](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000543).
- Mohamad, H. (2008). Distributed Optical Fibre Strain Sensing of Geotechnical Structures. *Thesis*, (August), 214.
- Mohamad, H., Kueh, A. B. H., & Rashid, A. S. A. (2015). Distributed optical-fibre strain sensing in reinforced concrete structures. *Jurnal Teknologi*, 74(4), 93–97.

- Poulos, H. G. (1995). Design of reinforcing piles to increase slope stability. *Canadian Geotechnical Journal*, 32(5), 808–818. <https://doi.org/10.1139/t95-078>
- Soga, K., Mohamad, H., & Bennett, P. J. (2008). Distributed fiber optics strain measurements for monitoring geotechnical structures. In *International Conference on Case Histories in Geotechnical Engineering* (pp. 1–9).
- Sun, Y., Shi, B., Zhang, D., Tong, H., Wei, G., & Xu, H. (2016). Internal Deformation Monitoring of Slope Based on BOTDR. *Journal of Sensors*, 2016. <https://doi.org/10.1155/2016/9496285>
- Viggiani, C. (1981). Ultimate Lateral Load on Piles used to Stabilize Landslides. *Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering Stockholm*, 3, 555–560. <https://doi.org/10.1038/cmi.2014.34>
- Wang, B., Li, K., Shi, B., & Wei, G. (2009). Test on application of distributed fiber optic sensing technique into soil slope monitoring. *Landslides*, 6(1), 61–68. <https://doi.org/10.1007/s10346-008-0139-y>
- Zhu, H. H., Shi, B., Yan, J. F., Zhang, J., Zhang, C. C., & Wang, B. J. (2014). Fiber Bragg grating-based performance monitoring of a slope model subjected to seepage. *Smart Materials and Structures*, 23(9). <https://doi.org/10.1088/0964-1726/23/9/095027>
- GEOSLOPE International Ltd. (2018). AIR/W. Retrieved from <https://www.geoslope.com/products/air-w>
- Ltd., G. I. (2018). CTRAN/W. Retrieved from <https://www.geoslope.com/products/ctran-w>
- GEOSLOPE International Ltd. (2018). TEMP/W. Retrieved from <https://www.geoslope.com/products/temp-w>
- GEOSLOPE International Ltd. (2018). QUAKE/W. Retrieved from <https://www.geoslope.com/products/quake-w>
- GEOSLOPE International Ltd. (2018). SIGMA/W. Retrieved from <https://www.geoslope.com/products/sigma-w>
- GEOSLOPE International Ltd. (2018). SEEP/W. Retrieved from <https://www.geoslope.com/products/seep-w>
- Ltd., G. I. (2018). SLOPE/W. Retrieved from <https://www.geoslope.com/products/slope-w>