SLOPE STRAIN MONITORING USING SOIL-EMBEDDED DISTRIBUTED OPTICAL FIBRE SENSOR

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DEDICATION

This thesis is dedicated to my late father, who taught me that the best kind of knowledge to have is that 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.

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ABSTRACT

Slope monitoring is essential in periodical geotechnical monitoring exercise as slope behaviour would change over a period of time subjected to the surrounding environment. The conventional instrumentations for slope displacement monitoring are inclinometers, tiltmeters and extensometers, but main drawbacks of using available instrumentation are the difficulties in handling as well as high cost of equipment installation at a complex geological terrain and massive size of slope. The downside of these equipment can be overcome by alternatively employing a distributed optical sensing fibre technology for slope monitoring programme. However, current applications of distributed fibre optic sensor were limited by attaching the sensor onto the geo-structure surfaces such as soil nailing, anchor bolts or geotextile but the arrangement of sensors on soil-embedded soil slope is still under uncertain evaluation due to the non-linear soil behaviour. Therefore, this study focuses on efficiency of the soil-embedded distributed fibre optic sensing system based on Brillouin Optical Time Domain Analysis (BOTDA) technology as an innovative instrumentation apparatus to monitor deformation event of an unsaturated soil slope. BOTDA could be attractively employed for soil slope monitoring since it allows a continual measurement of strain along its interrupted length of fibre optic cables. In this study, a soil-embedded strain sensor placement approach was proposed which was achieved via the horizontal planting of a three-layered optical fibre cable in S-curve forming in the physical laboratory soil slope. The residual soil slope model was also instrumented with tensiometers to measure suction distribution and subjected to different simulated rainfall intensities and surcharge loading until failure. At the same time, the progressive failure images were also captured using DSLR camera which then analysed using Particle Image Velocimetry (PIV) method to compare with the new optical fibre sensor instrumentation set up. A total of ten laboratory schemes was performed including four preliminary infiltration tests subjected to three different rainfall intensities of no-rainfall, 1-hour and 24-hour infiltration and slope inclination of 27° and 45°. Before the infiltration tests, calibration experimental work on optical fibre was performed due to the non-linear soil behaviour which influences the true strain deformation of the soil slope. From the preliminary laboratory tests, the results show the soil-embedded sensing fibre arrangement has efficiently detected and measured the strain deformation due to both rainfall and loading. The captured strain data indicated a progressive deformation behaviour of a soil slope when there were changes in suction distribution and loading-induced activity on a soil slope as rainwater infiltration has gradually weakened the unsaturated shear strength of the soil by reducing soil suction, and rapid surcharge loading has also caused the development of excess pore pressure. This phenomenon had resulted in declining of soil effective stress that led to undrained bearing capacity failure. A series of numerical simulations were later conducted by employing the commercial software of SEEP/W and SIGMA/W to analyse further the deformation behaviour which also acted as a comparative case against to the PIV images and the experimental results. In comparison to the PIV measurements, the optical fibre sensor was found to be capable to exhibit overall deformation of the soil slope when placed under an optimum configuration layout of the sensor. The optical fibre sensor has effectively captured the deformation behaviour of the unsaturated soil slope model in the presence of rainwater infiltration and imposed surcharge loads. The outcomes from this study had contributed to important results in terms of the design of field deployment of soil-embedded optical sensing fibre in unsaturated natural soil slope and embankment subjected to rainfall infiltration or any similarities to the saturated and unsaturated condition.

ABSTRAK

Pemantauan cerun sangat penting dalam pemantauan berkala geoteknik kerana sifat cerun tanah yang akan berubah mengikut masa dan tertakluk kepada persekitarannya. Penggunaan alat konvesional yang lazim digunakan untuk memantau anjakan cerun adalah seperti *inclinometer, tiltmeters dan extensometers*. Walaubagaimanapun, terdapat kelemahan dalam penggunaaan alat-alat tersebut seperti kesukaran dalam mengendalikan alat-alat tersebut dan juga tertakluk kepada kos pemasangan yang tinggi sekiranya melibatkan pemasangan di kawasan geologi yang kompleks dan ukuran cerun yang sangat besar. Kelemahan penggunaan peralatan ini dapat diatasi dengan menggunakan teknologi sensor gentian optik untuk program pemantauan cerun. Setakat ini, penggunaan teknologi tersebut hanyalah terhad kepada pemasangan di permukaan geo-struktur seperti kaedah pakuan tanah, bolt penambat dan geotekstil tetapi masih tiada penilaian yang jelas mengenai sensor gentian optik yang ditanam langsung ke dalam tanah. Ini adalah kerana sifat tanah yang tidak linear menyulitkan pemasangan sensor gentian optik ini di dalam tanah. Oleh kerana itu, kajian ini fokus pada kecekapan sistem sensor gentian optik di dalam tanah dengan menggunakan teknologi *Brillouin Optical Time Domain Analysis* (BOTDA) sebagai alat untuk memantau perubahan tanah cerun. BOTDA juga amat sesuai digunakan untuk pemantauan cerun berkala kerana sistem tersebut boleh mengukur pergerakan tanah sepanjang kabel gentian optik. Kabel gentian optik telah ditanam di dalam model makmal cerun tanah dengan berbentuk huruf S secara selari antara satu sama lain. Apabila model tersebut dikenakan simulasi hujan dengan corak hujan yang pelbagai dan bebanan terhadap tanah sehingga runtuh, *tensiometers* juga diletakkan dimana alat ini bertujuan untuk mengukur taburan sedutan dalam tanah. Pada masa yang sama, kamera DSLR juga digunakan untuk mengambil gambar yang menunjukkan proses cerun tanah runtuh di mana gambar–gambar itu akan dianalisa menggunakan kaedah analisa velocimetri imej zarah (PIV) untuk tujuan perbandingan dengan bacaan pergerakan tanah dari sensor gentian optik. Sejumlah sepuluh siri ujian makmal termasuk empat model makmal cerun tanah dibina untuk data permulaan. Simulasi pelbagai corak hujan terbahagi kepada tiga kategori iaitu tiada hujan, 1-jam dan 24-jam penyusupan hujan dengan cerun 27° dan 45°. Ujian penentukuran bagi kabel gentian optik juga dilakukan sebelum ujian penyusupan hujan kerana sifat tidak linear tanah akan mempengaruhi nilai pergerakan tanah yang sebenar. Keputusan ujian makmal dari data permulaan menunjukkan sensor gentian optik dalam tanah tersebut dapat mengukur pergerakan tanah tertakluk kepada hujan dan lebihan bebanan di atas cerun tanah. Data pergerakan tanah dari sensor gentian optik menunjukkan proses perubahan cerun tanah apabila dikenakan hujan dan bebanan tambahan. Penyusupan hujan ke dalam cerun tanah telah menghilangkan kekuatan daya ricih tanah disebabkan pengurangan sedutan di dalam tanah. Seterusnya, simulasi berangka dilakukan dengan mengunakan perisian komersial SEEP/W dan SIGMA/W untuk analisis lebih lanjut terhadap perubahan struktur tanah dan perubahan tersebut akan dibandingkan dengan hasil siri ujian makmal dan PIV. Kesimpulannya, sensor gentian optikal telah didapati boleh menunjukkan gambaran mengenai perubahan bentuk model cerun tanah di mana konfigurasi sensor di dalam tanah telah diletakkan secara optimum. Sensor gentian optik telah berjaya menunjukkan perubahan bentuk model cerun tanah apabila dikenakan penyusupan hujan dan bebanan tambahan. Hasil kajian daripada projek telah menyumbang kepada keputusan penting dari segi reka bentuk sensor gentian optik di dalam tanah bagi penggunaan lapangan bagi kecerunan semulajadi atau tambak tertakluk kepada keadaan ketepuan akibat penyusupan hujan.

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LIST OF ABBREVIATIONS

ANN	-	Artificial Neural Network
GA	-	Genetic Algorithm
PSO	-	Particle Swarm Optimization
MTS	-	Mahalanobis Taguchi System
MD	-	Mahalanobis Distance
TM	-	Taguchi Method
UTM	-	Universiti Teknologi Malaysia

LIST OF SYMBOLS

δ	-	Minimal error
D, d	-	Diameter
F	-	Force
v	-	Velocity
p	-	Pressure
I	-	Moment of Inersia
r	-	Radius
Re	-	Reynold Number

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Mountainous profile in Malaysia is prone to the rainfall-induced landslides consisting of an abundant of deep residual soil deposit. Residual soil is defined as a soils formed in-situ subjected to the weathering process and had not experienced any transportation during the formation (Yunusa, 2015). The soil is found to be abundant especially in tropical regions (Agus *et al.,* 2001; Bujang B.K. Huat *et al.,* 2013) and commonly existed in unsaturated condition for soil slope with a deep groundwater table (Rahardjo *et al*., 2005, 2009, 2012). Fredlund *et al*. (2012) stated that the stability of tropical residual soil slope is subjected to the influence of additional shear strength parameter namely negative pore water pressure (or matric suction) in the unsaturated soil mass. The rainwater intrusion into unsaturated part of a soil slope can reduce the matric suction and subsequently caused the additional shear strength to diminish due to prolonged wet periods (Melinda *et al*., 2004; Li *et al*., 2005; Huat *et al*., 2006; Rahardjo *et al*., 2012). Zhang *et al*. (2005) also found that the rainfall infiltration caused a reduction of matric suction as well as significant changes both hydraulic and shear strength properties of unsaturated soil. The changes of hydraulic and shear strength properties sufficiently embark the initiation of failure plane as wetting front develops considerably during rainfall infiltration; either during an intense or prolonged period of rain.

Most of the previous research work by Derbyshire (2001), Tsaparas *et al*. (2002), Rahardjo *et al*. (2004, 2005, 2009, 2014), Zhang *et al*. (2011, 2005), Tohari *et al*. (2007), Lee *et al*. (2009), and Leung and Ng (2015) on the unsaturated soil slope concluded that rainfall infiltration is the most significant triggering factor to slope instability in either tropical or subtropical regions. These research works were essentially considering how the distribution of suction and its redistribution affected slope stability. However, as stated by Wu *et al*. (2015) it is a great challenge to accurately address the effect of rainfall to slope failure as the mechanisms of rainfall-triggered slope failures are very complex due to several factors including erosion, soil softening, seepage, stress redistribution and other different failure modes. Lee *et al*. (2014) studied slope in Hulu Kelang area also claimed that the main causes which have contributed to the slope failure were still debatable as the failures keep recurring during rainy season.

Due to unpredicted and sudden occurrence of slope failure, the geotechnical instrumentation is nowadays essential to slope engineering works in providing slope instability information for both natural and man-made slope. The geotechnical monitoring instrumentation plays a role to assess the safety condition of the geo-structures. The results of the monitoring instrumentations are used to characterize site condition, verify design assumptions, determine the effects of construction, understand the geotechnical structures behaviour when subjected to different loadings (Klar *et al.*, 2006), impose the quality of workmanship and provide indicators to failures (Zhang *et al.*, 2014).

There are several geotechnical instrumentations for slopes which are commonly performed to observe and monitor the slope stability, for instance through photogrammetric techniques, scheduled monitoring using total stations, mapping using Global Positioning System (GPS) and instrumentation monitoring which is at foremost as to observe the movement of soil slope mass. Common slope instrumentation monitoring devices are the borehole inclinometer and borehole extensometer that are known to measure the subsurface movement of slopes. The movement are triggered by many factors such as geological features, rainwater infiltration, excessive vibration from earthquakes, human construction activities, natural topography or combination of these factors (Basile *et al.*, 2003; Rahardjo *et al.*, 2005, 2014; Yunusa, 2015). However, the point-wise of conventional monitoring instrumentation had restricted the reliability of data in general. The distributed measurement concept was based on the nature of Brillouin back scattered light principle which responsive to the variation of temperature and strain along the cable. The inherent characteristic has made the system involved Brillouin signal would perform in a distributed measurement manner. Moreover, it is very expensive to have multiplexed sensors or to increase the number of sensors to enhance the quality of data monitoring.

As an alternative instrumentation monitoring, the recent use of relative cheap optical fibre as a monitoring sensor had been extended to structural and geotechnical monitoring instrumentations because of the measurement accuracy abilities (Mohamad *et al*., 2012). There are three types of optical fibre sensors used in civil engineering application such as the Fibre-Bragg grating sensor (FBG), low coherence interferometry Surveillance d'Ouvrages par Fibres Optiques (i.e., SOFO) which is the long-gauge optical fibre sensor, and the time-domain reflectometry-based sensor, TDR (Rodrigues et al., 2013). Recently, the distributed optical fibre sensing (DOFS) schemes like Brillouin optical time-domain reflectometry, BOTDR and Brillouin optical time-domain analysis, BOTDA was developed based on the TDR concept (Mohamad, 2008). The distributed optical fibre sensors have been used to monitor pile foundation (Klar *et al.*, 2006; Mohamad *et al.*, 2011), tunnel (Shi *et al*., 2003; Mohamad *et al*., 2012) and slope which were only restricted to deployment at the soil nailing and integration with an inclinometer (Shi *et al*., 2006; Amatya *et al*., 2008; Minardo *et al*., 2014).

However, the application of optical fibre directly embedded in the soil mass is still limited owing to the uncertainty of co-deformation between the optical fibre cable and soil displacement (B.-J. Wang *et al*., 2009). The major setback on proper placement of optical fibre directly in the soil slope mass is still in research because the previous researchers were only limited to the application on homogenous soil slope specifically on the granular material and only the regular shape of optical fibre (round type). Therefore, thorough explorations are in need as an innovation to the slope monitoring system.

1.2 Problem Statement

Rainfall infiltration has been recognised as one of the important factors that lead to unsaturated residual soil slope failure in Malaysia. The pore water pressure experiences a substantial fluctuation during the dry and wet condition for Southwest and Northeast monsoons, respectively. The rainwater infiltration into the unsaturated residual soil slope would cause a reduction in additional shear strength provided by the matric suction and triggering slope failure (Melinda *et al*., 2004; Li *et al*., 2005; Rahardjo *et al*., 2005, 2009, 2011, 2012; Huat *et al*., 2006).

Previous studies on slope stability assessment when subjected to the distribution of matric suction in soil slope concluded the soil mass loses the additional soil strength due to the reduction of negative pore water pressure and this has directed to a strain deformation in the soil mass. The risk of slope failure could be carefully monitored through periodic soil movement. The conventional monitoring instrumentation such as borehole inclinometer monitors the magnitudes of the subsurface movement of a slope with several limitations. The disadvantage of the inclinometer as an instrument is the accuracy of reading, where the field accuracy within the range of ±1 to 6 mm accumulated over 50 readings. The readings are discretely recorded at every 0.5 m along the inclinometer casing length. Moreover, the tedious installation of inclinometer at complex geological terrain plus the enormous size of the slope would anticipate an extreme cost to expense. Alternatively, optical fibre technology was introduced in geo-structure instrumentation monitoring including natural slopes or embankments due to unsusceptible nature of optical fibre sensor to electromagnetic fields, corrosion, moisture, or ageing (Mohamad, 2008). However, the uses of optical fibre in slope monitoring from past research works were limited only to the deployment onto the geo-structure surfaces such as soil nailing, anchor bolts or geotextile. The directly surface contact to soil slope sensors arrangement is still under uncertain evaluation due to the non-linear soil behaviour that influences the true strain deformation of the soil slope. In addition, the scope of studies for the previous research works had not clearly explain the strain development during the transition effect of unsaturated to saturated condition.

In this study, the laboratory-sized slope test model used the distributed optical fibre technology known as BOTDA system and the monitoring sensors were arranged directly contact on the soil slope. The sensors measured the horizontal strain deformation of an unsaturated soil slope soil mass when subjected to rainwater infiltration and surcharge load-induced failure. The study focuses on the effectiveness and functionality of optical fibre sensor as instrumentation monitoring tools for Malaysian residual soil slope owing to local climate condition.

1.3 Aim and Objectives

This study aims to investigate the performance of distributed fibre optic sensor as alternative monitoring instrumentations for the unsaturated residual soil slope when subjected to rainfall infiltration and surcharge loading. The research objectives are the following:

1) To characterize the residual soil in a homogeneous soil slope model in laboratory.

2) To determine the BOTDA configuration parameters and soil-fibre interface behaviour through calibration experiments and pull-out test, respectively.

3) To develop a soil-embedded distributed optical fibre sensing system for the laboratory-scale residual soil slope model.

4) To assess the strain development of distributed fibre optic sensor by considering the after-effect of rainfall infiltration and surcharge loading.

1.4 Scope of Work

This study used a distributed optical fibre strain sensing (DOFS) system to investigate the horizontal strain deformation behaviour of a residual soil slope. An optical fibre sensor technology based on ‘distributed’ measurement concept in comparison to the conventional sensor which mostly measure in a discrete manner (point-wise measurement). The distributed measurement concept was based on the nature of Brillouin back scattered light principle which responsive to the variation of temperature and strain along the cable. The inherent characteristic has made the system involved Brillouin signal would perform in a distributed measurement manner. There were two research methods used to achieve the aim of this study: (i) laboratory modelling and (ii) numerical simulations using commercial software of SEEP/W, SLOPE/W, and SIGMA/W.

In the first stage of laboratory modelling, a bulk of soil samples were acquired from Block P16 of the Faculty of Electrical Engineering to produce a representative sample for the laboratory modelling. The site is a sloping site located within the premises of Universiti Teknologi Malaysia (UTM), Johor Bahru campus. The soil arrangement of the laboratory slope model is representative of the soil arrangement at the study site by manipulating the gravimetric water content and volumetric water content. Firstly, soil characterization tests were conducted to obtain the index and engineering properties as the input parameters for the laboratory modelling experiments and later in numerical analyses. Further explanation would be elaborated in Chapter 3 of this thesis. Secondly~~,~~ the statistical analyses of historical local rainfall were simultaneously performed to obtain different rainfall intensities according to time of infiltration. The rainfall intensities were determined based on statistical analyses of local (Johor Bahru) rainfall data, which had generated from the polynomial equation for the shorter duration and Intensity Duration Frequency (IDF) curve for the 24-hour duration. Next, the mineralogy and micro fabric arrangement of residual soil were determined to enhance the soil properties data. Finally, the optical fibre sensor had undergone the mechanical and thermal calibration tests for the BOTDA interrogator set up and soil/fibre interfacial behaviour.

In the second stage of the first research method, the physical model set-up comprising of the construction of soil slope model, arrangement of soil-embedment optical fibre sensor, artificial rainfall and photogrammetry using digital single-lens reflex (DSLR) camera. The physical model was designed as a finite slope model~~;~~ with a well-defined crest and toe with limited extent which defined by the critical length to depth ratio (L/H) of a slope. The study focused on a homogenous system of residual soil slope with two different configurations of slope angles; 27° and 45° inclinations because the natural and man-made slope exist at these angles where the rainfall-induced slope failure mostly occurred with. In addition, Jabatan Kerja Raya (JKR), Malaysia has specified the slope gradient of 1V:1H (45°) for the cut areas and 1:2 (27°) for the fill areas when using the conventional technique of balancing earthwork for embankment construction (Jabatan Kerja Raya Malaysia, 2010). The placement of the optical fibre sensor was the soil-embedment type and the artificial rainfall was calibrated to an intended intensity prior for each test. The DSLR camera was about ±1.5 m in position from the front view of the acrylic chamber to capture images during loading.

The subsequent stage in this research study was the data collection from the simulation of infiltration and loading tests. The physical testings performed were subjected to two different slope inclinations, two rainfall patterns and no rainfall as a control tests. The strain data were evaluated to relate to the progressive failure process in a soil mass when subjected to infiltration and surcharge loading. The strain data is defined as the horizontal strain developed due to the rainfall and loading-induced which later would cause the slope failure. At the same time, images of the progressive failure process were also captured using DSLR camera. They were then analysed using Particle Image Velocimetry (PIV) method to process the captured images for comparison to the new optical fibre sensor instrumentation.

Finally, the second research method is the numerical modelling stage. The numerical simulations were using the commercial software of SEEP/W and SIGMA/W (GeoStudio 2012). The progressive strain deformation results from the laboratory modelling; both from the optical sensing fibre and PIV analyses were compared to the numerical analyses of the soil slope model.

1.5 Limitations of Study

The research work is subjected to several limitations as listed:

(a) The simulated rainfall intensity in the laboratory modelling experiments were estimated and applied through the rainfall simulator using trial and error method.

(b) The ideal environment in the laboratory with controlled precipitation and the room temperature was assumed to be representative of the actual climate condition.

(c) The soil materials used in laboratory modelling are assumed to be homogenous.

(d) The type of optical fibre used is limited to 12-ribbon Fujikura cable.

(e) The optimum size of the model was designed as 1.0 m in length and 0.5 m in height to represent slope inclination angles: 27° and 45°.

(f) The size of the chamber was limited to 1.0 m in length due to limited space in the laboratory.

1.6 Significance of Study

The study contributes to a piece of new knowledge and advanced idea for the slope monitoring implementation and provides a better understanding of the usage of optical fibre technology as an innovative sensor in monitoring slope movement. The findings are also valuable to the local civil engineers as it considers the tropical soil condition and contributes to new knowledge in slope engineering design and geotechnical monitoring programme.

1.7 Thesis Organization

This thesis consists of six chapters: Introduction (Chapter 1), Literature Review (Chapter 2), Research Methodology (Chapter 3), Preliminary Data (Chapter 4), Physical Test Model Set-up (Chapter 5), Result and Discussion (Chapter 6) and the final Chapter 7 Conclusion and Recommendation. At the end of each chapter, concluding remarks are provided to briefly discuss and summarize the content of the chapter.

Chapter 1 describes the background of problems associated with the slope movement monitoring method for tropical residual soils as well as the objectives, scope and significance of the present study.

Chapter 2 presents descriptions, comparisons, concepts of appropriate theories published in the literature of this thesis. Besides that, Chapter 2 also outlines the laboratory modelling techniques and methodologies employed in previous studies.

Chapter 3 Research Methodology describes the methodologies involved in the laboratory modelling; (i) soil sample characterizations, (ii) data obtained from probability distribution rainfall analysis using Gumbel's method, and (iii) optical fibre characterizations through several calibration experiments. The methodologies of the laboratory modelling set up also had also been explained in this chapter, which consisted of the construction of soil slope model, data configuration set up of optical fibre sensor, loading system set up and rainfall simulation. The chapter ends with a brief description of numerical analysis modelling and PIV method.

Chapter 4 presents and discusses the preliminary data obtained from experimental data works as described in Chapter 3.

Chapter 5 presents the physical model set-up and results acquired from the pilot laboratory tests which illustrating the efficiency and functionality of the soil-embedded sensing fibre to monitor soil slope.

Chapter 6 discusses mainly on slope behavior resulted from the effect of rainfall infiltration and surcharge loading to the strain development which gathered from the embedded optical fibre sensing system. Also, the matric suction measurements were discussed for the homogenous soil slope model. Lastly, numerical simulations were also explained in modelling the deformation behaviour of the homogenous soil slope model as captured from the innovative sensor

The final chapter of the thesis (Chapter 7) covers the summary of the thesis and conclusions drawn from the present study as well as the recommendations for further researches.

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LIST OF PUBLICATIONS

Indexed Journal (SCOPUS)

1. **Ismail, D. S. A.**, & Kassim, A. (2020). Monitoring of Deformation Behaviour of Unsaturated Soil Slope using Distributed Optical Fibre Sensor. International Journal of Integrated Engineering, 12(9), 199-207.

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