BUILDING CONCRETE STRUCTURE ASSESSMENT USING IMAGE-BASED NON-DESTRUCTIVE TECHNIQUE

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

Faculty of Built Environment and Surveying
Universiti Teknologi Malaysia

DECEMBER 2018

DEDICATION

To my beloved family and friends

ACKNOWLEDGEMENT

It is with immerse gratitude that I acknowledge the support, guidance and advice of my supervisor, Prof. Sr Gs Dr. Mazlan Bin Hashim and co-supervisor, Dr. Jaw Siow Wei throughout the completion of this study. This thesis would have remained a dream without them.

It is a great pleasure to express my acknowledgement to Universiti Sains Malaysia (USM) for providing the GPR device and technical support during experimental data collection. Not to forget those who had helped a lot during the data acquisition. Also, thanks to RDG Supply Sdn. Bhd. for the valuable technical information and assistance during the study. My sincere appreciation also extends to Universiti Teknologi Malaysia (UTM) and all dedicated staffs of Faculty of Built Environment and Surveying (FBES) for their most attentive fulfilments of any requests concerning this study.

Recognition should also be given to my fellow friends, lab mates, and others for their help and support on several occasions. Their opinions and tips are useful indeed. Unfortunately, it is impossible to list all of them due to the restricted space. Last but not least, thanks again to all who had contributed, either directly or indirectly in the completion of this study.

ABSTRACT

Building concrete structures deficiencies, a crucial issue highlighted by the building and construction industry worldwide is happening at an alarming rate. Deteriorations of these structures are accelerated by several factors such as environmental impacts, population growth and human activities. Hence, maintenance plays an important role to assure that the building is at its topmost service condition to extend its service life. However, the building maintenance aspects in Malaysia are still unsatisfactory where repairs are only conducted after service breakdown. Thus, to overcome this problem, an image-based non-destructive technique comprising numerical modelling and ground penetrating radar (GPR) is introduced for building concrete structures assessment. To address the first objective of the study, characterising and modelling backscatter from high frequency GPR for concrete inner structure and deficiency features were conducted with numerical modelling using finite-difference time-domain (FDTD) method. These were performed on concrete slabs with various types of defects and conditions for 1, 1.5 and 2 GHz frequencies antennas. Next, the second objective targets the application and assessment of the simulated models in laboratory scale and real structures. Aladdin GPR system with 2 GHz full-polar antenna was employed for surveying a reinforced concrete beam specimen with cracks induced by continuous hydraulic loadings as well as four in-service buildings. Results indicated that the backscatter for each object was unique and can be distinguished from one another. The 2 GHz frequency antenna had the highest resolution among the three antenna frequencies and identified cracks as small as 3 mm. Meanwhile, changes in the concrete inner structure due to cracks can be determined as the cracked area has a distinct signal trace from its surroundings. The outcomes obtained from the numerical modelling and GPR inspections have a good agreement between each other, and the results confirmed that the high frequency GPR can be adopted for building concrete structures assessment which can reduce maintenance costs and prevent catastrophic failures.

ABSTRAK

Kecacatan struktur konkrit bangunan merupakan isu penting yang diketengahkan oleh industri bangunan dan pembinaan di seluruh dunia dan berada pada tahap yang membimbangkan. Kemerosotan struktur ini dipercepatkan oleh beberapa faktor seperti kesan alam sekitar, pertumbuhan populasi dan aktiviti manusia. Oleh itu, penyelenggaraan memainkan peranan penting untuk memastikan bangunan itu berada pada tahap perkhidmatan tertinggi untuk melanjutkan hayat perkhidmatannya. Walau bagaimanapun, aspek penyelenggaraan bangunan di Malaysia masih kurang memuaskan di mana pembaikan hanya dilakukan selepas berlaku kerosakan. Oleh itu, untuk mengatasi masalah ini, teknik tidak merosakkan berasaskan imej yang terdiri daripada pemodelan berangka dan radar penembusan tanah (GPR) diperkenalkan untuk penilaian bangunan struktur konkrit. Untuk menangani objektif pertama kajian ini, ciri dan pemodelan hamburan balik dari GPR berfrekuensi tinggi untuk struktur dalaman dan kecacatan konkrit dikendalikan dengan pemodelan berangka menggunakan kaedah *finite-difference time-domain* (FDTD). Ia dilakukan untuk papak konkrit dengan pelbagai jenis kecacatan bagi antena berfrekuensi 1, 1.5 dan 2 GHz. Seterusnya, objektif kedua mensasarkan aplikasi dan penilaian model simulasi dalam skala makmal dan struktur sebenar. Sistem GPR Aladdin dengan antena kutub penuh 2 GHz digunakan untuk mengukur spesimen rasuk konkrit bertetulang dengan keretakan yang disebabkan oleh beban hidraulik yang berterusan serta empat bangunan dalam perkhidmatan. Keputusan menunjukkan bahawa hamburan balik untuk setiap objek adalah unik dan boleh dibezakan dari satu sama lain. Antena berfrekuensi 2 GHz mempunyai resolusi tertinggi antara tiga frekuensi antenna dan mengenal pasti retak sekecil 3 mm. Sementara itu, perubahan struktur dalaman konkrit akibat retakan boleh ditentukan kerana kawasan retak mempunyai jejak isyarat yang berbeza dari persekitarannya. Hasil yang diperoleh daripada pemodelan berangka dan pemeriksaan GPR mempunyai persetujuan yang baik antara satu sama lain, dan hasilnya mengesahkan bahawa GPR berfrekuensi tinggi boleh digunakan untuk penilaian bangunan struktur konkrit yang dapat mengurangkan kos penyelenggaraan dan mencegah malapetaka kegagalan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

1D - One-dimensional
2D - Two-dimensional
3D - Three-dimensional
ABC - Absorbing boundary condition
AC - Asphalt concrete
ADI - Alternating-direction-implicit
ANN - Artificial neural network
BCA - Building condition assessment
BIS - Building information system
CCC - Certificate of Completion and Compliance
CDH - Crack Detection Head
CF - Certificate of Fitness
CFRP - Carbon fibre reinforced polymer
CMOS - Complementary metal-oxide-semiconductor
CMU - Concrete Masonry Unit
DPSH - Dynamic Probing Super Heavy
DT - Destructive testing
DWT - Discrete wavelet transform
EFIT - Elastodynamic Finite Integration Technique
ELM - Extreme Learning Machine
EM - Electromagnetic
FD - Finite-difference
FDTD - Finite-difference time-domain
FE - Finite element
FEM - Finite element model
FRP - Fibre reinforced polymer
FT - Flash thermography
GFRP - Glass fibre reinforced polymer
GPR - Ground penetrating radar
HCP - Half-Cell Potential

HH - Horizontal transmitter antenna and horizontal receiver
HMAC - Hot-mix asphalt concrete
IC - Intermediate crack
ICF - Insulated Concrete Form
IE - Impact echo
IRT - Infrared thermography
ISAR - Inverse Synthetic Aperture Radar
KNN - K-Nearest Neighbours
LiDAR - Light Detection and Ranging
MAC - Modal Assurance Criterion
NDT - Non-destructive testing
PCA - Principle Component Analysis
PCC - Portland cement concrete
PEC - Perfect electric conductor
PMC - Perfect magnetic conductor
PML - Perfectly Matched Layer
PRF - Pulse repetition frequency
PSPA - Portable seismic property analyser
PSD - Power spectral density
PSG - Pad survey guide
PTT - Pulsed thermography technique
PVC - Polyvinyl chloride
RBFNN - Radial basis function neural network
RC - Reinforced concrete
RCS - Radar Cross Section
ROC - Receiver operating characteristic
RSM - Response Surface Method
RTM - Reverse Time Migration
SAFT - Synthetic Aperture Focusing Technique
SFRC - Steel fibre reinforced polymer
SIBIE - Stack imaging of spectral amplitudes based on the impact echo
SHM - Structural health monitoring

SNR	-	Signal to noise ratio
SR	-	Spatial resolution
SS/TF	-	Mur and Scattered/Total Field
STFT	-	Short-time Fourier transform
SVM	-	Support Vector Machine
TLS	-	Terrestrial laser scanner
UPE	-	Ultrasonic pulse echo
UPV	-	Ultrasonic pulse velocity
USW	-	Ultrasonic surface wave
VV	-	Vertical transmitter antenna and vertical receiver
WVD	-	Wigner-Ville distribution

LIST OF SYMBOLS

ε_{rs} - DC (static) relative permittivity of the medium

$\varepsilon_{r\infty}$ - Relative permittivity at theoretically infinite frequency

τ - Relaxation time of the medium

σ - DC (static) conductivity of the medium

μ_r - Relative permeability of the medium

σ^* - Magnetic conductivity of the medium

t - Time

q_v - Volume electric charge density

$*$ - Convolution

$\bar{\bar{\epsilon}}$ - Permittivity of the medium

$\bar{\bar{\mu}}$ - Permeability of the medium

$\bar{\bar{\sigma}}$ - Conductivity of the medium

v - Wave velocity

c - Speed of light or wave velocity in the vacuum

ε_r - Relative dielectric permittivity or dielectric constant of the medium

λ - Wavelength

f - Antenna frequency

R - Resolution

s - Target size or distance between targets

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Concrete amounts to the largest of all artificial materials in quantity (Ramachandran, 2001). It has existed as the most widely used construction materials for a few decades due to its economical and outstanding technical properties (Popovics, 1992). However, defects or deteriorations influenced the service condition and lifespan of concrete structures. Both macro or micro defects are detrimental to the health of the concrete structures and can lead to deterioration rely on the extent of their presence, surroundings conditions and maintenance carried out during the life cycle. After all, macro defects cause more damage and faster deterioration compared to micro defects as it has a larger size (The Constructor, 2014a).

Meanwhile, deterioration is an unavoidable natural process which begins at the moment of constructing the concrete structures (Assaf *et al.*, 1996; Zuraidi *et al.*, 2011). The population growth, low funding, increased loading in several sectors that grow significantly, without uniformity and consistency in design, construction and operation routines, poor quality installation, insufficient investigation and maintenance, and narrower environmental and health prerequisites speeded up their structural ageing process (Kabir *et al.*, 2009). Learning the causes of concrete structure damage is critical for the repair and rehabilitation work (Woodson, 2012) and thus, Table 1.1 presented the causes and relating symptoms of concrete distress and deterioration (Woodson, 2009; 2012).

Table 1.1 Causes and relating symptoms of distress and deterioration of concrete (Woodson, 2009; 2012)

Causes	Symptoms							
	Construction Faults	Cracking	Disintegration	Distortion/ Movement	Erosion	Joint Failures	Seepage	Spalling
Accidental loadings		×						×
Chemical reactions		×	×				×	
Construction errors	×	×				×	×	×
Corrosion		×						×
Design errors		×				×	×	×
Erosion			×		×			
Freezing and thawing		×	×	×		×		×
Settlement and movement		×		×				×
Shrinkage	×	×						
Temperature changes		×				×		×

Surface-breaking cracks may display on concrete structures as results of the chemical attack, repeating service loads or weathering. Structural failures may lead eventually by cracks extending into the material, starting from the surface, or play a role in the concrete reinforcement corrosion (Goueygou *et al.*, 2008). In material science, to monitor the deterioration process, locating of cracking processes inside structures is often a good sign before failures (Grosse, 2013). Loss of life is the worst scenario as a result of failure while at best is the loss of asset use and therefore a financial loss (Elfergani *et al.*, 2013). Performing defects and deterioration detection regularly can prevent structural failure as it is essential to extend the operational life and ensure the structure is in good condition. However, until today, although concrete structures inspection and investigation had been introduced and performed since a few decades ago, structural failures and collapses are still happening around the world. Some of the major structural failure and collapse cases around the world (1995 to 2016) are shown in Table 1.2.

Table 1.2 Major structural failure and collapse cases around the world from 1995 to 2016

Year	**Name of the Structure**	**Type**	**Location**	**Causes**	**Casualties: death; injury; missing**
1995	Sampoong Department Store	Commercial building	Seoul, South Korea	Design error, construction error, overloading	501; 937; 6
2001	Versailles wedding hall	Wedding hall	Jerusalem, Israel	Design error, construction error, overloading	23; 380; -
2011	Canterbury Television building	Commercial building	Christchurch, New Zealand	Earthquake	115; -; -
2013	Building (under construction)	Residential building	Thane, India	Substandard construction material, poor construction quality	74; 62; -
2013	Rana Plaza	Industrial building	Dhaka, Bangladesh	Substandard construction material, overloading	1130; 2500+; -
2014	Synagogue Church of All Nations building	Church	Lagos, Nigeria	Design error, construction error	116; 100+; -
2015	Dharahara	Ancient tower	Kathmandu, Nepal	Earthquake	180+; -; -
2016	Weiguan Jinlong	Residential building	Tainan, Taiwan	Earthquake	115; -; -

A large number of the death toll and huge financial and economic loss caused by these structural failures and collapses alerted the world about the importance of concrete structures inspection. The absence of suitable, scientific and systematic maintenance and inadequacy of understanding of the environmental status holds responsible for the non-functioning or failure of a concrete structure to its wished service quality (The Constructor, 2014b). Inaccurate assessment such as undetected degradations may induce catastrophic accidents, or overestimation of damage can cause investments loss due to unnecessary repair work or reinforcement. The top-level accuracy and efficiency are therefore needed by the inspection methods to fulfil the demands of the structure management (Rhazi, 2001).

At present, two form approaches adopted for concrete structures inspection are destructive testing (DT) and non-destructive testing (NDT). These methods have diverse efficiencies on various kinds of deterioration (Aldahdooh and Bunnori, 2013). Visual inspection of the structural surface is cost-effective and simple for mechanical damage evaluation, but precise information on crack depth cannot be obtained (Goueygou *et al.*, 2008). At times, visual inspection is backed by laboratory analysis on samples of materials derived from drilling for estimating the durability parameters (Rhazi, 2001). Reliable and useful results can be obtained since the cores are mechanically tested to destruction. However, this expensive and time-consuming method allows only rather few tests to be performed on a large structure (Tuncan *et al.*, 2008). Therefore, NDT can be used as a preliminary to subsequent coring in reducing or minimising the number of collected cores as coring has severe damage to the concrete (IAEA, 2002).

NDT approaches have been proven to be assured and may give early warning of structural failure due to the non-destructive nature and ability to examine the concrete structures plus an extensive and dense amount of data with a high efficiency. Early warning is notably crucial considering it is allegedly too late to perform repair works when substantial rebar corrosion, cracks, delamination and spalling emerge at the concrete surface (Lai *et al.*, 2010a). Repair expenses for the existing structures are able to be marked down significantly by the systematic employment of NDT approaches and supervising within a structure management system (Kohl *et al.*, 2005).

Specifically, from the economic perspective, repair and restoration of flawed concrete structures are more preferential than constructing a new one, particularly if works are attempted as soon as the damage is induced (Shah and Ribakov, 2008). Therefore, it is contributing to the demand for the advancement of efficient inspection approaches ahead of repair works (RILEM Technical Committee, 2010).

In Malaysia, periodic inspection of buildings is mentioned in Section 85_A of Act 133 Street, Drainage and Building Act 1974 in the Laws of Malaysia. According to this act, the buildings that are exceeding five storeys and more than ten years from the date the Certificate of Fitness (CF) or Certificate of Completion and Compliance (CCC) was issued, required a periodic inspection. During this inspection, a visual inspection is performed and when essential, a full structural investigation is conducted by a registered professional engineer (AGC, 2014). The engineer needs to prepare either the report for visual inspection or full structural inspection of the building's condition after the inspection. This is important for buildings maintenance and rehabilitation, but unfortunately, the act is not strictly enforced. There are still lacking in the building maintenance aspects, although buildings are constructed under strict supervision and in line with the British Standard. The scenario is worsened as sometimes, without much attention paid to the civil and structural elements, building maintenance is observed just about the electrical and mechanical system (Suffian, 2013). To overcome this problem, high frequency ground penetrating radar (GPR) is employed in this study for building concrete structure assessment.

GPR is among the most promising NDT techniques for concrete structure assessment. It has been demonstrated in geophysics for soil assessments for several decades and nowadays, smaller structures are possible to be investigated alongside the advancement in high frequency antennas and powerful computer systems (Kohl *et al.*, 2005). In recent years, GPR has been preferred as an effective means to 'look through' concrete structures (Lai *et al.*, 2009) and it has been employed for periodic examination and maintenance of the masonry and reinforced concrete (RC) structure. Depths inspection is relatively shallow in civil engineering applications and only microwaves or short pulses electromagnetic (EM) waves are used (Zheng *et al.*, 2003).

Hence, GPR of higher frequency EM waves is utilised for small and shallow target detection as it has a shorter wavelength and promising better resolution.

1.2 Problem Statement

Concrete structure assessment plays an important role in buildings maintenance and rehabilitation. It should be carried out on a regular basis to keep the service condition at a satisfactory level and extend the service life of the building. The occurrence of disastrous events such as structural failures and collapses can also be prevented by monitoring and evaluating the buildings from time to time. Visual inspection and non-imaging NDT techniques are utilised traditionally for in-service concrete structure assessment, but only shallow qualitative data is provided. Quantitative and more precise information can be obtained from imaging NDT methods. With the advancement in technology, high resolution subsurface imaging of concrete structure can be achieved by using high frequency GPR. However, interpreting the recorded radar signal is complicated and it requires a skilled and experienced operator. To increase the understanding and knowledge on the radar backscatter and aid in interpretation, numerical modelling for various types of defects in the concrete structure is performed. Although there is literature in determining and characterising the radar backscatter of concrete structural deficiencies, the types of defects simulated are limited. Besides, the numerical models are created mostly for GPR antennas with frequencies of 1 GHz or less and there are only a few studies which conducted for GPR antennas with higher frequencies. Thus, to bridge this gap, GPR responses for concrete inner structure and several types of deficiencies, such as rebar corrosion, voids of different materials and fillings, and concrete with different moisture contents are modelled for GPR antennas with three higher frequencies of 1, 1.5 and 2 GHz.

Surprisingly, visual inspection still remains as the most widely used method for concrete structure inspection and investigation. This method is relatively simple, but subjective to the skill and experience of the operators. Moreover, only qualitative and surface information can be provided. Therefore, other NDT approaches can be employed as a complement to visual inspection. GPR is among the most promising NDT technique for concrete surveys, but it is less applied in developing countries, although it has been introduced and available in the market for more than 30 years. The lack of knowledge and expertise on the technology contributes to the less popularity of the method in these countries. NDT methods such as rebound hammer, ultrasonic testing and impact echo are adopted for concrete examination, but these methods do not reveal the subsurface condition since they are non-imaging. As an imaging approach, GPR is employed for concrete structure assessment, but lower frequency antennas are often utilised and there are only several studies which deployed antennas with frequencies of 2 GHz or higher. Thus, high frequency 2 GHz GPR antenna is proposed in this study as it can provide high resolution and detailed subsurface images. This allows embedded targets and anomalies to be detected.

1.3 Objectives

The aim of this study is to perform building concrete structure assessment using image-based NDT technique. The specific objectives are:

(a) To characterise and model backscatter from high frequency GPR for concrete inner structure and deficiency features.

(b) To apply and assess the simulated models in laboratory scale and real structures.

1.4 Scope of the Study

The scope of the study is as follows:

(a) Simulation is carried out for concrete inner structure such as rebars and deficiency features including RC slab in good condition, RC slab with defects, RC slab containing defects with different moisture content, RC slab with cracks, RC slab with honeycombs, RC slab with voids, RC slab with a variety of conditions in rebars and concrete slab with voids of different materials and fillings. These deficiencies are selected as they represent the problems in the concrete structure.

(b) Numerical modelling is performed for GPR with 1, 1.5 and 2 GHz antenna frequencies. Antenna frequencies less than 1 GHz is not considered in this study as generally antenna frequencies of 1 GHz and above is utilised in concrete structures inspection.

(c) Finite-difference time-domain (FDTD) technique is employed for numerical modelling. This approach is chosen as it is comparatively simple and allow the simulation of realistic GPR models. Simulation is carried out with GprMax software while the outputs are displayed with coding in MATLAB software.

(d) An experimental study is carried out at the laboratory on an RC beam specimen with hydraulic loads exerted to induce cracks. GPR scanning is conducted in the initial state and on every 50 kN intervals of increasing loads until the specimen failed. This permits radar signal collection for cracks under a controlled environment.

(e) Case studies are conducted for four in-service concrete structures, including newly completed building, five-year-old building, concrete wall to be demolished and concrete floor with a poor waterproof design to examine the effectiveness of GPR in detecting defects in real-world condition. These four structures are chosen as they are from different building categories and have a different condition or defect.

(f) The Aladdin GPR system with 2 GHz full-polar antenna is utilised for both experimental study and in-service concrete structure survey. This high frequency antenna is suitable for concrete structures inspection as high resolution and more detailed data can be obtained. Data acquisition is done simultaneously in two perpendicular directions and the required survey time is reduced by 50%. K2FastWave and GRED HD software by IDS are used for GPR data acquisition and processing, respectively.

1.5 Significance of the Study

Building concrete structure assessment is an effective approach for reducing the life cycle costs of the structure from construction to maintenance. GPR surveys can be conducted as a part of building condition assessment (BCA) and the acquired high resolution concrete subsurface images can be integrated into the building information system (BIS). When as-built drawings are absent, the information recorded by GPR can be utilised for construction details determination. The correctness of the available structure drawings can be assured besides evaluating the feasibility of the suggested structure works. Surveyors, engineers and contractors can employ a GPR system for deficiency detection prior to fix and repair works. Detailed views of the concrete subsurface are obtained from the surveys and the most appropriate repair method is suggested based on the available information. This permits maintenance and repair to be carried out easier. The risk of injury or accidents can be minimised by finding potentially hazardous materials that are embedded in the structure. This is of utmost importance particularly when the public is concerned, as any of such accidents can be calamitous.

Infrastructure and property developers can apply this technique for construction site monitoring and structural health assessment on a regular basis. Stakeholders such as MASS Rapid Transit Corporation Sdn. Bhd. and Prasarana Malaysia Berhad can monitor the structures under construction to prevent shoddy construction. The constructions are often carried out on location with heavy traffic flows and any accidents can be disastrous. In-service structures should also be inspected and examined periodically to ensure that they are safe for use. PLUS Malaysia Berhad and Malaysia Airports Holding Berhad can use GPR system for regular assessment of the expressways and airport runways, respectively, and maintenance can be carried out with reference to the data acquired and information gathered.

Government departments and agencies, such as the Department of National Heritage can use the data acquired by the GPR system for conservation and rehabilitation of historical landmarks and buildings. As-built structural drawings are commonly not available for these structures and hence, the recorded radar signal is important for identifying the construction details. These structures are usually subjected to defects and deteriorations due to their ages. The backscatter of the deficiency features can be studied to suggest the most suitable and proper repair works to preserve the historical buildings as these buildings are important assets of the country. Local authorities, for example, Kuala Lumpur City Hall and Iskandar Puteri City Council can use GPR system for inspecting and monitoring in-service buildings regularly as it induces only minimal disruption to occupied buildings. Maintenance can be carried out on time to cut down the maintenance costs and extend the operational life of the structure.

1.6 Organisation of the Thesis

This thesis outlines the study conducted for building concrete structure assessment using an image-based non-destructive technique. Radar backscatter recorded by GPR is evaluated and analysed to detect deficiencies in concrete structures. The thesis is divided into five chapters to describe the successful implementation of the method for concrete structure assessment and deficiency detection.

The thesis starts with chapter 1, the introduction chapter where the background, problem statement, objectives, scope and significance of the study are identified and determined. The thesis organisation is presented in the last part. The literature review can be observed in chapter 2 where based on previous studies, a comprehensive review is made about the methods and techniques applied for concrete structure deficiency assessment and evaluation. This is followed by chapter 3 and chapter 4 which correspondingly explained the methodology used and the results obtained in this study. Last but not least, the thesis ends with chapter 5 where conclusion, limitation and recommendation derived from the study is shown.

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