RECONSTRUCTION OF GROUND PENETRATING RADAR BACKSCATTER OF SUBSURFACE FEATURES FOR UTILITY MAPPING

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This work is dedicated with love and passion to

my father, Jaw Ah Fat

my mother, Chan Wai Fong

my brothers, Siong Meng & Siong Kin

my sisters-in-law, Stacey & Kah Teng

my nieces, Jane & Winnie

my boy-friend, Tiong Chiong Ung

my best friend, Lim Meng Chan

and not forgotten

my friends, Chin Yow Cheong, Tam Tze Huey, Foo Yen Sin,

Tan Kian Pang, Yap Xen Quen, Norsheilla Binti Mohd Johan & Nurul Nadiah

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Thank you very much for all your encouragements, support and help

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ABSTRACT

Ground Penetrating Radar (GPR) is one of the trenchless technologies; widely used for subsurface utility detection and mapping. However, in the context of subsurface utility mapping, constraints of achieving specific accuracy requirements so far have not been addressed by each system manufacturer and users. This research investigates the utilization of GPR for subsurface utility mapping, with the following specific objectives: (i) to design and built a calibration site for analysing locational and detectability accuracies of GPR; (ii) to examine and analyse the effects of GPR data acquisition approaches to the locational and detectability accuracies; (iii) to characterize GPR backscatter for recognition of utility's material based on digital image processing techniques for retrieving the uniqueness of backscatters from respective utilities, and (iv) to examine and model GPR backscatters constraints for detecting and mapping stacked subsurface utilities in both vertical and horizontal orientations. Dual frequencies (250 and 700 MHz) GPR system was used in this study, experimented in both lab controlled and in-situ environments with settings of the system and scene parameters. Optimum values obtained in the lab for both system and scene parameters were then adopted for acquisition of data from in-situ measurement and also used in the Finite-Difference Time-Domain (FDTD) numerical modelling for validating the results of the study. Results of this study contributed three main findings: (i) the GPR locational and detectability accuracies for subsurface utility mapping are directly proportional to the data acquisition scanning techniques, where the 'along-pipe' scanning, which is rarely practised in the industry, yields the best locational and detectability accuracies, confirming to Quality Level A utility data; (ii) GPR backscatters with appropriate treatment can yield unique backscatter signature for recognition of utility's material, hence, opening a platform for new valuable addition to the GPR application for utility's material recognition besides utility detection and localization of buried utility; and (iii) the locational and detectability error trend and constraints of GPR measurements within crowded subsurface utility infrastructures yield a "best practice" procedure for determining the safe buffer zone for maintenance works; very crucial aspects in installation of new utility infrastructure and detecting aging utility.

ABSTRAK

Ground Penetrating Radar (*GPR*) adalah satu teknologi *trenchless*; digunakan secara meluas untuk pengesanan dan pemetaan utiliti bawah tanah. Walau bagaimanapun, dalam konteks pemetaan utiliti bawah tanah, kekangan keperluan untuk mencapai ketepatan tertentu setakat ini masih tidak ditangani oleh setiap pengeluar sistem and penguna. Penyelidikan ini menyelidiki penggunaan *GPR* untuk pemetaan utiliti bawah tanah. Objektif spesifik penyelidikan ini adalah untuk: (i) merekabentuk dan membina satu tapak penentukuran bagi menganalisis ketepatan lokasi dan kebolehkesanan *GPR*; (ii) menguji dan menganalisis kesan pendekatan perolehan data *GPR* kepada ketepatan lokasi dan kebolehkesanan; (iii) mencirikan serak balik *GPR* bagi pengecaman bahan pembuatan utiliti berdasarkan teknik pemprosesan imej digital dalam memperoleh semula keunikan serak balik dari utiliti tertentu; (iv) menguji dan memodel kekangan serak balik *GPR* bagi pengesanan and pemetaan utiliti bawah tanah yang bertindan dalam kedua-dua orientasi menegak dan mendatar. Dua frekuensi (250 dan 700 *MHz*) sistem *GPR* telah digunakan dalam penyelidikan ini, dilaksanakan dalam dua persekitaran makmal terkawal dan di-lapangan dengan tetapan parameter sistem dan pandangan setempat. Nilai optimum yang diperolehi di makmal untuk kedua-dua parameter sistem dan pandangan setempat, kemudiannya diterima pakai untuk perolehan data dari pengukuran di-lapangan dan digunakan dalam pemodelan berangka *Finite-Difference Time-Domain (FDTD)* bagi pengesahan keputusan penyelidikan. Hasil penyelidikan ini menyumbang tiga penemuan utama: (i) ketepatan lokasi dan kebolehkesanan GPR bagi pemetaan utiliti adalah berkadar terus dengan teknik pemgimbasan perolehan data, dimana pengimbasan "*sepanjang-paip*" yang jarang diamalkan dalam industri menghasilkan ketepatan lokasi dan kebolehkesanan yang terbaik, mengesahkan pada data utiliti Tahap Kualiti A; (ii) serak balik *GPR* dengan rawatan yang sesuai dapat menghasilkan tanda serak balik yang unik untuk pengecaman bahan pembuatan utiliti, justeru, menambah aplikasi baru yang berharga untuk aplikasi *GPR* bagi pengecaman bahan pembuatan utiliti selain pengesan dan mengenalpasti utiliti bawah tanah; dan (iii) pola ralat dan kekangan lokasi dan kebolehkesanan untuk pengukuran *GPR* dalam infrastruktur utiliti bawah tanah yang sesak dapat menghasilkan tatacara "amalan terbaik" untuk menentukan zon penimbal yang selamat bagi kerja-kerja penyelenggaran; aspek yang sangat penting dalam pemasangan infrastruktur utiliti baru dan pengesanan utiliti lama.

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D - Depth of the target

v - Electromagnetic wave travel velocity

t - Two-way travel time (TWT) of electromagnetic wave

X', Y' - Coordinates for points at subsurface

x, y - Coordinates for points at the ground surface

X_m, Y_m - Mean of transformed points

x_m, y_m - Mean of the observed points

N - Number of points observed

rx_i, ry_i - Residual of a sample point

Z_o - Observed depth

Z - Computed depth

Δt - Time delay

ε_r - Dielectric relative permittivity

c_m - Speed of light

t_n - Echo delay in position y_n

t_0 - Echo delay

i_0, j_0 - Hyperbola apex

Γ_2 - Voltage reflectance coefficient at a lower surface

σ_t - Material's cross-section

d - Distance travel by signal

τ - Layer thickness

μ - Magnetic permeability

σ - Electrical conductivity / standard deviation

T - Threshold values

n - n^{th} of utility

λ - wavelength

$\hat{o}$ - Object distribution

$R_1 (t)$ - Backscatter amplitudes

T_n - Distance from the antenna to point (x_1, y_1, z_1)

x_t, y_t, z_t - Location of transmitter

$x_{r_n}, y_{r_n}, z_{r_n}$ - Location of the receiver

LIST OF ABBREVIATIONS

ABS - Acrylonitrile-butadiene-stryrene
ANOVA - Analysis of variance
APWA - American Public Works Association
ASCE - American Society of Civil Engineering
BGS - British Geological Society
CAT - Cable Avoidance Tool
CCTV - Closed-circuit television
CEM - Computation electromagnetic methods
COTS - Commercial Off-The-Shelf
DC - Direct Current
DE - Differential Equation
DI - Ductile Iron
EM - Electromagnetic
EPSRC - Engineering and Physical Sciences Research Council
FDTD - Finite-Difference Time-Domain
FGRE - Faculty of Geoinformation and Real Estate
FMCW - Frequency Modulated Continuous Waveform
FRP - Fiberglass Reinforced Plastic
GIS - Geographical Information System
GPR - Ground Probing Radar/ Ground Penetrating Radar
GPS - Global Positioning System
HDD - Horizontal Directional Drilling
HDPE - High Density Polyethylene
IDS - Ingegneria Dei Sistemi
IE - Integral Equation

JUPEM	-	Jabatan Ukur dan Pemetaan Malaysia
KDI	-	Knowledge and Data Integration
MDPE	-	Medium Density Polyethylene
MOSTI	-	Ministry of Science, Technology and Innovation
MS	-	Mild Steel
MTU	-	Mapping the Underworld
NETTWORK	-	Engineering Programme Network in Trenchless Technologies
PADU	-	Pangkalan Data Pemetaan Utiliti Kebangsaan
PE	-	Polyethylene
PML	-	Perfectly Match Layer
PVC	-	Polyvinyl chloride
R&D	-	Research and Development
RMSE	-	Root mean square error
RTK	-	Real-time Kinematik
SAR	-	Synthetic-Aperture Radar
SFCW	-	Stepped Frequency Continuous Waveform
SNR	-	Signal-to-Noise Ratio
SOP	-	Standard Operation Procedure
SUE	-	Subsurface Utility Engineering
SYABAS	-	Syarikat Bekalan Air Selangor
TWT	-	Two-way travel time
UHF	-	Ultra High Frequency
UKWIR	-	UK Water Industry Research
UTHM	-	Universiti Tun Hussein Onn Malaysia
UTM	-	Universiti Teknologi Malaysia
VHF	-	Very High Frequency
WADGPS	-	Wide Area Differential GPS

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Utility infrastructure such as electricity, water, gas, sanitary sewers and telecommunication has played a significant role in facilitating agriculture, industrial, business activities and sustaining human's daily life since ancient civilization until present. Rapid urbanization as well as fast paced urban population growth has caused the expansion of these utility infrastructures. Since World War II, the utility infrastructure in United States (U.S) has increased approximately 14 million miles (GeoSpec LLC, 2002). Whereas the electricity, treated water, and communication coverage in the rural areas of Peninsular Malaysia, Sabah and Sarawak is expected to reach almost 100% and 99% respectively by year 2015 (Economic Planning Unit, 2010). It is particularly essential to meet the demands of utility infrastructure in order to cater to the economic activities and luxurious life of the cities. As such, this has resulted in booming of construction work in the utility industry to replace or maintain the aging utility infrastructure for expansion of utility services to the backward and underserved areas.

In this context, utility owners adopt a measure to place their utility networks in the subsurface for space saving and have better design of the urban landscape (Jorge et al., 2010). Moreover, by burying the utility pipeline in the subsurface, it can reduce the use of unnecessary by-pass cables which may tarnish and jeopardize the city landscape. However, rapid development over the country has led to the limited use of surface land, property on the land and underground spaces. Most of the densely populated countries especially the Hong Kong, Taiwan, Singapore and Japan are experiencing issue of land shortage. The spaces within the subsurface are extremely limited; yet the utility owners still persistently placed their networks in the subsurface. The shallow subsurface in urban, industrial and environmentally sensitive areas are now fully occupied by different utility networks; forming a labyrinthine network of utility networks (refers Figure 5.10).

Under such utility congestion circumstance, it is exceedingly difficult and troublesome to map these buried utilities as they are invisible to the naked eye. Moreover, most of the utilities that have been buried since long ago, are generally not archived. Even if, they are archived, the records are mostly in the form of two-dimensional hardcopy map. In this sense, mapping of buried utility has become more challenging task especially with deficiency of buried utility information. It often contributes to the increment of utility damaging incidence and adverse impacts to the contractors, utility owners and even the public. The impacts not only inconvenience the urban dweller, in the form of interruptions in electricity, telephone, traffic system, water and gas supplies, it may also causes explosions and mortalities when the workers accidentally hit the utility pipelines, especially the gas pipe or electrical cable.

The numbers of utility damages are increasing rapidly in response with increasing numbers of construction work for utility maintenance and rehabilitation. The costs of these damages are often notable and on the rise. In each single year, approximately USD 12.9 billion has been expended by Malaysia government for construction work of utility maintenance caused by failed excavation. In US, total loss of utility damages in year 1993 was exceeding USD 83 million and around USD 0.7 million in year 1997 (Costello et al., 2007; Doctor et al., 1995; Economic Planning Unit, 2006; Stinson, 1998). In UK, the spending for third party utility damages are USD 227.4 million while the social expenses per year for street work due to traffic relocation, air pollution, business disruption, etc. is almost USD 77 billion (Costello et al., 2007; Doctor et al., 1995). In fact, the cost of losses for utility damages is not little, because the stakeholders often underreported the actual cost of losses due to utility damages. According to Heinrich (1996) and Lorenc and Bernold (1998), the originally construction cost for utility maintenance is expected to be twenty times more than the original costs that reported in the media.

Subsurface Utility Engineering (SUE) - an engineering practise is developed to address the problems of inaccurate utility mapping. It is the engineering survey that used to determine the position or location of the natural or manmade structure on, above or beneath the earth's surface. According to American Society of Civil Engineers (2002), SUE is the engineering practise that developed to manage the risks related to utility mapping under appropriate quality level, utility relocation, precise utility coordination, implementation of utility related policies and others responsibility related to utility sectors. SUE, which comprises civil engineering practises, geophysical imaging technologies, surveying and data management skills, are widely used for acquiring good quality utility's information in majority of the mapping projects (Jeong et al., 2003). With precisely locating the buried utility and presenting it in the form a map, it can ease the task of utility relocation and installation; avoid construction delays, incidents and damages to the third party utility networks.

According to Metje et al., (2007), the Cable Avoidance Tool (CAT) is the conventional utility detection tool. It contains a magnetic field sensor which operates in either the power, radio or generator mode. Although CAT was commonly used in UK for detecting the buried utility, it still has limitation in detecting the utility which laid closely together, overlay or crossing among each other. In an attempt to overcome this problem, development of technology has led to the innovation of new non-destructive system namely Ground Penetration Radar or Ground Probing Radar (GPR). At present, GPR is one of the useful instruments in trenchless technology for examining the man-made structure in determining its location and depth. GPR is now the top sensing tool among all the equipment that is commercially available in today's market due to its advantages in providing high resolution imagery, fast data acquisition and good interpretation results (Enes et al., 2010; Jeng et al., 2011; Jorge et al., 2010; Lester and Bernold, 2007; Millington et al., 2009; Ni et al., 2010; Roger et al., 2009). It is highly recommended for use in subsurface investigations, specifically for application of military, civil or environmental engineering, geology, geophysics or transportation studies in detecting subsurface utility, building rebar or cavities, spatial distribution of biogenic gas from peatland and also landmines (Bello and Kamarudin, 2012a; Ahmet and Mehmet, 2011; Annan, 2005; Francke, 2011; Neal, 2004).

The development of new technology such as broadband in modern civilized life has lead to increasing of new construction and expansion of subsurface utility networks. GPR is often used to determine the location of the buried utility infrastructure in a utility mapping project. It is now an essential means to reduce the adverse impacts of utility damages before any construction work starts (Jeong et al., 2003). Despite diligent efforts to detect these buried utility infrastructures before the excavation, the occurrences of utility damage during excavation work are still arising. The losses due to these excavation accidents can reach astronomical numbers and have caused dangerous and hazardous effects to the environment and public. In this sense, there is always unprecedented demand for precise and high efficiency subsurface utility mapping within the utility industry. According to Common Ground's study, determination of utility's location and retaining of accurate mapping information is essential for preventing utility damages (refers Figure 1.1). Securing reliable information of the buried utility is, hence, urgently required by current utility industry for preventing these excavation accidents to recur. Therefore, mapping the attributes of subsurface utility features at the present time is a significant task in the utility industries, particularly for the expansion and upgrading the subsurface utility features (Balaogun et al., 2011; KPUP, 2006).

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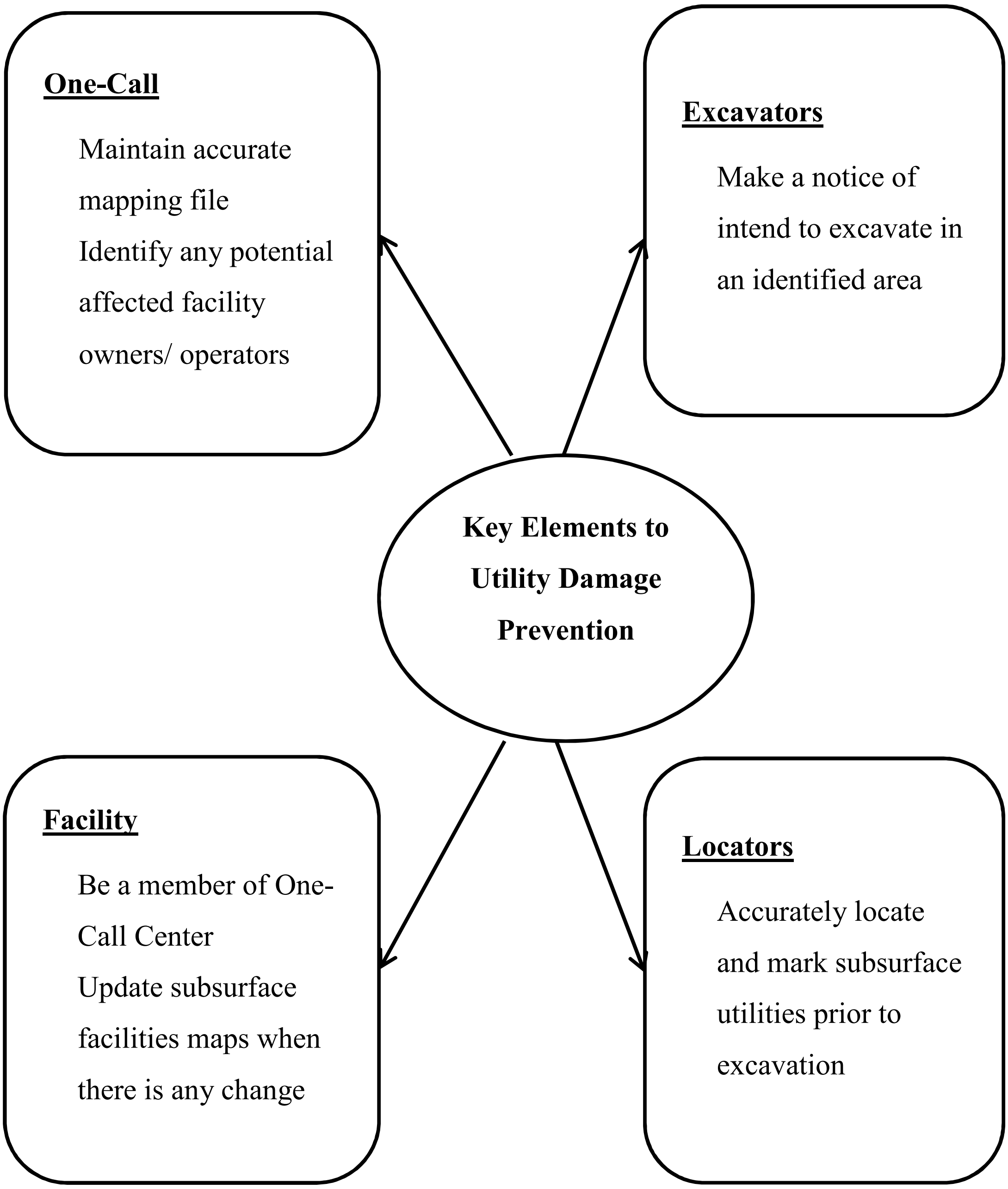

Figure 1.1: Key Element to Damage Prevention (Source: Common Ground Alliance, 1999)

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1.2 Problem Statement

GPR has been categorised as the best trenchless detection tool for subsurface detection and mapping. However, the GPR signal is often affected by factors of the host material's physical properties, soil moisture, congestion of utility networks, clutter due to non-targeted features and etc. By using an uncalibrated GPR system to acquire data for the mapping subsurface features, it has led to problems of poor data quality and data interpretation, due to the high uncertainties in imprecise subsurface utility mapping. In this sense, this lead to the risk of "vulnerable" errors and created uncertainties for buried utilities safety in most of the mapping projects. GPR systems, hence, require calibration to minimise the risk of "vulnerable" errors before it can be used for subsurface utility mapping. A practical calibration site is necessary to overcome the shortcomings of current GPR systems. This is because real time GPR calibration is exceedingly costly and currently there is a lack of absolute calibration sites to assess the performance of the GPR equipment. All the calibration for the commercially available GPR system is done relatively without any investigation; hence, the results are highly ambiguous for subsurface utility mapping and give rise to high ambiguity in the mapping industry.

Despite the fact that GPR has been given considerable attention in subsurface investigation application, current utility industries still less exposed to extensive guidelines on proper procedures and accuracy requirement for subsurface utility mapping. As such, it has created a gap between engineering practises and mapping disciplines for understanding the GPR capabilities in subsurface utility mapping. For this reason, "rather hit and miss" principle are practised widely by the street worker throughout the utility mapping projects. With regard to this, "rather hit and miss" affair, it has contributed to increment of failed excavation cases due to insufficient acquainted with their duty of engineering survey (Costello et al., 2007; Lester and Bernold, 2007; Metje et al., 2007). For every single year, many "dry hole" - the hole that digs during excavation but failed to detect any utility has been left behind as a result of failed excavation caused by imprecise subsurface utility mapping. Thereby, proper mapping approach is essential for performing accurate subsurface utility mapping in order to prevent “blind” excavation and undesirable consequences during construction works of utility maintenance and rehabilitation.

Moreover, the stakeholders, like decision makers, utility owner, contractors, surveyors, and even excavators, often overlook the need to perform precise subsurface utility mapping because they assume that the utilities are usually buried in the subsurface and invisible to the naked eye. The stakeholders even tend to underestimate the destructive power caused by utility damages due to failed excavation, hence, they often believe there is no need for accurately detect the position of the buried utilities (Koo and Ariaratnam, 2006). The stakeholders did not giving priority attentions to the detection accuracy and the potential errors of mapping. Additionally, to-date, there are not much published literature regarding GPR data acquisition approach effect on locational and detectability accuracies has been covering comprehensively. With regard to this, a thorough investigation is required to be conducted for examining and analysing the effects of data acquisition techniques on locational and detectability accuracies, is needed urgently by current utility industry. This is to solve the issue of failed excavation due to imprecise subsurface utility mapping which has been continuing to occur and exacerbated.

Although GPR is established entirely for geophysical application in understanding the location and depth of the buried utilities within local coordinate system, it is somehow “underutilize” for understanding utility’s radiometric properties such as utility’s fabrication material, radius or diameter and utility’s condition. At present, only limited utility’s geometric properties, such as planimetric location and depth, are being taken seriously by the stakeholders. The industry actually misconception that GPR is only beneficial for extracting the geometric information of the buried utilities. However, the reality is that backscatters from the object which acquired by the GPR has enormous potential to be used to report the physical properties of the object. The “feature information” of the object such as its shape, size and condition, can be extracted from its backscatters. In this sense, the issues of (i) object material recognition; (ii) object dimension estimation; and (iii) object size estimation are still remaining open for research because plenty of research that currently conducted are focused on object detection and localization issue only. However, complete details of the buried utilities in term of its geometric and radiometric properties is actually essential for the industry to perform civil engineering and surveying work, particularly excavation for utility installation and repair. With these complete details, it will ensure safe excavation with minimal traffic flow and business disruption.

The prerequisite for extracting buried utility's geometry and radiometry physical properties is through accurate interpretation of backscatter image, so call radargram. Nowadays, GPR data processing and interpretation work are performed totally by commercial software that is associated with the GPR system. This commercial software belongs to the Commercial Off-The-Shelf (COTS) product, where end-users are unable to configure any processing flow of the software for the necessity of their works. In this context, most of the existing GPR software is aimed for commercial use and not for research (Vera et al., 2008). The theory and source code that are used in the software is not disclosed to the end-users, due to trade secret, thereby, the processing and interpretation work can only be done in "black-box" manner. For every individual processing and interpretation work done in the majority of the mapping projects, there is no statistical assessment. This is because the results are depending mainly on the operator's interpretation experience and prior knowledge regarding the structure of the subsurface features. The purpose of good interpretation for retrieving information from the radargram which enables characterisation of subsurface physical or natural properties rather than just to "see something" in the radargram are never being practised in the industry. Numerical modelling analysis which able to simulate subsurface properties and realistically represent the geometry and structure for subsurface feature and GPR antenna under varying complex environment is, therefore, ideal for extraction of subtle interpretation information from the radargram.

Utility services are the foundation of modern living for supporting the industrial, agriculture and affluence life of the city. In relation to population growth and increased of telecommunication technology such as the broadband services, it has causes many new construction, reconstruction and development of new subsurface infrastructure to be conducted around the world (Lester and Bernold, 2007). The utility owners attempt to accommodate their networks randomly stacked (both vertically and horizontally) in the first three meters of the subsurface, due to the deregulation of utility service. As such, the shallow subsurface are now congested with different types of utility networks such as oil and gas, electricity, sewer, water, cable TV, traffic signals, sanitary sewer, street lighting circuit and even fibre optics. Under such congestion situation, the works of utility maintenance and rehabilitation become difficult and often give rise to damage the third party utilities. During the excavation, the machinery such as Horizontal Directional Drilling (HDD), backhoe excavators, and plows are often could not "see" the third party utilities when they are getting too close with it, unless remarkably precise location of the utilities is provided by the utility owners. Herein, a uniform practice for alteration of an existing installation, relocation of utilities or new utility installation within the shallow subsurface is needed particularly to minimise the adverse effects on third party utility safety, operations and maintenance. Therefore, all the problems mentioned above were apparently resulted in the needs of conducting this research.

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1.3 Objectives of the Study

The main aim of this study is to reconstruct ground penetrating radar backscatters for subsurface utility features utilizing three digital image processing techniques namely; image analysis, attribute analysis and modelling. The specific objectives of this study are:

i) To design and built a calibration site for analysing locational and detectability accuracies of GPR;

ii) To examine and analyse GPR data acquisition approaches effect on locational accuracies and detectability of subsurface utility features;

iii) To characterize GPR backscatter for recognition of utility’s fabrication material based on digital image processing technique of retrieving the uniqueness of backscatters from various utilities; and

iv) To examine and model GPR backscatters constraints for detecting and mapping stacked subsurface utilities in both vertical and horizontal orientations.

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1.4 Scopes of the Study

The scopes of this study are as follows:

1. A field-based test site for understanding the operation of GPR system and its reflection for utility's fabrication material property characterization is required by the industry, especially for underground utility mapping, archaeological studies, civil engineering, geotechnical inspection and mine exploration. This test site is designed uniquely in such a way, to mimic the real world's subsurface civil infrastructure. With such design, it can enable correlation between the existing civil engineering structure and the geophysical anomalies in the real world for the calibration of all frequencies GPR system and other non-destructive geotechnical instruments. In this context, field-based test site is deliberately designed and built in this study, according to the existing civil engineering structure for calibrating the GPR system and providing a better understanding on the capability of GPR system for precisely locating the buried utilities particularly utilities that located in areas with complex pipelines network.

2. The commonly used scanning technique for data acquisition in subsurface utility mapping is perpendicular to pipe scanning. However, no related guideline has proved that perpendicular to pipe scanning is the most effective technique to be used. Moreover, there is no evidence to show that other scanning techniques are not appropriate for utility mapping data acquisition. In this sense, three GPR data acquisition scanning techniques that are regularly used for various subsurface investigation applications such as (i) perpendicular-to-pipe scanning; (ii) along-pipe scanning and (iii) variation-angles scanning were used in this study to investigate the locational accuracy and detectability of subsurface utility features.

3. GPR backscatter is not "fully utilized" in extracting the inherent elements of the subsurface utility features. The inherent elements that can be retrieved are relating to its physical properties, including: (i) geometric characteristic

concerning with planimetric position and depth and (ii) radiometric characteristics for detection of utility's fabrication material concerning of depth variation and host material variation. For geometry properties extraction, planimetric position and depth of the buried pipe or cable are extracted from the hyperbola formed in the radargram. Whilst for the radiometry properties, the fabrication material types (ductile iron, mild steel, clay, polyvinyl chloride and etc.) are extracted from the radargram using the GPR backscatters function.

4. Modelling analysis is required for understanding the backscatter characteristic of the subsurface utility features. In order to understand the relationship between subsurface utility features and its GPR backscatters, numerical modelling is needed. A commonly used numerical modelling tool namely Finite-Difference Time-Domain (FDTD) model is used in the study to simulate theoretical data of the field-based physical model mentioned earlier. The absolute value of the electrical properties such as dielectric permittivity (ε), magnetic permittivity (μ) and electrical conductivity (σ) of the subsurface civil structure are used as the input for FDTD numerical modelling for constructing field-based model data theoretically. These field-based models data are reconstructed using different scene parameter such as typical utility's fabrication material that used by current industry, position and depth of the utility as well as host medium that commonly used for construction. Subsequently, the unique backscatter characteristic of each utility features can be identify from these reconstructed theoretical data and, therefore, can be used for validate the practical data acquire using GPR system.

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1.5 Significance of the Study

As mentioned earlier, the problems of inability in locating the buried subsurface utility features accurately without resorting to excavation are still there and have contributing serious social, economic and environmental consequences to the country. Moreover, the aim of utility mapping is not reached without extensive guideline because the work is just "trial and error". The unplanned strikes on buried utility due to 'blind' excavation still happen every year. For this reason, this study conducted to assist the beneficiaries (surveyors, engineers, constructors, planners, municipalities, government agencies, utility companies, statutory bodies' agencies, researcher, software and hardware developer and etc.) to solve their problems in the subsurface investigation industries, particularly the utility mapping industries. The importance of this study to the field of utility mapping were from innovate field model for testing and calibrating GPR system, data acquisition, interpretation and result assessment. Explanations for a series of benefits for this study are summarized below:

In this study, a test site, which serves as the "testing or calibration device" for GPR system, was established. Although there have been few test sites available on the market (refers Figure 2.1), the test site that is proposed in this study is distinct from others because it provides unique advantages, which can overcome the shortcoming of existing test sites. With the special arrangement of the utility in the test site that deliberately designed in the manner of superimpose on one another, it can represent the actual civil engineering structure in the real world. Through this design, it enables the actual civil engineering structure and the geophysical anomalies in the real world to be correlated with this test site with no doubt during research. This is valuable for understanding either the performance of the GPR system or the GPR reflection for material property characterization, particularly for subsurface investigation applications such as utility mapping, archaeological studies, civil engineering, geotechnical investigation, and mine exploration. Moreover, this test site is for experiment purpose, where its structure and host material can be randomly altered according to user personal preferences. It is thus beneficial to the subsurface investigations related research for providing solutions to address the problems that currently faced by the utility industry.

As mentioned by Jol (2009), good data acquisition technique is the key parameter for producing good interpretation. The data acquisition scanning technique is thus essential for producing precise subsurface utility mapping later. In this regard, the locational and detectability accuracy for three commonly used data acquisition scanning techniques which reported in the finding of this study prove that precise utility mapping is essential to social and economic development for a country as the losses caused by utility damages can reach astronomical figures. In this sense, by knowing the locational and detectability accuracy of each scanning technique, the stakeholder can have a better planning for construction work of utility installation, maintenance and rehabilitation. In addition, the possibility of utility services disruption owing to misidentify or mislocate buried utility during construction work can be reduced also by using the good practises of data acquisition. As such, the proposed scanning technique successfully creates a new benchmark for data acquisition using GPR in order to locate subsurface utility features precisely. With such finding, it can be a reference to the authorities in preparing the standard operating procedures (see Section 3.2.5) for subsurface utility mapping in the future.

Many practices have been committed to the production of typical utility map and maintenance of a database of subsurface structure. There is lack of related publications studying the capabilities of GPR for utility mapping applications. However, this study successfully explained the uncertainty and confusion in utility mapping application which claimed that GPR is only for geometric information retrieval. The research finding proved that inherent elements of the subsurface utility feature can be retrieved from the radar backscatters recorded in the radargram. As such, the finding of determining the fabrication material of the subsurface utility feature would be a significant step forward in the industries, regardless of surveying, civil engineering or software development engineering. With continuous exploration in this aspect, the good agreement between the backscatter reflections of the GPR with specific subsurface utility feature in term its radiometry properties such as the fabrication material and condition, is useable for civil infrastructure management and maintenance. Thereby, this advantages opening new platform for constructive addition to the application of ground penetrating radar with new material recognition facility in the near future aside from the established utility detection and localization facilities. Moreover, the material property recognition indicators produced from this study is ready for intake as feature recognition interface tool. These indicators are needed for future research and development of GPR hardware or software which are crucial to the utility mapping applications.

Even since, non-destructive testing technology is adopted in subsurface investigation work, the data processing and interpretation task are typically according to one's experience and prior knowledge about the supervision site. Sometimes, the judgement may be incorrect and lead to an inaccurate interpretation of data caused by poor data quality or interpretation. Numerical modelling, which apply to link the subsurface properties with GPR data, was performed in this research. In doing this, a model for the subsurface region can be created based on the electrical properties of the subsurface features as defined by the user, in order to simulate the data acquisition for a region of interest. With the GPR model, users can have a better understanding for GPR imaging, especially the factors that affected the quality of data, how the spatial variability being captured or extracted from the GPR data, etc. This model is, therefore, necessary to current mapping industries to solve the problems faced by the development of GPR technology, as a limitation of existing GPR often blocks advancement.

At present, the subsurface spaces are buried with different types of utility features in order to support the growing demand for utility services. The shallow subsurface currently saturated with a wide range of utility networks. The utility owners often have difficulty in accurately determining the required utilities among a bunch of complicated utility networks. In addition, current non-destructive technology only able to provide approximately location of the buried object, where the multiple stacked subsurface utility features in both vertical and horizontal orientations often being miss-out from the redundant or overlapping reflection in an image. To date no study has successfully addressed the problem of detecting multiple stacked subsurface utility features. In this regard, the method of combining field model that specifically designed to mimic the current subsurface civil structure and FDTD numerical modelling are presented in this research for attempting these problems. The locational and detectability accuracy of the multiple stacked utility and the potential of GPR in detecting such multiple stacked utilities are tested. Based on the finding from this study, a better understanding about the potential and limitation of GPR system can be provided to the manufacturer. The efficiency of GPR system in detecting the buried utility that located in an area that contains a wide range of utility networks is achievable with advancement from the findings of this research. This is conducive to the development of a new GPR system in the future with inclusive of high precision sensing of buried utilities, particularly sensing in an area with complex utility networks.

In short, this research has innovated a practical experimental test site which is ideal for testing and calibrating all types of frequency GPR system (see Table 3.2) available on the market for providing a solution to problems that faced by industries through persistent investigation or research. Apart from this, some experiments have also been established to resolve the issue of imprecise mapping, explore the new capabilities of GPR and attempting to solve the limitation of current technology in sensing multiple stacked subsurface utility features by combining field model scanning and numerical modelling. All the designated experiments that established in this study, are targeted to determine the locational and detectability accuracy of mapping subsurface utility features, improve GPR imaging, as well as to refine efficiency of GPR in characterisation of fabrication material for utility features, and in detecting buried utility in an area that contains a wide range of utility networks. Therefore, this not only can improve the performance of GPR in locating buried utility features, but also can fully explain the excellent performance of the GPR, thereby promoting better development of the existing GPR technology.

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1.6 Research Design

Before developing the research plan, a thorough review of the literature was conducted to understand the current trends of utility mapping, in order to figure out research needs in the utility industry. From the review, four main stages of procedure were scheduled for implementation: (i) design and built test site; (ii) investigate effects of GPR data acquisition approaches on locational accuracy and detectability of subsurface utility features; (iii) characterised GPR backscatter for material recognition, and (iv) detect and map stacked utilities. Figure 1.2 depicts a flowchart indicating an overview of the sequence of research methodology in implementing these four main stages of the procedure.

Based on the review, test site which allows absolute calibration of GPR system, was found to be particularly pertinent to current mapping application for testing the performance of the GPR equipment in terms of its locational accuracy and detectability. With this regard, a GPR test site which contains unique advantages, which can overcome the shortcoming of existing test site is designed and built in this research. Then, field data was acquired using dual frequencies GPR system at the test sites with both lab controlled and in-situ environments with different system and scene parameter settings. The optimal value obtained in the lab was then adopted for in-situ measurement. The same parameter was also used for reconstruction of theoretical data through numerical modelling like FDTD, to verify the results of the research. These data were subsequently subjected to pre-processing, and followed by interpretation. Feature detection was done to determine real reflection of each buried utility through the hyperbola reflection illustrated in the radargram. These GPR backscatter with proper treatment can then yield unique backscatter signature for recognition of utility's fabrication material, thereby opening a new facility, in addition, to current utility detection and localization facility. Consequently, three new main finding were contributed from this research:

i) The locational accuracy and detectability of subsurface utility features using GPR in utility mapping are directly proportional to the data acquisition scanning techniques. The rarely practiced scanning technique, ‘Along-pipe’ scanning produces the best locational and detectability accuracies of ± 0.10 m equivalent to Quality Level A utility data;

ii) Unique backscatter signature yielded from appropriate treatment is beneficial for recognition of utility’s fabrication material, thereby, opening new facilities for GPR application in subsurface investigations addition to current GPR utility detection and localization; and

iii) The locational and detectability error trend and constraints of GPR measurements within crowded (such as in horizontal and vertically stacked) subsurface utility infrastructures yield a “best practice” procedure for determining the safe buffer zone for maintenance works; which is crucial aspects in installation of new utility infrastructure and detecting aging utility.

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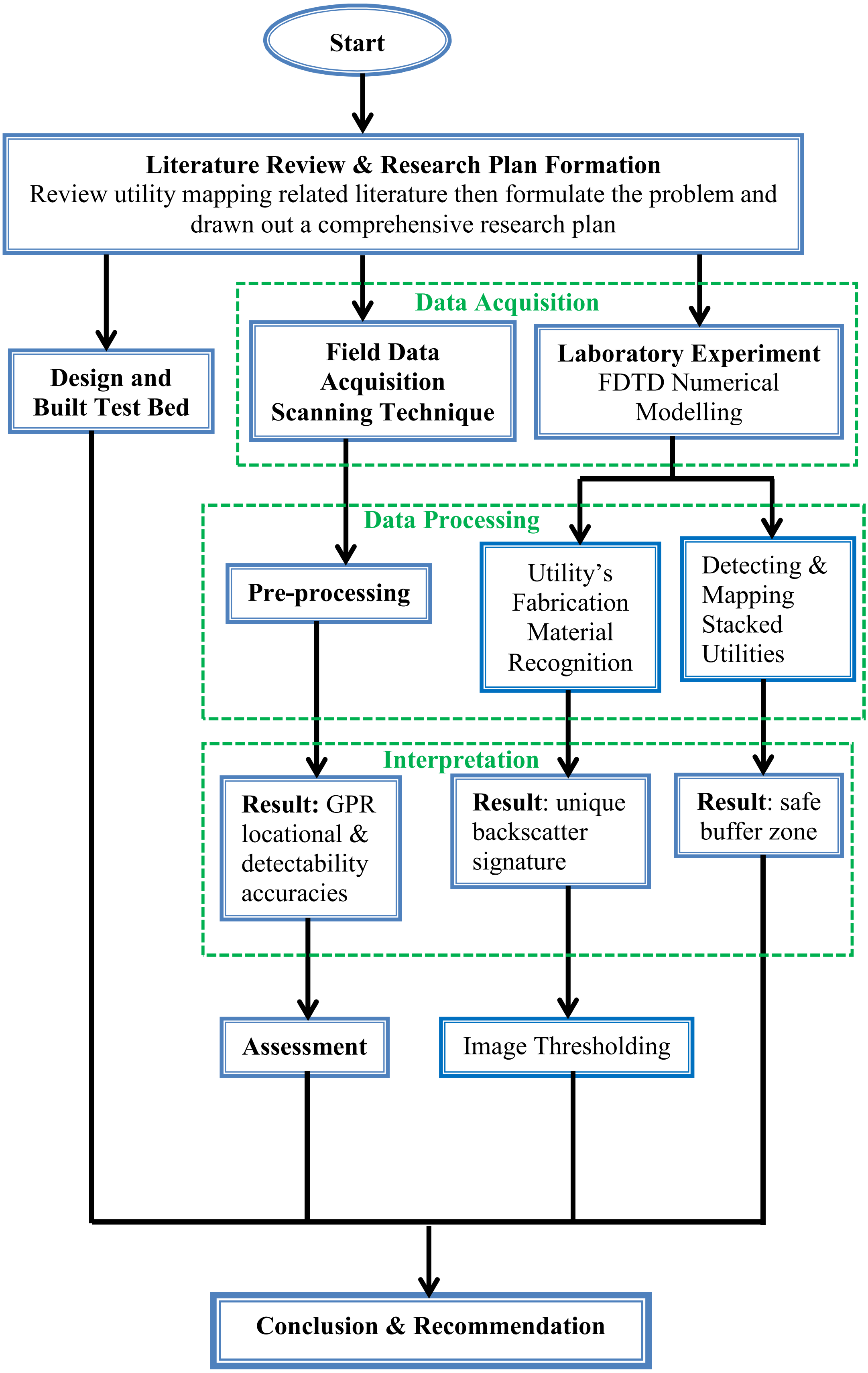

Figure 1.2: Research Plan Flowchart

1.7 Organization of the Thesis

The theme of thesis is reconstruction of ground penetrating radar backscatter for subsurface utility features in utility mapping. The backscatter of the subsurface utility feature which recorded by the GPR were reconstructed using different settings of (i) system parameter- instrument's frequencies (250 MHz and 700 MHz) and data acquisition scanning techniques; and (ii) scene parameter- various types of utility features that commonly used in current industry (water pipe, electrical cable, gas and sewer pipe), utility's fabrication material (mild steel, ductile iron, Polyvinyl chloride, medium and high density polyethylene), utility's position and depth, and commonly used construction host material (sand, loam, rock etc.). The overview of the research procedures involved for the successful implementation of the work were enumerates in the following thesis structure:

Chapter 1: Introduction to background of this research, problems currently faced by the utility mapping industries, the objective for achieving the aims of this research, the scopes of research, and overview of the research plan as well as the thesis structure which highlighted the importance, needs, value and urgency of this research to be conducted.

Chapter 2: Explanation to GPR calibration test site. A field-based test site is designed and built to understand the scanning mechanism and data formation of any frequencies GPR system that commercially available on the market. The steps involved in the construction of the test site and the benefits derived from this test site are clearly explained in this chapter.

Chapter 3: GPR data acquisition is the key parameter to determine the quality level and interpretation results of the utility data. The importance of securing reliable locational information of the buried utilities to avoid "blind" excavation and third party's utility pipeline damages was highlighted through materials and methods used to examine and analyse the GPR data acquisition approaches effect on locational and detectability accuracies. The main findings of this research indicating that GPR locational and detectability accuracies for utility mapping are directly proportional to the data acquisition scanning techniques is derived from this chapter.

Chapter 4: Utility's fabrication material recognition is mistaken by current utility mapping industries as one of the impossible application. The industry defined that application of GPR in the investigation of subsurface heterogeneities such as sandstone, rock, utility features and tunnels are only limited to extract geometry properties. On the contrary, this is one of the foremost GPR capabilities which need to be discovered as the GPR backscatter with appropriate treatment can yield unique backscatter signature for recognition of its inherent radiometry properties. Therefore, this research was conducted to exploit research gap in utility mapping industries focusing on utility's fabrication material recognition using GPR backscatter. This chapter enumerates in details the research procedure to achieve utility's fabrication material recognition, hence, contributing a new platform for valuable addition to current GPR application for utility mapping.

Chapter 5: Detecting and mapping stacked subsurface utilities is an application that must be examined in current utility mapping industry. More and more utility pipeline are being accommodate randomly stacked in both vertical and horizontal direction in the shallow subsurface. This causes utility congestion in subsurface, hence, leading to difficulties in assessing the location or condition of the buried utility pipelines. In this context, the "best practice" procedure which implemented in this chapter comprising of data reconstruction, interpretation, and assessment for yielding a safe buffer zone for utility maintenance work is essential for eliminating the locational and detectability constraints and error trend of GPR measurement within utility congestion condition.

Chapter 6: Conclusions and recommendations chapter summarised all the conclusions obtained in aforementioned chapters and highlighted recommendations which would be beneficial for future research based on these conclusions.

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