MODELLING OF GROUND PENETRATING RADAR BACKSCATTER FOR WATER PIPILINE LEAKAGE DETECTION

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DEDICATION

A special dedication

To

My beloved family,

Whom I can always return to;

INSTeG, and The numbered acquaintances out there,

For your supports, and

For the insight and guidance.

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ABSTRACT

Subsurface water leaks not only waste precious natural resources, but also create substantial damages to the transportation system and structures within urban and suburban environments. While many geophysical techniques have been suggested for detecting water leakage including ground-penetrating radar (GPR), acoustic devices, gas sampling devices and pressure wave detectors, there is no ideal solution for it. Nonetheless, GPR, a non-destructive geophysical technique which uses high frequency electromagnetic waves to acquire subsurface information has been regularly utilized as GPR responds to the changes in electrical properties, which is a function of soil and rock material, and moisture content. To evaluate the feasibility of GPR in detecting water pipe leakage, a finite-difference time-domain (FDTD) numerical modelling is conducted together with water pipe leakage detection fieldwork and experimental test. To properly design the features of the imaging approach, and test its capabilities in controlled conditions, the synthetic data was generated in a two dimensional FDTD forward modelling solver capable of accurately simulating real world GPR scenarios. Different types of simulate conditions involving sizes of leakage area, frequencies (250 MHz and 700 MHz), pipe materials (AC, DI, PVC, MS and HDPE) and pipe sizes (100mm, 200mm and 300mm) were conducted. For the fieldwork, case studies were carried out using GPR scanning equipment (Detector Duo) to validate FDTD numerical model. For the experimental test, Detector Duo was used to collect data on top of District Metering Areas testbed. More understanding regarding the signature of leakage was gained in radargram. Compared to a distinct hyperbola or line as shown in radargram of intact pipes, the leakage zone is disturbed by the wave reflection caused by saturated soil. Numerically simulated results seem to be in agreement with the case studies and experimental results. The signature of pipe and leakage are clearly visible in the simulated radargram compared with those in the case studies and experimental radargram. Therefore, GPR survey seems promising as an efficient non-destructive geophysical technique for leakage detection approach. This finding is useful to provide protocols for GPR profile interpretation, particularly in underground water pipe leakage detection.

ABSTRAK

Kebocoran air bawah tanah bukan sahaja membazirkan sumber alam semula jadi tetapi turut menyebabkan kerosakan besar terhadap sistem pengangkutan dan struktur di persekitaran dan pinggir bandar. Walaupun banyak teknik geofizik telah dicadangkan untuk mengesan kebocoran air termasuk Radar Penembusan Tanah (GPR), peranti akustik, peranti pensampelan gas dan pengesan tekanan gelombang tetapi masih tiada jalan penyelesaian yang sesuai untuknya. Walau bagaimanapun GPR, iaitu teknik geofizik yang tidak merosakkan yang menggunakan gelombang elektromagnetik berfrekuensi tinggi untuk mendapatkan maklumat bawah permukaan telah kerap digunakan kerana GPR bertindak balas kepada perubahan dalam sifat elektrik, yang merupakan satu fungsi kepada bahan tanah dan batuan serta kandungan kelembapan. Untuk menilai kebolehlaksanaan GPR dalam mengesan kebocoran paip air, pemodelan berangka perbezaan terhingga domain masa (FDTD) dilakukan bersama dengan kerja lapangan dan ujian eksperimen pengesanan kebocoran paip air. Untuk merekabentuk ciri-ciri pendekatan pengimejan, dan menguji keupayaannya dalam keadaan terkawal, data sintetik dihasilkan dengan penyelesai pemodelan dua dimensi FDTD yang mampu mengsimulasi senario GPR dalam dunia sebenar. Pelbagai jenis simulasi yang berbeza seperti saiz kebocoran, frekuensi radar (250 MHz dan 700 MHz), bahan paip (AC, DI, PVC, MS dan HDPE) dan saiz paip (100mm, 200mm dan 300mm) telah dijalankan. Bagi kerja lapangan, kajian kes dijalankan menggunakan peralatan pengimbas GPR (Detector Duo) untuk mengesahkan model berangka FDTD. Bagi ujian eksperimen, Detector Duo digunakan untuk mengumpul data di permukaan kawasan pengujian permeteran daerah. Pemahaman lebih lanjut mengenai tanda kebocoran diperoleh daripada radargram. Berbanding dengan hiperbola atau garisan berbeza seperti yang ditunjukkan dalam radargram, kawasan bocor terganggu dengan pantulan gelombang yang disebabkan oleh tanah tepu. Hasil simulasi secara berangka adalah sesuai dengan kajian kes dan keputusan eksperimen. Isyarat paip dan kebocoran kelihatan jelas dalam radargram simulasi berbanding dengan kajian kes dan ujian eksperimen. Oleh itu, kajian GPR adalah sesuai sebagai teknik geofizik yang tidak merosakkan untuk mengesan kebocoran. Dapatan ini sangat berguna untuk menyediakan protokol dalam pentafsiran profil GPR, terutamanya dalam mengesan kebocoran paip air bawah tanah.

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LIST OF ABBREVIATIONS

2D		Two-dimensional
3D	-	Three-dimensional
AC		Asbestos cement
AWWA		American Water Works Association
DI		Ductile iron
DMA		District Metering Areas
DSLR	-	Digital Single-lens Reflex
EM	-	Electromagnetic
EMP	-	Electromagnetic pulse
FDTD		Finite-difference time-domain
FEM	-	Finite element method
FIT	-	Finite integration technique
FW		FastWave
GPR		Ground penetrating radar
GPS		Global Positioning System
GUI		Graphical user interface
HDPE		High-density polyethylene
HPC		High-performance computing
IRT		Infrared thermography
IWSA		International Water Supply Association
MS		Mild steel
NRW		Non-Revenue Water
PBAPP	-	Perbadanan Bekalan Air Pulau Pinang
PML		Perfectly matched layer
PTP		Port Tanjung Pelepas
PVC		Polyvinyl chloride
SPAN		National Water Services Commission
SPD		Symmetric positive unequivocal
TEM		Transverse electromagnetic
TM		Transverse magnetic

LIST OF SYMBOLS

d_1	-	Length from sensor 1 to leak
d	-	Gap between two sensors
c		Sound wave propagation velocity or speed of light
t_{peak}		Time difference between the arrival of identical frequencies to each sensor
λ		Signal wavelength
fm		Signal frequency
$\widetilde{D}$		Electric flux density
$\tilde{E}, H$		Vectors in three dimensions
ε_{rs}		Relative permittivity of the medium
$\varepsilon_{r\infty}$		Relative permittivity at theoretically infinite frequency
Ŧ		Relaxation time of the medium
σ		Conductivity of the medium
μ_r		Relative permeability of the medium
σ^*		Magnetic conductivity of the medium
Δt		Time step

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Water pipe leakage is currently one of the most critical issues in water industry. This is mainly due to the waste of precious natural resources and of increasing water demand (Fontana and Morais, 2016). Moreover, water leakage has a very high potential that lead to the damage of transportation system and structures within urban and suburban areas. According to an investigation made by the National Water Services Commission (SPAN) in 2013, the measurement of lost or 'unaccounted-for' water from the water pipes is commonly 20 to 30 percent of aggregate water generation (Cheong, 1991; Ghazali, 2012; SPAN, 2013). Some other distribution systems, mostly older ones, may reach until 50 percent (AWWA, 1987). The substantial amount of water has lost in water conveyance frameworks while travel from the treatment plants to the end users. Whilst the 'unaccounted-for' water is normally due to spillage, metering blunders or thievery (Cheong, 1991; Salleh and Malek, 2012; SPAN, 2013). According to the International Water Supply Association (IWSA) survey, the major cause of water losses is leakage (Cheong, 1991; Salleh and Malek, 2012).

The water distribution pipelines in Malaysia were used since ten years ago, where almost 50% of the total water production was lost and contribute to unaccounted-for-water (AWWA, 1987). According to Salleh and Malek (2012), there are about 127,275 km in length of water pipe of various types in the whole of Malaysia. These pipes are of asbestos cement type (AC) of 44,282 km (34.80%), mild steel pipe (MS) of 29,372 km (23.10%), HDPE pipe of 22,111 km (17.37%), un-plasticised polyvinyl chlorine (uPVC) of 18,683 km (14.70%), ductile iron pipe (DI) /CI of 9,885 km (7.70%) and other types with total length of 2942 km (2.30%) (Salleh and Malek, 2012). Among 127,275 km of water pipelines throughout

Malaysia, the main reason for high physical loss of water are caused by leakage of these old water pipelines and dilapidated asbestos-cement (transmit) pipes where its pipe materials and structure are damaged due to aging, weathering and natural disasters like flood (Puust *et al.*, 2010). These water losses happen in mostly all old distribution pipelines, even for those that are appropriately managed and maintained. Some of these water losses are not detectable as the pipelines are buried underground and do not cause severe disturbance to the water services. Water losses from these leakages can be active for a long time if no immediate actions are taken. As days go on, it is resulting in high volumes of lost water which indirectly prompts out the issues of Non-Revenue Water (NRW) in Malaysia.

Table 1.1 shows the terminologies employed to evaluate the urban water supply system (Alegre *et al.*, 2000). Non-revenue water (NRW) can be defined as the difference between the volume of water put into a water distribution system and the volume that is billed to customers. NRW is comprised of three components, i.e. real losses, apparent losses, and unbilled but authorised consumption. Actual losses are determined by losses in the service infrastructure, from the raw water to the point at which the water reaches the final user. Apparent losses are associated with unauthorised consumption and metering inaccuracies. While unbilled but authorised consumption is associate with unbilled metered consumption and unbilled unmetered consumption. Water management for each city will be inefficient if the levels of water losses continue getting higher.

suitable for PVC pipe. This is because the acoustical attributes of leakage indicators in PVC and metallic pipes are different, where PVC pipes are "quieter" and don't transfer echo or fluctuation as capable as metallic ones. Issues that are usually faced by spotting leakage using acoustic devices, e.g. meddling activity signs, and exhaustion of leakage indicators along pipes, turn even worse for PVC pipes (AWWA and NRC, 2010).

The infrared thermography (IRT) method is based on detecting the temperature differences between the surroundings and piping systems. The thermal characteristics of soil adjacent to the pipe with a leak have a more massive heatsink compared with a pipe without a leak. Infra-red scanners are used to identify thermal anomalies above the pipes (Hunaidi *et al.*, 2005). However, the IRT method can only be used with pipe structure with liquid or gas that has a higher temperature than its surroundings, such as the pipeline system for hot water or steam. Various elements may affect the capability of this method, for example, cloud cover, solar radiation, ambient temperature and surface conditions of the test area (Burn *et al.*, 1999).

On the other hand, ground penetrating radar (GPR), a non-destructive image-based technique used for locating objects or interfaces buried beneath the earth's surface or located within a visually opaque structure was introduced. GPR can detect both metallic and non-metallic targets in non or partially-conducting host materials. It measures and maps changes in the complex dielectric permittivity in the ground as a function of depth for any particular observation point. The main operational advantage of this technique is that the radar antennae do not need to be in contact with the surface of the earth, enabling rapid surveying. Besides that, GPR has advanced with its penetration proficiency until a few meters into the subsurface (Puust *et al.*, 2010; Jaw and Hashim, 2011).

Ground penetrating radar technique produced a never-ending record or cross-sectional of subsurface options. Strategies like this are accustomed to discover leakage in water pipes by detection either signal distortion reflection from subsurface made by leaking water due to high moisture content around leakage area or by recognition of abnormalities of pipe deepness as measured by the measuring system.

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