EXPERIMENTAL AND ANALYTICAL STUDY OF INVISIBLE WATER LEAKS DETECTION USING GROUND PENETRATING RADAR

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ABSTRACT: Water pipes leakage is one of the problematic issues for current water industry. Leaky pipes not only lead to waste of precious natural resources (e.g.: non-revenue water), they create substantial damage to the transportation system and structure within urban and suburban environments as well. For solving this issue, many non-destructive geophysical techniques have been suggested as tools for detecting water pipes leakage, including electromagnetic or radio frequency devices, acoustic devices, gas sampling devices and pressure wave detectors. In this paper, the feasibility and implications of well-known geophysical tools (i.e. Ground Penetrating Radar) was evaluated through comparison of numerical modelling and physical work for water pipes leakage detection at real world. For this study, finite difference time-domain (FDTD) numerical modelling is used to simulate water pipe leakage condition for obtaining a comprehensive set of simulates images. These images were then compared with the data acquired at the selected site which contains leaky pipes for analysing the functionality of commercially-available Ground Penetrating Radar in detecting water pipes leakage. Through the distinctive signature of leakage of a 300 millimetre (mm) diameter fire hydrant ductile iron (DI/CI) pipe in the radar profile which generated from numerical modelling and acquired from selected site using Ground Penetrating Radar, it shows that the leakage zone is disturbed by the wave reflection caused by saturated soil as compared to the hyperbola signature of intact pipe in the radar profile acquired from both methods. Thereby, the good agreement of distinctive signature of water pipe leakage between the simulated radar profile and commercially-available acquired radar profile, proving that Ground Penetrating Radar is hence a useful geophysical non-destructive water pipe leakage detection approach. With such convincing results shown in this paper, it contributes new valuable addition to the implications of ground penetrating radar to the underground utility mapping industry other than utility detection and localization only.

1. INTRODUCTION

A large percentage of water is lost in many water distribution systems while transmitting from the treatment plant to the consumer. This lost or unaccounted-for water is known as non-revenue water (NRW). It is measured as the amount of water "lost" before it reaches the consumer as a part of the net water produced. The losses can be categorised into two categories, which are real or physical lost due to leaky pipe and apparent lost due to the issue of metering errors, or theft (Salleh and Malek, 2012; Suruhanjaya Perkhidmatan Air Negara, 2013). Moreover, water leaks can be further classified into visible leak or invisible leak. The visible leak is defined as water leak which can be detected by naked eye while invisible leak is defined as water leak which hardly can be detected by naked eye as most of the invisible leak occurs in the subsurface. The major cause for water lost or issue of unaccounted-for water according to survey done by the International Water Supply Association (IWSA) is due to water pipeline leakage (Salleh and Malek, 2012).

As proven by the inquiry made by SPAN in year 2013, the amount of lost or unaccounted-for water is typically 20 to 30 percent of total water production (Ghazali, 2012; SPAN, 2013). For some of the distribution systems in Malaysia where the pipeline systems are used since ten years ago, it achieved the amount of lost or unaccounted-for water for 50 percent of total water production (AWWA, 1987). Among these 127,275km of water pipe in 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 material and structure is damaged due to aging, weathering and natural disasters like flood (Puust et al., 2010). As such, the level of NRW in each states of Malaysia for year 2012 still yet to achieve the desired rate as shown in Table 1 where the issue of NRW remain a problematic issue for current water industry in Malaysia.

According to the article published by Association of Water and Energy Research (AWER), the total amount of financial loss due to wastage of water is estimated to be RM 1.6 billion (SPAN, 2011). It is clear that the tasks of reducing the NRW levels are hence daunting and challenging. In recent years, different geophysical non-destructive measurement techniques or tools has been adopted for locating water outflow of pipes. Among these, acoustic correlation analysis, infrared imaging technique and ground-penetrating measuring system survey are foremost well-liked (Ghazali, 2012). Acoustic strategies observe the sound wave generated by the outflow, use correlation analysis and wave rate within the pipe to pinpoint the outflow. This technique is widely used for metal pipes only as previous studies indicate that it's problematic once being employed for plastic pipes (Brennan et al., 2008). While for infrared imaging uses infrared camera to observe the thermal distinction caused by the temperature distinction between soil and water. This technique is simple to implement, however previous study shows that it'll fail once there's no temperature distinction. As proved by Fahmy and Moselhi (2010), when field experiment conducted by using mistreatment infrared camera in summer and winter, no sign of leak has been detected as there are no major temperature distinction between soil and water.

For this reason, more reliable geophysical tool, such as ground penetrating radar (GPR) was need indeed for underground water pipe leakage detection. Therefore, this study was conducted to analyse the functionality of ground penetrating radar in detecting underground water pipe leakages. GPR has been selected as the efficient non-destructive subsurface utility mapping tool due to its distinctive advantages which is non-sensitive to pipe material, pipe shape, seasonal effect and acoustic noise as compared to others geophysical tool (Jorge et al.,2010; Jeng et al.,2011; Jaw and Hashim, 2013). Moreover, GPR also well known for its advantages as remote damage detection techniques that is non-invasive and operational efficient, because it does not require direct contact with pipe or even ground. In doing this, a fieldwork to collect data 'leakage' is done in the realistic phenomenon of pipe leakage. A comprehensive set of B-scan radar profile was acquired using commercially-available GPR. Thereafter, numerical modelling was performed using finite-difference time-domain (FDTD) method to generate simulated GPR profile, which has similar parameter with the GPR profile obtained in fieldwork. Comparison of numerical modelling and physical work of underground water pipe leakage detection was performed for evaluating the feasibility and implication of this well-known geophysical device in detecting underground water pipe leakage

Table 1. Statistic of NRW level in each state of Malaysia for year 2011 and 2012 (Source: SPAN, 2013)

State	Year	
	2011	2012
P. Pinang	18.4	17.6
Labuan	22.0	20.4
Melaka	25.1	23.8
Johor	29.2	27.8
Perak	30.4	30.1
Sarawak	30.5	29.4
Selangor	32.3	33.1
Malaysia	36.7	36.4
Terengganu	37.0	36.8
N. Sembilan	44.6	40.4
Kedah	47.8	50.6
Sabah	50.9	49.9
Kelantan	55.7	53.9
Pahang	56.2	54.2
Perlis	59.8	66.4

2. MATERIALS AND METHODS

2.1 GPR System Description

A dual frequencies GPR system which commercially-available on the market, namely IDS Detector Duo (refers Figure 1) manufactured by IDS Ingegneria Dei Sistemi, was used in this study to acquire data at the selected site which suspected to have invisible pipeline leakages. A comprehensive set of data was acquired by using GPR system to scan along the direction parallel to the pipeline at the area with and without water pipeline leakage. This GPR system was selected to use in this study as it is impulse radar which consists of ground-couple radar where the antenna is directly in touch with the ground surface with frequencies of 250 MHz and 700 MHz, the optimum frequency for underground utility mapping which has footprint of approximately 60 x 37 centimetres (cm). With such design, it can minimise the environmental interference but increase the resolution and depth penetration. In addition, this GPR system can display the radargram of deep and shallow antenna on same screen simultaneously which allows real time results marking and determination of the data quality and position of the utility buried in subsurface. As such, it allows faster data acquisition with less manpower and time consuming. This is the major reason why IDS Detector

Duo was being selected as the principle investigation tool for detection of invisible water leaks in this study (refers Table 2).

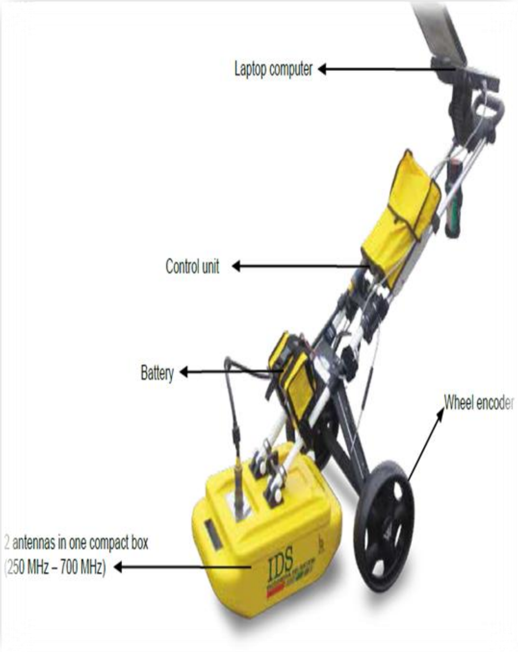


Figure 1: IDS Detector-Duo device with 250MHz and 700MHz antenna (Source: IDS, 2014)

Table 2. Technical specification for Detector Duo(Source: IDS, 2014)

Manufacture Company	IDS Ingegneria Dei Sistemi, Italy
Weight (with battery and without laptop)	15 Kg (33 Pounds)
Dimension/ size	68 x 80 cm
Survey speed	9 Kmh (5.6 Mph)
Weight	15 kg
Positioning	Metric wheel and/or GPS interface
Antenna Footprint	60 x 37 cm
Data collection type	2D (single antenna)
Number of antennas	2
Antenna Type	Ground-coupled, bowtie antenna
Antennas central frequencies	no. 1 at 250 MHz no. 2 at 700 MHz
Collection speed	100 scans/second
Sampling interval	2. 5 cm
Type of calibration gain	Automatic
Typical range	Automatic (128 nanoseconds)
Operating systems	Windows 2000 Pro / XP Pro

2.2 Data Acquisition

Two types of radar profile were used in this study, i.e. FDTD simulation radar profile and radar profile acquired by physical work at selected site which suspected to have water leak by using GPR system, where the information of water leak is provided by utility owner. For FDTD simulation data which executed in MATLAB® software based on leaky water pipe scene parameter settings, where the electrical properties information, such as dielectric permittivity (ε_r), magnetic permeability (μ), and electrical conductivity (σ) for each testing parameter was collected through literature search and laboratory testing. The empirical relationship between the testing parameter and its electrical properties of the targets are established as the GPR backscatter is the function of the electromagnetic properties (Reppert et al., 2000; Martinez and Bymes, 2001). Then, GprMax electromagnetic simulator was executed in MATLAB® to generate a comprehensive set of radar profile with/without leakage condition based on "ideal" condition with the assumption that the backfill soil materials are assumed to be homogenous. In this study, only 250 MHz GPR system was taken into consideration for the simulation after the preservation for its spatial resolution, penetration depth and system portability, as 250 MHz is the optimum operation frequency for most of the underground utility works according to the equation (1) provided by Pasolli et al. (2009).

$$\text{Signal wavelength, } \lambda = \frac{c}{f_m \times \sqrt{\varepsilon_r}} \qquad \text{Equation (1)}$$

where, ε_r represents the dielectric permittivity of the backfill material and $f_m = 3 \times f_{centre}$.

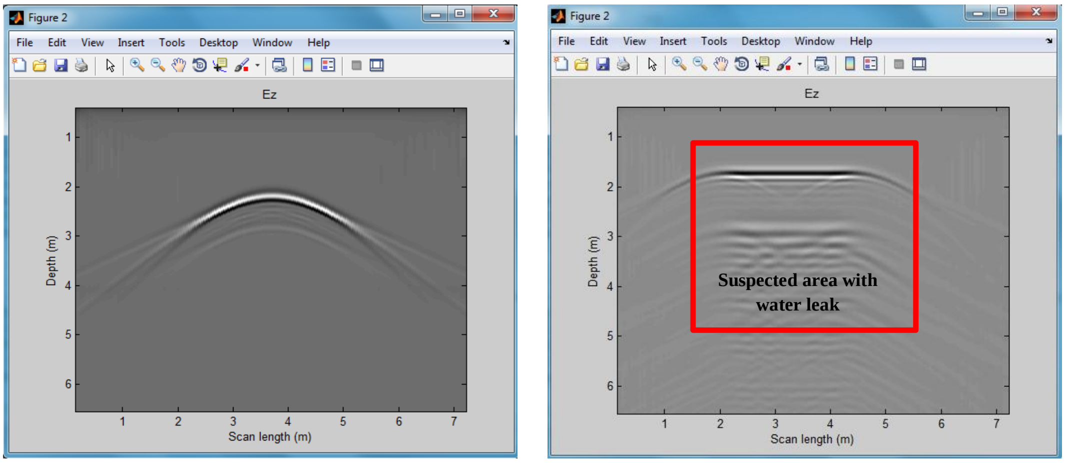
Thereafter, the selected GPR system (i.e. IDS Detector Duo) was used to acquire data under real world leakage situation at Port of Tanjung Pelepas (PTP) at Gelang Patah, Johor Darul Ta'zim. The IDS Detector Duo, dual frequencies GPR system is used to scan over the suspected site which contains water pipe leakage to acquire few sets of data as it has good system parameters with optimal frequency range which suitable for underground utility mapping. The GPR B-scan was then processed for further interpretation. The along-pipe scanning which mentioned earlier was used in the study throughout the data acquisition process. According to the work of Jaw and Hashim, 2013 and Hashim et al., 2010, along pipe scanning data acquisition technique is the best technique for field data collection as it has better detection accuracy and target detectability, as well as deeper depth penetration. Afterward, these comprehensive sets of data acquired at the selected site were subjected to further processing for image quality enhancement and unwanted echoes and background noise removal.

2.3 Data Processing

All the raw data which acquired at the selected site are subjected for some pre-processing where the image quality is improved and the unwanted echoes is removed. In doing this, the data were initially being correct its geometry where the depth of the data were aligned to the original depth at the site by correcting the time zero layer which may affected by poor site condition. Then, the unwanted background noises due to the ground waves were removed in the steps of background removal where better signal-to-noise and focused images were produced. After that, filter ranging from simple bandpass to sophisticated domain transform filter was used to filter the noises which arise in the horizontal and periodic direction and suppressed the noisy components which obscured the reflection of the targets. By using these “clearing” filters, the regions which have higher or lower frequency than the targeted signal bandwidth of GPR system (i.e. the peak of the GPR signal bandwidth) are removed. Lastly, the smooth and linear gains were applied for better visualization and image quality enhancement. Thereafter, the data collected at the selected site are ready for detection of invisible water leak by identified the difference of signal amplitudes between areas with/without water leaks.

3. RESULTS

A series of simulation images were generated using GprMax simulator, where only the best results for the simulation is shown in Figure 2 (a) and (b) to prove that usability and capability of GPR in detection of invisible water leaks, apart from underground utility position detection and localization. GPR is hence proved to be an efficient tool for detecting the area contains an invisible water leak which is hardly seen by naked eye. As seen in Figure 2 (a) and (b), the unique signature of intact pipe and leaky pipe can be differentiate easily as saturated or wet soil causes additional reflections, which will disturb the signature of the ductile iron pipe which is normally appear to be very sharp hyperbola or V-shape in radar profile. With such findings, it is confirmed that GPR is a potential to be used as an efficient investigation tool for leakage pipe detection.



(a) Intact pipe reflection (b) Leaky pipe reflection

Figure 2. Reflection signature for intact pipe and leaky pipe

4. DISCUSSIONS

Under the Ninth and Tenth Malaysia Plan (RMK9 and RMK10), Federal Government has allocated USD 0.95 billion and USD 0.35 billion respectively for implementation of various NRW programs to reduce the rate of NRW for duration of ten years. Almost 99% of the allocation has been spent specifically to upgrade all the water piping system throughout Malaysia (Economic Planning Unit, 2006 and 2010). However, it is still hard to achieve the nationwide NRW target of 25% by year 2020 as the current national average rate of NRW is fluctuating in the range of 37.7% to 38.5% from year 2007 -2010 (National Audit Department, 2011). As the money spend not for the root of the problem, water leaks is still remain as the main reason contributing to the issue of increasing NRW rate at each states in Malaysia. According to the report of Hatimuda Sendirian Berhad, consultant for Syarikat Air Negeri Sembilan Sdn Bhd (SAINS), the problem of real losses is contributing most of the percentages for water losses is due to leakage of transmission/distribution system (5.0%), reservoir overflow (1.4%) and service pipes (9.0%) as compared to the apparent losses due to unauthorized consumption (1.0%) and meter inaccuracies (3.7%). An effective monitoring system for water piping system is therefore needed urgently as an efficient NRW reduction strategy to show the effectiveness for managing the water loss.

For this reason, this study is therefore conducted to evaluate the feasibility and implications of GPR in detecting invisible water leaks, as the invisible water leaks is hardly seen by naked eye. The physical work of water pipe leakage detection was conducted at PTP using commercially-available dual frequencies GPR system for results validation purposes. The results obtained from the physical work at real world were surprisingly good as it is in agreement with the results obtained through numerical modelling simulation under "ideal" condition. It is hence proven that GPR is an underground close-range sensing tool that can efficiently detecting the water leak (refers Figure 3) among the available non-destructive technologies. With such convincing results obtained by both simulation and practical works, together with adequate technical understanding, it can improve operational efficiency in detecting and locating the invisible leaky pipe which are able to contribute to reducing the NRW rate through maintaining the volume of system input and increasing the billed authorized consumption.

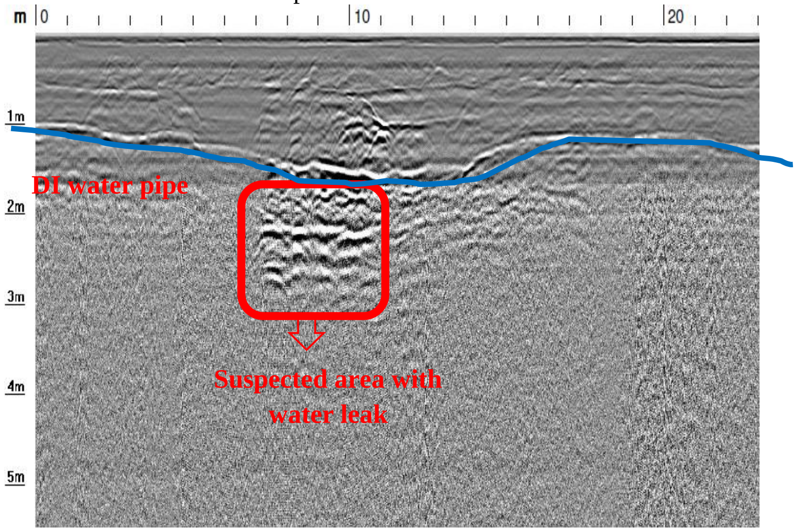


Figure 3: Results of passive water leak detection under real world conditions

For further validation, excavation was conducted immediately at the area which suspected to have water leaks through the observation done using the GPR system. The leak was found at the hydrant water pipe (see Figure 4 (a) and (b)). Subsequently, the results proven that the existing GPR has the potential to be used as an efficient geophysical measurement tool which contributing unlimited benefits for current subsurface utility mapping industry as it opens up new facility to the application of existing GPR system with just detecting the position and depth of the buried utilities. GPR is hence useful for conducting subsurface utility condition assessment, particularly water leak in the near future.


(a)Leak found at the area detected using GPR


(b)Water losses

Figure 4: Leak found during excavation

5. CONCLUSION

With the convincing results obtained from this study through the experiment and practical work conducted for evaluating the feasibility of GPR for detecting the invisible water leak, GPR is certainly has the potential to be the top geophysical measurement tool for water leak detection purpose. By using these results, perhaps GPR is eligible for invisible water leak detection where the backscatter amplitude can be used as the indicator for reporting the utility condition or status, particularly the defects of subsurface utility pipes or cables due to aging and weathering.

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