DETECTION AND MAPPING OF SUBSURFACE UTILITY USING GROUND PENETRATING RADAR

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ABSTRACT: Ground penetrating radar (GPR) has been widely used in subsurface utility mapping. By using this non-destructive sensing tool, it can reduce the social inconvenient (traffic rerouting, noise, etc) especially in urban, industrial and environmentally sensitive areas during excavation. In subsurface utility mapping application, ground penetrating radar is used for extracting location, depth and others reliable information of the subsurface utility. However, the capability of these ground penetrating radar system which permits the characterization of subsurface objects made from different types of material is not fully exploited for material recognition purposes. In addition, the precise position (x, y and z) and material type's records of the subsurface utility are not having priority in subsurface utility mapping. The main aim of this paper is to report on results of study undertaken in using ground penetrating radar for retrieving subsurface utilities position and material type of these features are made of. The study focuses on subsurface utility mapping accuracy and to retrieve utility feature based on the backscatter characteristics. Results of this study indicated that commercial type reflective GPR system could achieved mapping accuracy (x, y and z) of RMSE $\pm$ 0.10 m, complying to Quality Level A utility data requirement. The study also confirmed good agreement between GPR backscatters with respective utility feature types using image thresholding. Hence, this could be used to report on the utility status or conditions, such as defects of pipes or cables due to aging and weathering.

1. INTRODUCTION

Rapid population growth increases the demand for basic utility service such as electricity, water, gas, telecommunication and even internet services. More and more utility pipeline are buried in the shallow subsurface along the pathway to serves as the basic resources for sustaining urban life of most of the people. This forming a labyrinth networks of underground structures lay underneath today's city street especially in urban, industrial or environmentally sensitive areas. With such underground saturation environment, the stakeholders from utility industries often having difficulty in determining the location and depth of these utility during maintenance and rehabilitation of deteriorate utility. For this reason, the stakeholders have aggressively maintaining these utility record based on the information supplied through continuous on-site trial hole investigations. However, most of these records are inaccurate, incomplete and out of date because many of today's utility have been laid underneath the streets since very long ago and the records of these utility are based on sketching from field observation only. In this sense, different trenchless techniques such as pulsed induction (inductive line location, inductive line tracer, conductive line tracer and passive line tracer), magnetic location (magnetic locator), electromagnetic (Ground Penetrating Radar and Electromagnetic locator), resistivity (resistivity locator) and acoustic (acoustic pipe tracer and pipe cable locator) are widely used for locating these buried utilities without excavation (Ni et al., 2010, Roger et al., 2009 and Cist et al., 2001).

Among these trenchless techniques, ground penetrating radar (GPR) which has been claimed as the top choice for underground investigation application are widely used in detecting, scanning, marking and locating the buried utilities. It is commonly used for retrieving the position and depth of the utility in most of the utility mapping projects. However, the data acquisition of utility mapping is used with no specified investigation for determine its achievable accuracy and target detectability. The stakeholders from the utility industries do not concern about the degree of locational accuracy and potential detection errors in utility mapping. They even tend to overlook the severity of neglecting the achievable accuracy in utility mapping practices. In this sense, the problems of utility mislocation are remains and become worst as day goes on. It has causes many cases of utility downtime, property damages, service breakdown and even injuries and lost lives to the nation and country (Metje et al., 2007).

Furthermore, the application of GPR in utility mapping is not fully utilized as it has been used for retrieving position and depth of the buried utility only. This leads to misunderstanding where GPR is only capable for extracting position and depth of the buried utility. However, the extraction of various parameters (depth, radius, spatial

orientation and the relative permittivity) of the buried utilities can be done based on the geometry of the objects (Ristic et al., 2009). In addition, the development of the non-destructive technique for underground investigation is somehow unexplored except for retrieving the position and depth of the buried utility. Most of current techniques do not come along with feature extraction package, users are unable to explore and retrieve more information from the underground. This rises up few issues in utility mapping application whether GPR is eligible for performing detailed mapping including feature detection/location, material recognition, dimension estimation and shape estimation. All these issues are still remain open for research in the future (Pasolli et al., 2009).

As the detection of buried utilities among a bunch of utility networks in complex environment becomes very tough, subsurface utility detection and mapping has become more challenging. In this context, the problems stated above were significantly leading to the needs of this study to be carried out. The aims of this study were to report the achievable accuracy of utility detection and material type recognition based on the hyperbola reflection recorded in the radargram. This is to correct the misconceptions in utility mapping industries which claimed that GPR is only for retrieving the position and depth of buried utilities. In doing this, a comprehensive set of data were acquired using dual frequency GPR system. These data were then subjected to pre-processing for removing the unwanted echoes and enhanced its visualization for producing a better focused image before feature identification was carried out. The results from this study highlights the confidence level of accuracy achieves in utility detection and indicates that GPR is entitled for material recognition in utility mapping. This information is crucial for development of the non-destructive techniques in the future as there is currently a growing interest by both private and government bodies related to widen the application of GPR for subsurface utility detection and mapping purposes.

2. SUBSURFACE UTILITY DETECTION AND MAPPING

2.1 Subsurface Utility Mapping Standard

There is a series of utility mapping guidelines provided by each country's local authorities such as Department of Survey and Mapping Malaysia (JUPEM) in Malaysia and American Society of Civil Engineers (ASCE) in United States. These operation guidelines need to be used by stakeholders (surveyor, utility owner, urban planner, decision maker, streetworkers etc) from around the world during utility mapping. In this operation guideline, it shows the requirement for subsurface utility mapping, quality level of the underground utility data, the role and responsibility of the stakeholders in subsurface utility mapping, the formation of utility maps and the development of the Underground Utility Database (or so called PADU). According to this guideline, the utility data acquired from utility mapping can be classified into four classes including Quality Level A, B, C and D. For Quality Level D, C and B, the accuracy requirement of the utility data is not specific, whilst for Quality Level A utility data, the accuracy of data acquisition is 10 cm or better for vertical and horizontal. This classification scheme is used for preparing final output of utility mapping for centralized underground utility database. With such standardize database, it will allows the project owner, engineer, constructor and utility owner to develop strategies to reduce risk by improving the reliability information on existing subsurface utilities in a defined manner. The catastrophic damage to the subsurface utilities which lead to interruption of utility services resulting from the "blind" excavation can be reduced or minimized as well. As such, this again emphasise the importance of knowing the accuracy of utility detection and the necessity of this study to be carried out.

2.2 GPR Imaging

In each GPR scanning, the transmitter of the GPR will transmits electromagnetic wave to the subsurface. Once the electromagnetic wave strikes with an interface of different dielectrics, a portion of the wave is reflected back to the surface and recorded by the receiver. The time delay which recorded by the receiver is somehow effected by the dielectric permittivity of the mediums. As such, even if the electromagnetic wave travels through the mediums with different electrical properties in same distance, the travel time recorded by the receiver is different. The signal that reflected back to the receiver is the information used for generates a radar scan by forming hyperbola reflection. In other words, these hyperbola reflections are so called backscatter amplitudes. When the antenna moves from X_a to X_b, by joining each end point of the lines which are orthogonal to the antenna's trajectory (X_J), it will form a hyperbola geometric shape. This is how a hyperbola arc is generated. These hyperbola arcs are then can be used for utility detection purposes with relating to its backscatter amplitudes. While the shortest line Y_k (hyperbola apex) in a radar scan is represents the depth of the target referring to Figure 1.
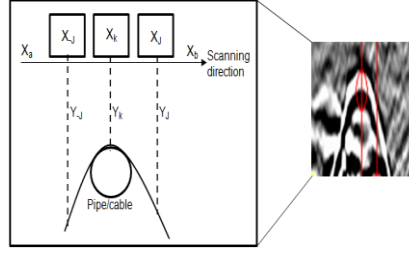
Figure 1: Formation of hyperbola arc

In each radargram, it contains of the backscatter amplitudes information which serves as the parameter that determined the electromagnetic discontinuity of the target. By using these backscatters amplitude, the geometric (radius/ shape) and radiometric (material type) of the utility can be estimated. The backscatter amplitude can be computed using equation (1) as stated by Toropainen (1995):

$$\sigma_{cp} = \sigma_{s\perp}\left[\frac{1-\exp(-2\sigma_t d)}{2\sigma_t} + 2[\Gamma_2]^2 d\exp(-2\sigma_t d) + \frac{|\Gamma_2|^4}{2\sigma_t}\exp(-2\sigma_t d)(1-\exp(-2\sigma_t d))\right] \qquad (1)$$

where Γ_2 represents the coefficient for reflectance from lower surface, σ_t represents the cross-section of the material which shows the power of scattering and absorbing. Referring to equation (1), the first term is the backscatter of the incident wave, the second term is the lower surface forward scattered wave and the third is the reduced incident wave backscatter that reflected from lower surface and incident wave position. In most of the situation, the third term is normally being neglected as its value is too small (power of 10 to the material, independent of Γ_2). In this sense, there is lack of articles in reporting the influences of different materials to GPR image formation relating to its backscatter amplitudes although this is the important parameter which determines the formation of the radargram. This is because GPR is only used for retrieving the position and depth of buried utility in current utility mapping industries. For this reason, this study is worth to be carried out for reporting the results of materials recognition in relation to backscatter amplitudes of the buried utilities.

3. MATERIALS AND METHODS

3.1 Data Acquisition

In this study, dual frequencies GPR system was used to scan over the test site due to its optimal frequencies (250 MHz and 700 MHz) that was suitable for real time underground detection and interpretation. This test site was specially designed to mimic the current situation of underground structure in the real world. There are nine different material types (manufacture material of utility features) and sizes (radius) utility being buried in various depths (refers Figure 2). During the data acquisition, HH polarization was used throughout the study using along pipe scanning. The scan lines consisted of A_1 to A_1', A_2 to A_2', A_3 to A_3', A_4 to A_4', A_5 to A_5', A_6 to A_6', A_7 to A_7', A_8 to A_8' and A_9 to A_9' where each scan line was along the direction of the utilities. The direction of the scan lines was shows in Figure 2.

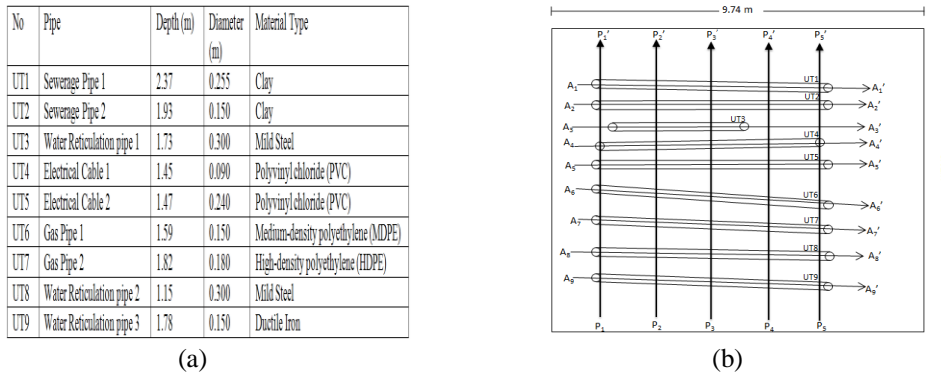| No	Pipe	Depth (m)	Diameter (m)	Material Type
UT1	Sewerage Pipe 1	2.37	0.255	Clay
UT2	Sewerage Pipe 2	1.93	0.150	Clay
UT3	Water Reticulation pipe 1	1.73	0.300	Mild Steel
UT4	Electrical Cable 1	1.45	0.090	Polyvinyl chloride (PVC)
UT5	Electrical Cable 2	1.47	0.240	Polyvinyl chloride (PVC)
UT6	Gas Pipe 1	1.59	0.150	Medium-density polyethylene (MDPE)
UT7	Gas Pipe 2	1.82	0.180	High-density polyethylene (HDPE)
UT8	Water Reticulation pipe 2	1.15	0.300	Mild Steel
UT9	Water Reticulation pipe 3	1.78	0.150	Ductile Iron

(a)　　　　　　　　　　(b)

Figure 2: (a) The details of the buried utilities, (b) The direction of scanning for data acquisition.

3.2 Data Processing

3.2.1 Data Pre-processing: In data pre-processing, the remove start time was first take place to align the depth scale of the acquired data to the actual position of the investigated area. In this steps, the signal-to-noise ratio (SNR) is improved. Then, the background removal process was done using Clear-X filtering algorithm. It is to remove the

unwanted reflection caused by the non-targets such as sands, rock or cavities along the X-axis as these noisy components often appear in horizontal and periodic in a radargram (Kim et al., 2007). After that, bandpass filtering was applied to remove the noise outside the specific region of the target's interest especially the region where the frequency was lower or higher than the main GPR signal bandwidth that defined by users (Jol, 2009). Lastly, the linear and smoothed gain functions were applied to the radargram based on the mathematical or multiplication operation that defined by the system itself or by the users. Then, the data was now ready for interpretation and analysis. The utility features can be easily identified from the radargram based on the user's prior knowledge regarding the embedded utility features.

3.2.2 Assessment: Three sample points of each detected utility were selected for root mean square error (RMSE) assessment. It was to determine the achievable accuracy of each data acquisition scanning technique based on the observed and computed position and depth of the detected utility. In order to compute the RMSE value for both planimetric position and depth, equation 2 is used (Reyes et al., 2010):

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left|observed_i - computed_i\right|^2} \tag{2}$$

Where N= number of points observed

3.2.3 Thresholoding Segmentation: The backscatter amplitudes of the detected buried utilities were retrieved from the reconstructed radargram. This technique was applied to select the optimal backscatter amplitudes value for the detected utilities. The backscatter amplitudes of each buried utility were separated from its complex background based on the image grey level histogram as the histogram thresholding works very well when the image grey level histogram is bimodal or nearly bimodal (Orlando et al, 2002). The range of the backscatter amplitude which belongs to the particular buried utilities features was selected using the rule where difference in threshold values (T) in successive iterations is smaller than T_0 (Initial T to start the iteration). The thresholded images were then produced using the criteria below:

```
for jj=1:row
    for kk=1:col
        if I(jj,kk)>=T₁± σ₁
            I(jj,kk)=0;
        elseif I(jj,kk)>=T₂± σ₂
            I(jj,kk)=0;
        elseif I(jj,kk)>=T₃± σ₃
            I(jj,kk)=0;
        elseif I(jj,kk)>=T₄± σ₄
            I(jj,kk)=0;
        elseif I(jj,kk)>=T₅± σ₅
            I(jj,kk)=0;
        else
            I(jj,kk)=255;
        end
    end
end
```

Table 1: Thresholding value for different material

|	Minimum	Maximum	Mean	Standard Deviation
PVC	-0.9858	-0.4537	-0.7252	0.0231
MDPE	-0.2386	0.2151	-0.0020	0.0289
HDPE	-0.1392	0.2569	0.0684	0.0255
MS	-1.3559	-0.8282	-1.0812	0.01724
DI	-0.5447	-0.3030	-0.4217	0.0203

Where T = threshold value;
T_1-T_5 and σ_1-σ_5= Value for thresholding by referring to Table 1
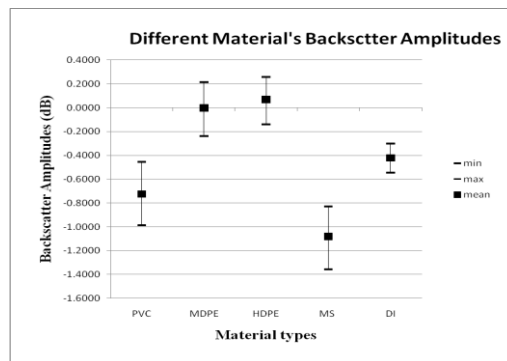
4. RESULTS AND DISCUSSION

4.1 Results

Figure 3 shows the results obtained from this study. The cross-section of the utility detected at various depths was represents by the circles in Figure 3(a).
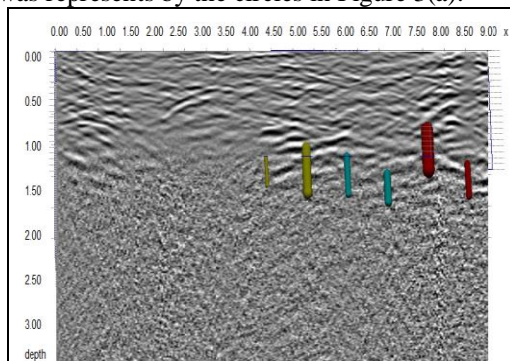
(a) (b)

Figure 3: (a) Target detected from radargram, (b) Backscatter amplitudes value according to utility material type

4.2 Discussion

According to the results of this study, the penetration of the GPR system is limited at first 2 m due to the effects of soil moisture as the test site is located in high water table areas. The percentage of soil moisture was directly proportional to the dielectric permittivity of soil and the signal penetrating power. This is proved by (Motoyuki et al., 2001 and Lunt et al, 2005) where the variation in soil moisture often affects the subsurface dielectric permittivity. While in term of RMSE errors of the sample points for each utilities, the data obtained using along pipe scanning is equivalent to Quality Level A (accuracy within the range of +/- 0.10 m) utility data as the accuracy for planimetric position (x,y) and depth were +/- 0.08 m and +/- 0.09 m. The paired samples t test was carried out to proof that there was insufficient of evidence to prove that the computed value and observed value of a sample point was different because $p= 0.632$ and 0.082 for planimetric position and $p=0.680$ for depth. The finding of this study was hence significant to the stakeholders in utility mapping industries. By knowing the accuracy of utility mapping, it can reduce the problem of mislocating buried utilities. More recently, about 15% of the users from the electricity company suffer from electricity interruption causes by third party damage due to "blind" excavation. By providing the accuracy information for excavation, the utility construction fees which were about USD 13.0 billion in Malaysia and USD 2.45 billion in UK according Economic Planning Unit (2006) and McMahon et al., (2005) can be reduced. The results of this study once again emphases that it was important to know the achievable accuracy of subsurface utility mapping using GPR especially during excavation works in complex environment consists of a bunch of utility networks.

Whilst in term of extraction of backscatter amplitudes of the detected utilities, the types of detected utilities were confirmed by in-situ verification and blueprint of the test site. This study proved that GPR is usable for subsurface utility mapping as it can provide comprehensive information of the buried utilities without excavation but through field verification and combining the non-destructive testing (Chen et al., 2010). Moreover, image thresholding was then used to select the optimal range of backscatter amplitudes value which belongs to each detected buried utilities (refers Figure 4). From this range, user can easily distinguish the types of utility except for MDPE and HDPE as both of them are from the same polyethylene category and what is difference between among them was its density and branching. The backscatter amplitudes were therefore nearly similar. This result shows that basic processing using the Commercial Off-The-Shelf (COTS) products that commonly used was insufficient for feature identification in current utility mapping industries. This was because the existing GPR system or processing tools do not have material recognition function. The stakeholders tends to overlook the role of backscatter amplitudes in feature interpretation as the interpretation and processing work in current utility mapping industries is much depending on operator's experience, skill and prior knowledge of the utilities during field observation. However, results from this study can be used as the reference developing new GPR system or processing tool which can identify the "feature information" in the future. This indirectly increases the value of these COTS products in the utility industries especially to the software developers.
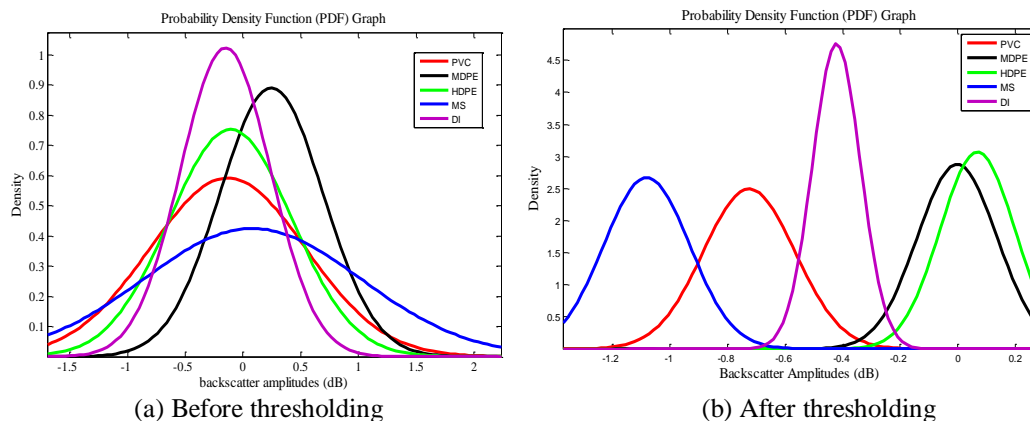

(a) Before thresholding   (b) After thresholding

Figure 4: Backscatter amplitude probability density function for different utility's material types

5. CONCLUSION

This paper is reporting on the results of study undertaken in using ground penetrating radar for subsurface utility detection and mapping in retrieving the position and material types of these utility made of. The findings of the study successfully clarified the ambiguities and doubts in the utility mapping industries as it able to pin-point the accuracy can be achieved in utility detection and to extract the backscatter amplitudes of the buried utilities with relating to its material types. In addition, the optimal threshold produced from image thresholding in this study also provides new finding to improve the existing processing tools and GPR available in the market in term of feature

material recognition. By using these finding for further interpretation, perhaps GPR is eligible for shape or dimension recognition and the backscatter amplitude can be used for reporting on the utility status or conditions, such as defects of pipes or cables due to aging and weathering.

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