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Urban Underground Pipelines Mapping Using Ground Penetrating Radar

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Abstract. Underground spaces are now being given attention to exploit for transportation, utilities, and public usage. The underground has become a spider's web of utility networks. Mapping of underground utility pipelines has become a challenging and difficult task. As such, mapping of underground utility pipelines is a "hit-and-miss" affair, and results in many catastrophic damages, particularly in urban areas. Therefore, this study was conducted to extract locational information of the urban underground utility pipeline using trenchless measuring tool, namely ground penetrating radar (GPR). The focus of this study was to conduct underground utility pipeline mapping for retrieval of geometry properties of the pipelines, using GPR. In doing this, a series of tests were first conducted at the preferred test site and real-life experiment, followed by modeling of field-based model using Finite-Difference Time-Domain (FDTD). Results provide the locational information of underground utility pipelines associated with its mapping accuracy. Eventually, this locational information of the underground utility pipelines is beneficial to civil infrastructure management and maintenance which in the long term is time-saving and critically important for the development of metropolitan areas.

1. Introduction

For better urban landscape design for space saving and wise use of land resources in the densely populated urban areas, most of the utility owners choose to bury their utility pipelines in the road shoulder within the depth of 3 meters or less under today's city street [1]. As such, current underground space are characterised by different types of utility pipeline, including fiber optics, electrical cables, water reticulation pipe and etc. As the demand for utility service increases, more and more utility pipelines being buried, mapping of underground utility pipelines become tougher and tougher due to the problem of utility pipelines saturation in the underground spaces. Mapping the underground utility pipelines for retrieving its as-built location is, hence, a challenging task, where stakeholders often having difficulty in retrieving the accurate as-built location of the underground utility pipelines for updating the urban underground cadastral database, not to mention for reporting the current condition of the pipelines.

With this regard, underground mapping, currently an engineering practice for scanning, detecting and locating of underground infrastructure, particularly the utility pipeline is introduced for retrieving the location of these buried underground utility pipelines utilizing non-destructive sensing tool without proving excavation [2]. Among these non-destructive sensing tool for underground utility pipelines mapping, ground penetrating radar has been selected as the top non-destructive sensing tool for underground utility pipeline mapping due to its good performance in providing high resolution imagery, fast and cheap data acquisition [3-4]. However, there are limited published work has been conducted in understanding the right approached for mapping the underground utility pipelines as

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well as investigating the locational accuracy for underground utility pipeline mapping using ground penetrating radar [5]. In this regard, many cases of undesirable accident caused by failed excavation in response to imprecise utility pipeline mapping has been reported annually. This failed excavation has led to the third party's pipeline damage which cost USD 12.9 billion (Malaysia), USD 83 million (United States) and USD 227.4 million (United Kingdom) for construction work [6].

Referring to such annual loss statistic due to failed excavation, it showed the importance of accurately mapping of underground utility pipelines. The as-built information of these buried utility pipelines is, hence, essential for update the underground cadastre database for ensure better planning of urban's infrastructure. With such up-to-date database, it can avoid accidents due to mislocation of utility pipeline that putting the population at risk, apart from reducing the losses brought by a third party's pipeline damage [7-8]. In this sense, acquiring accurate as-built information of the buried utility pipeline is always important and should not be taken lightly, as it relates to the safety living of a city.

Therefore, this study was conducted to acquire the as-built information of underground utility pipelines using the most popular non-destructive sensing tool, namely ground penetrating radar (GPR), without the need for excavation. In doing this, GPR system with 250 MHz and 700 MHz frequencies was used to acquire data at the selected sites, and numerical modelling analysis was used to validate the locational information of the buried pipelines, without requiring much effort to explore the nearest manhole for accuracy assessment as is commonly done in the conventional way of underground utility mapping. The finding of this study reported the geometric information of the buried pipeline together with its mapping accuracy. With such findings, it can provide the accurate as-built information of the buried pipelines in term of three-dimensional (3D) format in response to the concept of digital earth. Furthermore, this work also provides a time and cost effective way of underground utility pipeline mapping in the densely populated urban area with less disturbance to the neighbour traffic and business activities. By having the accurate geometric information in term of the planimetric position (x, y) and depth (z) of the underground utility pipelines and knowing the operating procedure for mapping, it is essential as the input for the urban underground cadastre database- an indicator for safe excavation during utility pipelines maintenance and management.

2. National Underground Utility Pipelines Database

Urban land resources are extremely limited in response to rapid urbanization and population growth as well as the development of the industrial sectors [1]. In order to address the problem of land shortage in the densely populated urban area, the utility owner is going deeper to the underground spaces for installing the utility pipeline. For this reason, all the information regardless of geometry or land unit data of these utility pipelines need to be updating to the current cadastre system, in two-dimensional drawing. As days go on, these underground utility pipelines information need to be acquired in 3D format, adopting for the 3D cadastre database system in most of the cities as a key development towards digital earth. In this sense, the x, y, z coordinate for the utility pipeline is vital for understand the 3D cadastral registration in the 3D cadastral databases, which contains the entire information for property located on the surface as well as infrastructure within the shallow subsurface.

However, most of the utility pipelines have been buried since a long time ago, where the record of these buried utility pipelines is not archived. Furthermore, the poor documentation of utility records within the industry and submission of proposed or schematics plan instead of the as-built plan of the buried utility pipeline has lead to the risks of accidents when contractors excavating the ground to replace aging pipeline or install new pipeline using manual and machinery methods. For this reason, contractor often hit or damage third party's pipeline during excavation as they could not "see" the existing utility pipelines unless remarkably precise location of the existing utilities is provided.

The efforts of protecting the underground utilities are, therefore, cannot be underestimated although the underground utilities are invisible to the public. In this context, precisely acquiring the reliable geometric information of the underground utility pipeline is needed before any excavation tasks take place. With regard to this, selection of right non-destructive geotechnical approach for underground utility pipelines mapping is critical as it directly determine the data quality and final output obtained. The underground utility pipeline data can categorise into four quality level (i.e. A to D). The quality level decreases from A to D where quality level A data contains the best mapping accuracy (i.e.: within ± 10 cm or better in planimetric position and depth) [9-11]. All the utility pipeline data that provided by the utility companies need to be compile and input into a national underground utility pipeline database. This database (refer figure 1) is developed for managing the utility data in systematic manner using Geographical Information System (GIS) approach with referring to the standard guideline for underground utility pipelines mapping [12].

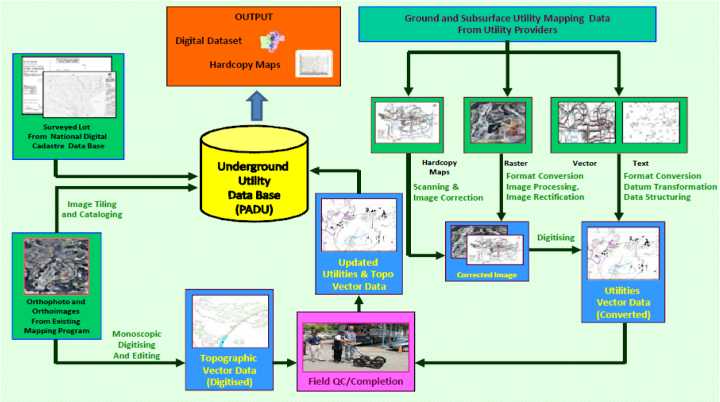


Figure 1. Example of national underground utility pipelines database developed in Malaysia (Source: Jamil et al., 2012).

3. Methodology

In this study, a commercially available GPR system with 250MHz and 700 MHz frequencies was employed to acquire data at the preferred test site that purposely built to mimic the true mechanical structure of the underground space. This GPR system was selected as it contains good system parameters and optimal frequency range that suit for underground utility pipelines mapping [13]. Throughout the data acquisition, along-pipe data acquisition scanning technique with HH polarization was used. This is because along-pipe scanning technique has excellent performance in target detectability and penetrating power as well as its capability in providing highest accuracy utility data, complying to the requirement of quality level A utility data [5, 14]. The same system where then used to acquire a comprehensive set of validation data under real world condition at selected site. Then, the entire data that acquired were subjected for pre-processing in order to enhance image quality and remove unnecessary echoes caused by background noise. The selection of pre-processing steps to be undertaken in the study were based on the researcher's personal preferences and data processing experience. In fact, different routines of pre-processing steps can be adopted as well according to user's preferences and experiences relating to types of GPR system being used.

Thereafter, the root-mean-square error (RMSE) for the sampling points that picked randomly according to Nyquist sampling criteria was computed for accuracy assessment. Equation 1 and 2 was used to compute the RMSE [15-16]:

$$\mathrm{RMSE}_{xy} = \sqrt{1/N\left(\sum_{i=1}^{N}\left(rx_i^2 + ry_i^2\right)\right)} \qquad (1)$$

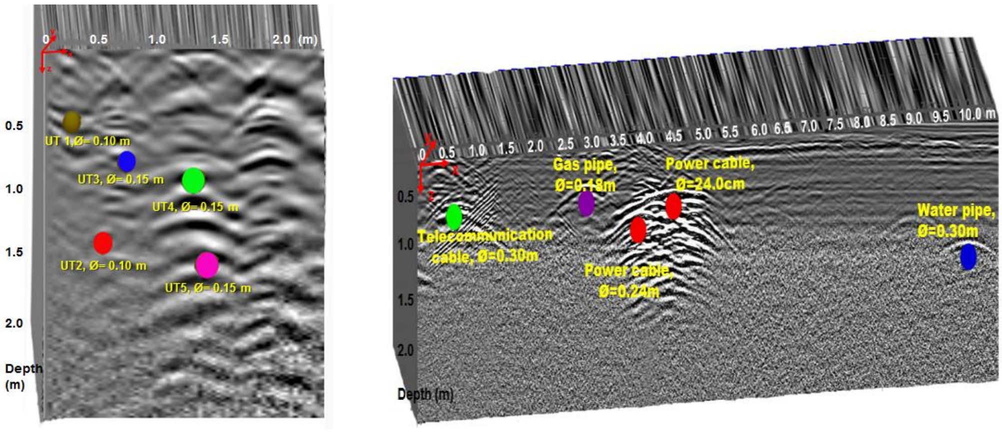
$$\mathrm{RMSE}_{Z} = \sqrt{1/N\left(\sum_{i=1}^{N}\left|Z_O - Z\right|^2\right)} \qquad (2)$$

where,

the number of points observed refer to N; residual of a sample point refers to rx_i, ry_i; observed depth refers to Zo, and computed depth refers to Z. By computing the RMSE of each sampling point, the locational accuracy (i.e. the underground utility mapping achievable detection accuracy), can be known. Then, numerical modelling analysis using Finite-Difference Time-Domain (FDTD) method was conducted for validation of the location information obtained from the data acquired at the test site and under real world condition. A series of simulation image were reconstructed based on the structure of the test site using theoretical assumptions of different utility's electrical and magnetic properties, such as the dielectric permittivity, magnetic permeability, and electrical conductivity. This simulation imagery was generated to validate the actual locational of each utility pipeline under "ideal" condition assuming that the surrounding medium were homogeneous, in order to minimize the effects of the surrounding medium to penetration of GPR signal.

4. Results and Discussion

Based on the RMSE computation of the selected sampling points, urban underground utility pipeline mapping using GRP yielded detection accuracy within ± 10cm, equivalent to the quality level A utility data. The result of target detection was shown in figure 2 while the summary of the mapping performance of GPR was summarised in table 1. The findings once again proved that the along-pipe scanning GPR data acquisition approach, which is rarely practises, surprisingly gives very superior performance for densely populated urban underground pipeline mapping. This can be included as reference for preparing a standard operating procedures for current underground utility mapping profession as using the right approach for data acquisition and the location accuracy are the basic requirement for the underground utility mapping task [17].



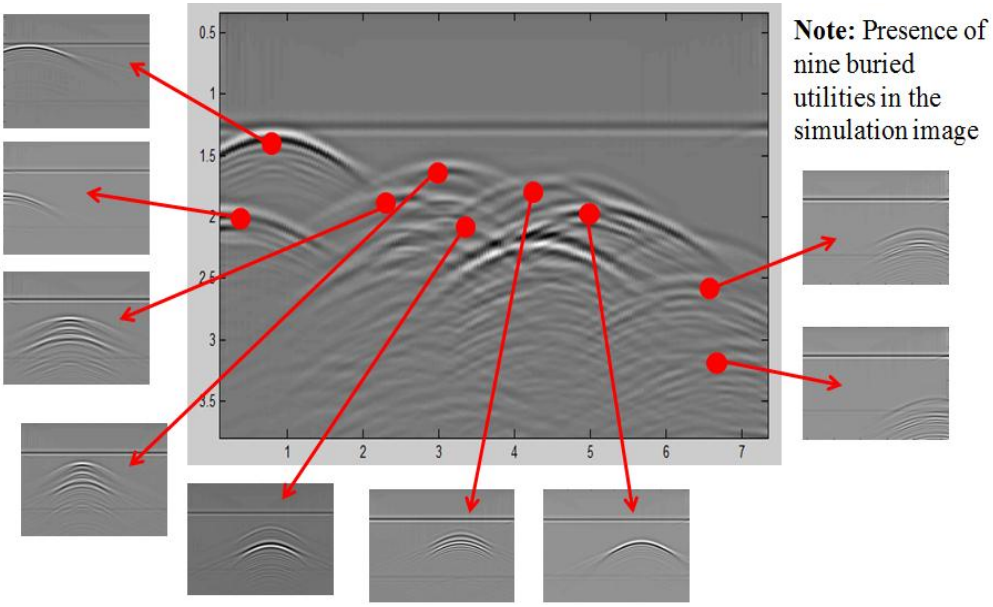
(a) (b)

Figure 2. Target detectability result for (a) physical data acquired at preferred test site; (b) validation data acquired at seleteced site under real world condition.

Table 1. Summary of Performance for data acquired under different conditions.

Study Area	**Target Detected**	**RMSE (m)**	
		Planimetric position (x, y)	**Depth (z)**
Physical data acquired at preferred test site	5/5	± 0. 086	± 0. 070
Validation data acquired at seleteced site under real world condition	6/8	+ 0.098	+ 0.095

According to the numerical modelling analysis, when the utility feature were buried too close to each other, one of the utility features may “missing” from the image (refers figure 3). The hyperbolic pattern of this feature was difficult to “see” in the image because the reflectance was obscured by the hyperbolic pattern of neighbouring utility features and this influences the detection results of the mapping project. However, with the aids of numerical modelling analysis, the hyperbolic pattern of each buried utility can be easily distinguished from its background (refers to small illustrations in figure 3). With regard to this, development of “best practise” procedure for determining the safe buffer zone for the maintenance works of utility pipeline, especially during installation of new utility pipeline and detection of aging pipeline, which buried since long ago is required. With such safe buffer zone between the utility pipeline, it can facilitating the task of underground utility pipeline mapping, particularly in the densely populated urban area and can avoid damaging third party’s utility pipeline during the maintenance routines using machinery.



Note: Presence of nine buried utilities in the simulation image

Figure 3. Utility pipelines that buried too close to each other, causes confusion in target detection and influences output of the underground utility pipeline mapping.

Furthermore, the demand of new utility services is booming locally and internationally in response to urban expansion. For this reason, more and more utility pipeline is installed within the limited space beneath the city’s street to support this massive demand from the public. Thereupon, difficulty in mapping the buried pipelines within the crowded underground infrastructure arrangement creates the need to establish well-written standard operating procedures (SOPs) to ensure the safety and operational efficiency of the underground utility pipeline mapping. With satisfactory results contributed by this study, it brings significant benefits to the development and use of SOPs are an integral part of a successful national underground utility pipeline database system in the future as it provides individuals with the information to perform a job properly, and facilitates consistency in the quality and integrity of a product or end-result.

5. Conclusion

This study was to conduct underground utility pipeline mapping using current well-known trenchless technologies – GPR in determining its target detectability and locational accuracy. With good practise of underground utility mapping, the surveying work of acquiring precise 3D utility data will become more efficient and failed excavation due to inaccurate utility information can be avoided. This good practise of underground utility pipeline mapping in densely populated urban area with refinement of the utility data quality is, thence, needed for the expansion and upgrading of utility pipelines and to ensure the sustainability of the urban underground spaces by means of accurate utility pipeline mapping and excavation in the future. In addition, securing precise utility data is also one of the basic needs of the 3D underground cadastral databases towards achieving the development of digital earth. Eventually, enormous benefits that derived from this study are essential to those who work in streets and, significantly, to the public, for preventing the manifest adverse consequences brought by failed excavation during pipeline maintenance and rehabilitation due to insufficient of as-built locational information of the utility pipelines in the future.

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