Acquiring underground infrastructure’s as-built information for cities’ sustainability

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Abstract. The rapid progress of urbanization around the world has lead to an issue of urban land shortage. As such, the urban infrastructure, especially the utilities infrastructure, were buried underground for space saving and better design of urban landscape. However, this has created difficulties in locating these infrastructures from ground surface since they are invisible to the naked eye. Therefore, this paper offers a method to secure as-built information of the underground utility feature without excavation. This is done by utilizing digital image processing, a series of experiments conducted on preferred test site and real model simulation. By securing these underground utilities as-built information, it can contribute to the sustainability of cities through better urban planning. Moreover, the significant findings achieved in this study also enable us to pinpoint that ground penetrating radar (GPR) backscatter with appropriate treatment can yield unique backscatter signature which functional for identification of the types of underground utility without proving excavation. Thereby, good agreement between the backscatter reflections of GPR with respective underground utility not only serves as input which can channelled into a city’s planning, but also uncovers the immense potential of GPR backscatter in reporting the “feature information” of the objects.

1. Introduction
Urban infrastructure, such as building, transportation, utility and etc. 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 urban infrastructure. This phenomena has lead to the optimum usage of urban land surface and underground spaces. For this reason, most of the densely populated cities such as Taiwan, Singapore and Hong Kong and even Manila, are experiencing issue of urban land shortage. Their urban land within the cities has become extremely limited. In this sense, the stakeholders are adopting a measure to going deeper for underground space to compensate for their limited land area. With this regard, the urban underground space is increasingly exploited for the purposes of transportation (e.g.: railway, rapid transit system, pedestrian tunnels), utilities (e.g.: water, sewerage, gas, electricity), and even public usage (e.g.: shopping mall, civil defense structures) [1].

In this context, the urban underground spaces are currently congested with various types of urban infrastructure, forming a labyrinthine network of infrastructure. Securing reliable information of these infrastructure is, thence, a necessity for the sake of better city’s planning in order to ensure cities’ sustainability. However, it is exceedingly difficult and troublesome to map these infrastructure under such congestion circumstance as the infrastructure is mostly invisible to the naked eye. Thereupon, underground mapping is being introduced to scan, detect, and locate the buried infrastructure, e.g. the

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Among these geotechnical instruments, GPR has been chosen as the most popular imaging tool for underground infrastructure based on its advantages in providing high resolution imagery, fast and economic data acquisition. At present, it has been extensively used in the crowded urban environment, commercial and environmentally sensitive areas for acquiring the as-built information of most of the underground infrastructure regardless of natural or artificial structure without proving excavation [2-3]. Nevertheless, current industries still less exploit to extensively acquire complete information of the underground infrastructure, specifically type, shape or even size of the utility infrastructure. The focus of each underground utility mapping project is to determine the geometric properties (i.e. planimetric position and depth) of the buried utilities only[4]. With this regard, most of the current published literature are focusing on studying the retrieval of geometric information of the buried pipeline using different types of trenchless technologies [5]. As such, it has created a gap between engineering and mapping disciplines for understanding the GPR capabilities in underground utility mapping. GPR is timely being misunderstood only applicable for retrieving geometry information of the buried infrastructure as well. In fact, the dielectric wave, which recorded by the GPR, is ideal for parameter characterization for feature identification, hydrology and soil mechanics [6]. It believes that this dielectric wave contains a variety of information which is essential for determination of soil properties, superficial body size and location as well [7].

As there are such valuable aspect of the dielectric wave has not yet attracted the attention of researchers; there are still plenty of research gaps, especially in terms of identify the types of buried infrastructure, its size or shape estimation apart from just detecting its location. This is because acquiring the complete set of as-built information for buried utility infrastructure is crucial for preventing excavation accidents to recur. Mapping the attribute of the buried infrastructure is now a significant task in the most of the industries, particularly the utility industry [8]. Therefore, this study was conducted to offer a method for acquiring the essential as-built information of the underground infrastructure, particularly the radiometric properties of the utility infrastructure which are rarely explored in the present. The focus of the study is to reconstruct the GPR backscatter to obtain radiometry properties of the buried utilities for identification of the types of pipe or cable based on its fabrication material (i.e: ductile iron, mild steel, polyvinyl chloride, clay and etc.) by utilizing digital image processing techniques. In doing this, the unique backscatter signature of each individual fabrication material was initially extract from the simulation images which generated by GprMax- an electromagnetic simulator that created by [9] based on different scene parameter settings. Thereafter, 250 and 700 MHz GPR system was used to acquire few sets of validation data at the preferred test site. Results obtained were then serve as an input to mainstream into a city’s Master plan for maintaining the cities’ sustainability.

2. GPR - A Popular Trenchless Technology for Mapping Underground Infrastructure

GPR is considered as a remote sensing technique, which effective for acquire information of the buried objects through transmitting the electromagnetic signals in the microwave region into the ground, and whenever these signals encountered with inhomogeneity, it will scatter back to the ground surface. The changes in dielectric and conductivity properties of the object will give respond to the GPR antenna, in the function of soil medium and moisture contents [10]. The detection is mainly to record these contradictions electrical discontinuity between the medium and the inhomogeneity of the buried objects, interface or visually opaque structure in less than 50m [11].

In an “ideal” world, the medium in the subsurface is homogenous; the penetration depth of the GPR signal can reached 8 feet below the ground surface [12]. However, a thing never was, and never will be perfect. In “real” world, the medium in the subsurface has been never homogenous as it is formed by combinations of asphalt pavement, rebar, backfill medium, and debris at varying degrees of saturation [12]. Despite the GPR signal transmits from the same distance, the signal will come back to the receiver at different time as they passes through different types of materials because the reflected signal was partially scatter in different dielectric relative permittivity (\(\varepsilon_r\)) medium. Heterogeneous soil is, hence, the key parameter which affects the signal transmission of the GPR system. For computing the time delay (\(\Delta t\)) of the wave, which travels along the distance (\(2d\)) from the transmitter and back to the receiver in the speed of light (cm), equation below can be used [13]:

\[
\Delta t = \frac{2d}{c}
\]
In this regard, the transmitted signals will reflect, refract, or diffract due to this dielectric discontinuity, depending on the material’s properties, incident signal’s wavelength and the geometry of the discontinuity. Subsequently, the receiver of the GPR system will record the entire signal that reflected back to the ground surface. The resulting reflectance, which reflected back to the ground surface, is depending on the dielectric and conductive properties of the medium which they encounter when it travels down into the ground and back to the surface with wide-angle bands. These signal’s reflectance is then transformed into backscatter amplitude for the formation of a GPR profile (or radargram) which contains the relative depth, signal strength and the shape of the object.

The formation of GPR profile is, therefore, influence by (i) types of soil or backfill material and (ii) water saturation amounts or soil moisture. This is proven in equation 2 [14], where the reflectance (backscatters) recorded by the GPR system is influenced by the dielectric properties of the material:

\[
\sigma_{cp} = \sigma_s\left[ \frac{1 - \exp(-2\sigma td)}{2\sigma_t} + 2[\Gamma_2]^2\exp(-2\sigma td) + \frac{[\Gamma_2]^4}{2\sigma_t}\exp(-2\sigma td)(1 - \exp(-2\sigma td)) \right]
\]  

where \( \Gamma_2 \) refers the voltage reflectance coefficient at a lower surface, \( \sigma_t \) refers the material’s cross-section and \( d \) refers the distance travel by the signal. According to the equation 2, the first term refers to the incident wave’s backscatters, the second term refers to forward scattered wave reflected from bottom subsurface and third term refers to backscatters of the reduced incident wave which reflected from bottom subsurface and transmission point of the incident wave. However, the third term is generally been neglected as the value is too small (i.e. layer thickness, \( \tau \) is to the power 10 of the material, respectively with different values of \( \Gamma_2 \)).

3. Materials and Methods

The investigation targets of this study was the pipeline that commonly used to distribute different utility services, such as water, electricity, sewerage, gas and etc. Table 1 shows the information of the utility features that buried at different depths in the test site.

| Pipe  | Material type                                                                 |
|-------|-------------------------------------------------------------------------------|
| Sewer | Clay                                                                         |
| Water | Mild Steel (MS) & Ductile Iron (DI)                                          |
| Electrical | Polyvinyl Chloride (PVC)                                                    |
| Gas   | Medium-density Polyethylene (MDPE) & High-density Polyethylene (HDPE)        |

For data acquisition, simulation image was initially generated from FDTD numerical modelling, executed in MATLAB® software based on different scene parameter settings. FDTD method was used in this study as it is theoretically simple, able to accommodate realistic antenna designs and features, for example dispersion in electrical properties [15-17] and accurate for arbitrarily complex models. The optimum value for different scene parameter were extracted from the laboratory experiments and literature search conducted throughout the study to gather the electrical properties information of investigation targets with the aim to establish the empirical relationship between the testing parameter and its electrical properties such as dielectric permittivity \( (\varepsilon_r) \), magnetic permeability \( (\mu) \), and electrical conductivity \( (\sigma) \). In doing this, the fabrication components of the pipes or cables which divided into metallic materials and non-metallic materials involving DI, MS, MSPE, HDPE, PVC and Clay were gathered. Then, the practical data were acquired at preferred test site by using dual
frequencies GPR system and validation data were acquired under real world condition at the Thean Hou Temple, near Robson Heights, Malaysia using along-pipe scanning approach which has been proven to be the best GPR data acquisition scanning technique for providing higher accuracy data, deeper signal penetration and better target detectability [18-20].

Thereafter, all the data were undertaken pre-processing to remove the unwanted echoes due to background noise. After pre-processed the data, feature detection was conducted based on recognition of the genuine reflection of the buried utilities relating to user’s experience and prior knowledge of layout for the buried utilities in the test site and through simulation. The simulation images that reconstructed based on different scene parameters settings that mentioned earlier were hereafter used to extract the absolute backscatter of the utility features. GPR backscatters with proper treatment can generate unique backscatter signature through image thresholding- one of the digital image processing technique for feature detection by relating the GPR backscatter to its manufacturing material such as clay, DI, MS, HDPE and MDPE under different soil condition [21]. The target backscatters which belongs to the respectively buried pipeline were selected using the rule where difference in the threshold values (T) in successive iterations which smaller than $T_0$, represents the threshold value for initiate the iteration to extract the genuine backscatter signature for respective utility features based on its manufacturing material. With such indication, it can use to identify the types of buried utility (e.g.: electrical cable, gas pipe, water pipe and etc.) without proving excavation. The methodology flowchart for utility feature identification is shows in figure 1.

4. Results and Discussion
The key discoveries that contributed from this study shows that unique backscatter signature (refers figure 2) can be yielded from the GPR backscatter after applying appropriate treatment. The backscatter signatures of the individual utility features with relating to its manufacture materials (PVC, DI, MS, and etc.) were successfully extracted utilizing image thresholding segmentation to distinguish the actual reflection of the utilities from the false reflection caused by non-target features due to surrounding mediums (refers figure 2).
Herein, the new findings of this study evidently proved that, GPR backscatter after applying appropriate treatment can yield unique backscatter signature for identification of different types of utility pipelines. Thereby, the finding successfully unearth GPR’s potential, especially in extracting more information about the buried utility without proving excavation. Indirectly, results obtained manage to clarify the misconception in the mapping industry which stating that GPR only for determining the location of the buried infrastructure. In fact, the complete set of as-built information for the underground infrastructure regardless of its location or types of features can be extracted from the GPR backscatters. With such complete set information of the infrastructure, it can ensure save excavation, hence, these information need to be obtained before the engineers, utility companies, constractors and the streetworkers start to conduct机械化 or manual excavation in the site. Through securing the as-built information of the buried infrastructure, it can overcome the serious social, economic and environmental consequences causes to the country as a result of failed excavation apart from ensuring better planning of urban underground space (i.e. a non-renewable resource) which are essential to the sustainability of the cities [1].
5. Conclusion

This study was conducted to exploit the functionality of GPR in acquiring as-built information of underground infrastructure. Through this study, the unique backscatters of different utility features which are essential for mainstreaming as the input for a city’s planning have been presented. This finding proven that backscatter reflection measured by the GPR is not only for extracting the geometry information of the utility, however, can apply for identified the types of buried pipelines. In this sense, complete set of as-built information of the buried infrastructure is, hence, can be secured for urban sustainability. Moreover, the findings of the study managed to clarify the misconceptions and ambiguities in underground mapping industry which believed that application of GPR is only for determining geometry information of the buried infrastructure as well. Therefore, the current research makes a notable contribution in opens up a new platform to the application of GPR specifically for utility industries with new material recognition facility, in addition, to present practical utility detection and localization facilities.

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