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Short Note

3D modeling of subsurface utilities using Ground Penetrating Radar (GPR) data

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Abstract: Accurate information regarding subsurface utilities during any construction or excavation work is needed so as to prevent any damages to the utilities or avert any mishap. 2D maps of the utility network is available but it lacks the satisfactory representation of the utilities. 3D visualisation provides better interpretation and also enhanced perception of the objects. In this study, we attempt to design 3D models of the subsurface utilities present in the study area and integrate them with the existing 3D city model that comprises of the buildings, trees and street furniture. The parameters required to model the utilities,i.e., width and depth, are extracted from the data acquired from Ground Penetrating Radar (GPR). Depth of the pipes were visible from the processed images retrieved from the GPR, whereas the width of the pipes were extracted by plotting a canonical hyperbola curve. This approach could be helpful for the implementation of the CityGML Application Domain Extension (ADE) for subsurface utilities.

Keywords: GPR, Subsurface utilities, 3D, Modeling

1. Introduction

With the emergence of smart cities, 3D modeling of real world data has become a routine task as the third dimension adds extra information of height or depth. Also, 3D modeling provides better visualisation and perception as compared to 2D maps. Modeling of 3D cities is done using above-surface data collected using techniques such as LiDAR, satellite images, airborne photography, etc. However, 3D city models generally ignore the inclusion of the subsurface utilities i.e. underground water pipelines, electrical cables, communication cables, gas pipelines, sewer lines, etc. (Hijazi et al., 2011). The uncertain information about the subsurface utilities could lead to accident or damage to the pipelines that lay underground during the construction works or any excavations (Döner et al., 2010). 3D modeling of subsurface utilities could also aide in real time fault detection and timely diagnosis. The information regarding underground utilities could be gained by mapping the existing network of utilities and this could reduce the risk that is present due to insufficient knowledge (Jeong et al., 2004). Ground Penetrating Radar (GPR) is an instrument apart from acoustics and physical surveying, which is used to detect the presence of subsurface objects which sends Electro-Magnetic (EM) waves beneath the earth surface and detects any waves that reflects back from an object (Martinez and Byrnes, 2001).

The parameters of the pipelines, extracted during the mapping of the subsurface utilities, could be used for the implementation of the CityGML ADE for subsurface utility network. CityGML is an XML format based open data model used to represent and exchange virtual 3D city models (Kolbe, 2009). It comprises of thirteen thematic modules for the representation of the 3D city objects and provides an extension module for the remnant classes named as Application Domain Extension (ADE). An ADE was proposed as the CityGML UtilityNetwork ADE which contains various utilities that could be integrated with the CityGML classes (Hijazi et al., 2011).

The aim of this study was to model the subsurface utilities (water and sewer pipelines) present in the study area using the data collected from GPR. Using the GPR data, depth and radius of the water and sewer pipes were determined. In this study, 3D modeling of the subsurface utilities using GPR data is presented.

2. Related studies

GPR is a non-intrusive remote sensing instrument used for subsurface geologic and engineering investigations. A geophysical method used to learn the narrow subsurface. It uses near-surface geophysical imaging technique for the capture of images. GPR transmits electromagnetic waves instead of acoustic waves for imaging the subsurface. It transmits the waves through the ground that means it penetrates any dielectric material with low loss. GPR instrument consists of a transmitter and a receiver placed in a fixed position (Martinez and Byrnes, 2001). It is moved over the earth’s surface which detects subsurface features. The Transmitter (Tx) sends the signal underground and if any utility is present, for example, water pipeline, the signal is reflected back towards the instrument. This reflected signal is sensed by the Receiver (Rx) present inside the GPR (as illustrated in Figure 1). Thus, an image is formed containing the signal returns through which presence of any object is determined. The image gives the depth of the surface from which the return signal reflected (Jol, 2008).

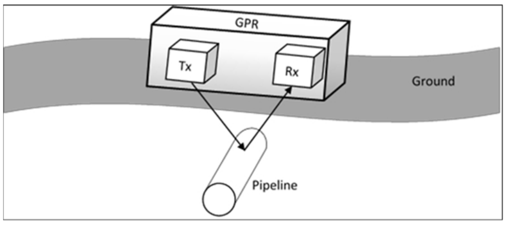

Figure 1: Illustration of GPR functionality

The radius of the subsurface utility pipes could be extracted from the images by using canonical hyperbola equation. The equation is derived based on the dependencies created between the hyperbola and the radius of the pipe and wave propagation velocity of the EM wave (Ristic et al., 2009; Shihab and Al-Nuaimy 2005; Wei et al., 2010). Figure 2 illustrates the geometry of the hyperbola that is fitted on the image obtained. The starting position of the GPR when the sensor started detecting the pipe is taken as 'x_i', the point at which the GPR is perpendicularly above the pipe is taken as 'x_o', and the radius of the pipe is assumed to be R. The wave propagation velocity is 'v' and the two-way time of the wave is 't_i' at the starting and 't_o' at the mid-point of the hyperbola. According to the geometry in Figure 2, Pythagoras theorem is applied on the triangle ABC which gives:

$$(r_i + R)^2 = (r_o + R)^2 + (x_i - x_o)^2$$

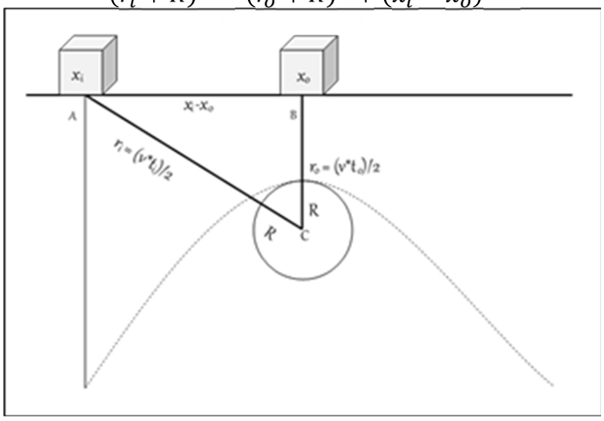

Figure 2: GPR scanning geometry illustration

The terms 'r_i' *and* 'r_o' are the distance travelled by the waves from the transmitter to the pipe which can be written in terms of speed and time. So, 'r_i' becomes $\frac{vt_i}{2}$ and r_o becomes $\frac{vt_o}{2}$. By putting the values of 'r_i' *and* 'r_o' and rearranging the equation (1), we get the following:

$$\frac{(t_i+\frac{2R}{v})^2}{(t_o+\frac{2R}{v})^2} - \frac{(x_i-x_o)^2}{(\frac{vt_o}{2}+R)^2} = 1 \qquad (2)$$

The equation (2) is the equation of hyperbola which is represented by equation (3).

$$\left(\frac{x}{a}\right)^2 - \left(\frac{y}{b}\right)^2 = 1 \qquad (1)$$

By comparing equations (2) and (3), we get $a = (t_o + \frac{2R}{v})$ and $b = (\frac{vt_o}{2} + R) = \frac{v}{2}$a. The values of axes '$a$' and b are obtained by the hyperbola fitting process, and further used to calculate the values of 'R' and 'v' (Ristic et al. 2009; Shihab and Al-Nuaimy 2005; Wei et al. 2010).

Furthermore, a CityGML ADE was proposed for the representation and integration of utility networks in the CityGML schema. Utility Network ADE provided a feature to add any utility networks such as gas pipelines, electrical cables, water pipelines, etc. into the existing schema (Hijazi et al., 2011). The network features inherit from CityGML cityobject classes and they represent topographic network objects such as pipe, tunnels, etc.

3. Study area

Indian Institute of Remote Sensing is taken as the area for this study. The institute is located in Dehradun, Uttarakhand, India and is spread in 78°02'35" to 78°02'52" East and 30°20'23" to 30°20'29" North. Figure 3 shows the map representing the study area. The area scanned for the subsurface utilities was approximately .02 km^2. Only the institute area was covered and not the residential area.

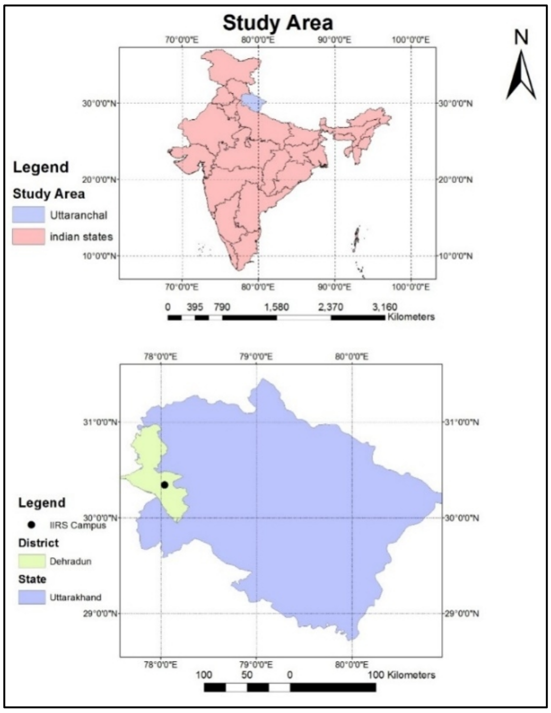

Figure 3: Location map of the study area

4. Methodology

3D Subsurface model

The 3D modeling of subsurface utilities required the pre-requisition of information regarding the utility network in the study area so that the GPR could be used to identify the network of pipelines and give the dimensions to model them. The waterline and sewage data were provided by the Construction and Maintenance Department and other utilities such as gas pipes and telecommunication data were not available.

Depth extraction

IDS Dual frequency GPR instrument was used in this project (Figure 4) with frequencies 200-600 MHz.

Figure 4: Frequency GPR

The 200 MHz frequency mode allowed the ground penetration up to 6 meters whereas, the latter mode did it up to 3 meters. The pre-requisite information of the water and sewage pipelines suggested that the pipes were 1 & 1.5 meters (water and sewage lines, respectively) below the ground surface. So, the 200 MHz mode was not required. GPR traces were collected and the amplitudes of EM signals were recorded with respect to the distance and the travel time. The GPR data needed a few processing after which, it was used to extract the subsurface pipeline images. The images are shown in Figures 5 and 6. Figure 5 is the two water pipes which are parallel to each other and are approximately 5 meters apart and are 1 meter below the surface. Figure 6 is the sewage pipe which is at a depth of 1.5 meters.

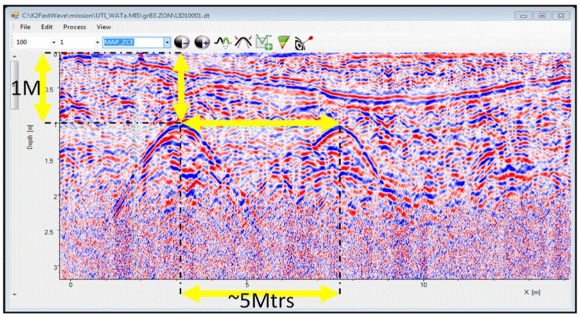

Figure 5: GPR processed image 1

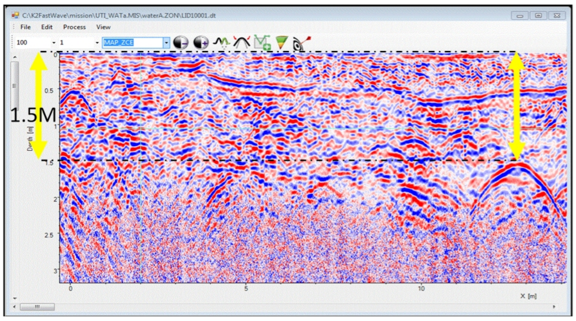

Figure 6: GPR processed image 2

Extraction of width of pipes

After the processing of the raw images and by fitting the curve in the IDS GRED HD software, value of wave propagation velocity v, the GPR position points x_i, and x_o, and the two-way times 't_i', and 't_o' (Figures 7, 8 and 9) can be obtained.

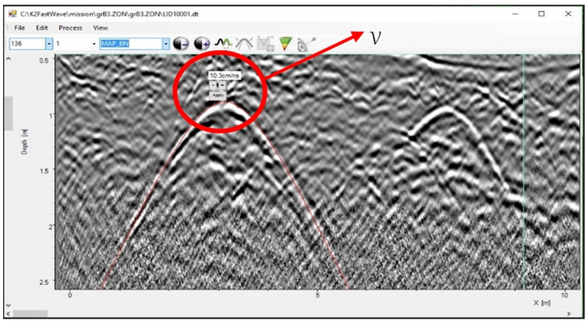

Figure 7: Wave propagation velocity

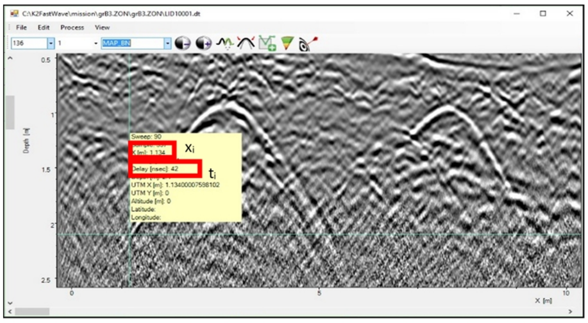

Figure 8: Information at the starting point of the hyperbola

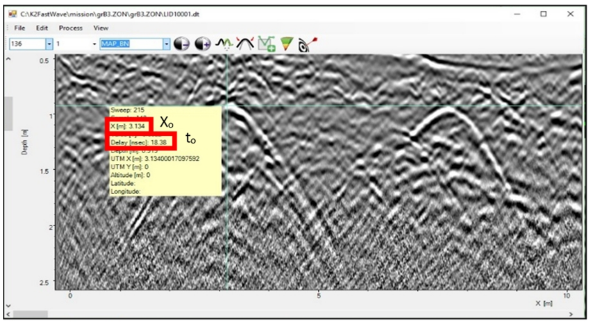

Figure 9: Information at the mid-point of the hyperbola

After the acquisition of the images and the values, the radii of the pipes were extracted by applying the Pythagoras theorem and utilising the concept as presented by (Ristic et al., 2009; Shihab and Al-Nuaimy, 2005; Wei et al., 2010). The equation (1) is expanded as follows:

$$r_i^2 + R^2 + 2r_iR = r_o^2 + R^2 + 2r_oR + (x_i - x_o)^2 \quad (2)$$

Rearranging the terms in Eq. 4, we get:

$$R = \frac{r_o^2 - r_i^2 + (x_i - x_o)^2}{2(r_i - r_o)} \quad (3)$$

Now, putting the values of 'r_o' and 'r_i' as discussed before and rearranging, the following equation will give the radius of the pipe.

$$R = \frac{\left(\frac{vt_o}{2}\right)^2 - \left(\frac{vt_i}{2}\right)^2 + (x_i - x_o)^2}{v(t_i - t_o)} \quad (4)$$

5. Results

We have v=10.3 cm/ns, t_i = 42 ns, t_o = 18.38 ns, x_i= 1.134 m and x_o = 3.134 m from Figures 7, 8 and 9 which are the figures of the water pipe. So with the help of equation (6), the value of *R is obtained* as 0.08 meters or 3.15 inches (see Table 1). This value was then validated with the pre-requisite data available and it was found that the accuracy of the result obtained was 95%. 3D models for subsurface utilities were designed after extraction of the radius and the depth of the pipes. Figure 10 shows the water pipelines whereas, Figure 11 shows the sewage pipeline. The buildings (Level of Detail 3 and 4) were integrated with the subsurface water pipelines and the sewage line as shown in Figure 12.

Table 1: Radius obtained of various pipelines

Radius obtained (in m)	Utility type	Description
0.038	Water pipe	Regular water pipe
0.080	Water pipe	Fire hydrant pipe
0.300	Sewage pipe	Drainage pipe

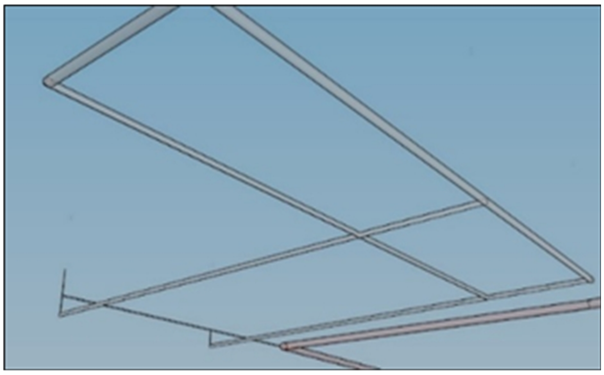

Figure 10: 3D model of water pipelines

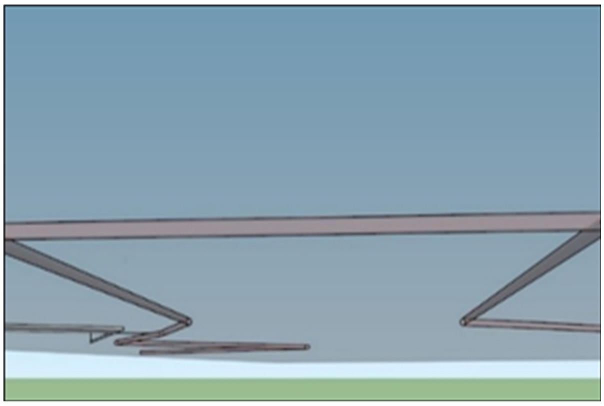

Figure 11: 3D model of sewage pipeline

Figure 12: Integrated 3D model of buildings and subsurface utilities

6. Conclusion

The study attempts to design the 3D model of the subsurface utility network present below the study area using the parameters such as radius and depth of the pipelines. The parameters are extracted using the GPR data. The GPR gives images of the subsurface objects that reflect the EM waves sent beneath the earth's surface. After the processing of the data, the depth of the underlying object could be seen in the image whereas, the radius of the pipe is extracted using canonical hyperbola plot fitting. These parameters were used for the process of 3D modeling of the utility network and the model was integrated with the 3D city model of the study area. The 3D city model was developed by us using Trimble SketchUp before the starting of this project. The utility networks that were designed could be linked with the CityGML schema using the UtilityNetworkADE. The two pipes that are designed are water supply and sewage. So, according to the ADE, the water pipes would come under the FreshWaterNetwork whereas, the sewage pipe would be under the WasteWaterNetwork. Further work could be done to model the electrical cable network and it could also be added in the CityGML UtilityNetworkADE.

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