<RESEARCH REPORT>

Feasibility Study for Underground Environment Exploration by GPR

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Abstract: The exploration of underground environments is important especially in urban areas due to the presence of cavities or utilities under road infrastructure. Ground penetrating radar (GPR) is a suitable tool to carry out subsurface underground environment exploration with high resolution thanks to the properties of electromagnetic waves. Since the application of GPR has increased and many GPR products now exist, users have to consider appropriate GPR instruments and consider whether GPR can be applied to their field or not. This paper describes the idea of a standard evaluation method aiming to evaluate GPR instruments and applicability to various fields for GPR objectively. After the definition of standard anomaly model, we define an evaluation process which reveals how much information can be correctly estimated by GPR exploration. This evaluation method was demonstrated by using a real GPR dataset. And as a result, we concluded the method is reasonable and valuable to the evaluation of GPR instruments and the investigation of GPR applications.

Key Words: underground environment, ground penetrating radar (GPR), standard evaluation method, standard anomaly, volumetric anomaly, linear anomaly

INTRODUCTION

The exploration of underground environments has become increasingly important in subsurface urban areas. In urban areas there are many buried utilities such as water pipes and gas pipes resulting in complications for road management. But utility infrastructures are not the only below-ground challenge. Cavities under roads have become significant problems and can lead to serious accidents.

If we can acquire three dimensional subsurface images of below-ground conditions then we can better manage underground environments using geographic information system (GIS).

Underground environments in shallow area (< several meters) are important for the utilities and cavities (decimeter order) which are existed in there. There are several exploration methods to acquire the information of underground environments, e.g., Magnetic surveys, Electrical prospecting, Elastic wave exploration and Ground Penetrating Radar (GPR). In order to explore the utilities and cavities, it requires: a) high resolution, b) high mobility and c) a non-destructive method. Nowadays, GPR has been recognised as a powerful tool with the above requirements to explore these objects (Uday et al., 2015).

Ground Penetrating Radar (GPR) utilizes properties of electromagnetic waves, i.e., penetration, reflection and diffraction. A typical GPR system consists of pairing of a transmitter and a receiver antenna. The transmitter antenna radiates electromagnetic waves into the ground. The radiated wave penetrates into soil and is reflected at a boundary of two materials which have different dielectric constants. The receiver antenna receives the reflected wave. By analyzing the amplitude, waveform and arrival time of the reflected wave we can characterize the underground environment. The exploration range of GPR is shallower than several meters.

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Conventional GPR instruments which scan in one direction transmit a signal and collect reflected signals at certain distances and a cross-section as 2D image along the scan direction (B-scan) can be acquired by integrating the collected signals as shown in Fig.1.

Recent years, new type of GPR, array GPR systems which have more than two pairs of transmitter/receiver antenna are becoming increasingly common due to its efficiency afforded by multi antenna pair resulting in a reduced survey line as shown in Fig.2 (Bell, 2014). Since array GPRs contain several antennas in one instrument we can acquire several B-scan images as 2D from just one GPR survey. Using this technology, it is becoming easier to scan two dimensionally and produce three dimensional subsurface images by integrating all acquired B-scan images. Horizontal GPR slices (C-scan) can be easily extracted from this 3D data, and allow us to acquire more detailed information of underground environments as shown in Fig.3.

Nowadays, although the application of GPR has become wider (Annan, 2009), there is no precept to investigate a capability of GPR exploration. If there is an objective evaluation method for GPR exploration then users can evaluate GPR instruments by themselves and investigate the applicability of GPR to their field site. Especially for the array GPR systems, three dimensional approach should be considered due to its characteristics.

For that purpose, we proposed the idea of standard underground anomaly and evaluation process based on practical analysis that we defined from user’s point of view, in order to establish reliable method for evaluation of array GPR instrument and its applicability to various fields of GPR exploration objectively. First the concept of standard anomaly and evaluation process are introduced. Then the proposed method is demonstrated through GPR measurement in a test field where various standard anomalies were buried.

1. METHODS

1.1 Underground anomaly

There are many objects in underground environments. All of them may have different dielectric constants compared to a surrounding medium. In other words, they are anomalies in the medium from an electrical point of view. We refer to these anomalies as “Underground Anomalies”. As explained in the previous section, GPR utilize reflected waves at a boundary having different dielectric constant. Therefore, we can say that GPR exploration is a method to estimate underground environments by detecting underground anomalies shallower than several meters.

Fig.4 shows a classification of underground
anomalies shallower than several meters. We classify underground anomalies into two groups: manmade objects and natural features.

Manmade objects can be divided into three subgroups: structures, buried objects and lost property. Structures include civil engineering structures such as building foundations, decks of bridges, road structures, and ancient civil engineering structures buried in soil. Buried objects are mostly buried infrastructures such as water or gas pipes, cables and tanks. Lost property consists of objects not in use anymore such as archeological artifacts, landmines, unexploded ordnance, and waste.

Natural features such as mineral resources, groundwater, cavities, cracks, stratum or glaciers also exist in underground environments and it is important to distinguish manmade objects from these features. Considering our definition of underground anomalies the heterogeneity of soil conditions also should be considered.

1. Concept of standard anomaly

As we discussed in the previous section there are a number of types of underground anomalies and these anomalies should be replaced with standard anomaly in order to develop a standard evaluation method.

To do so we first focused on the shape of underground anomalies. Although each underground anomaly has a different dielectric constant all underground anomalies can be divided into two groups in terms of their shape. We defined them as “Volumetric Anomalies” and “Linear Anomalies”. A volumetric anomaly is a mass of a material having a different dielectric constant than the surrounding medium. Considering the shape of underground anomalies listed in Fig.1, all seem to be volumetric anomalies. But considering the shape of a pipe and cable indicated by *, their shapes are always linear and this is a unique feature compared to the other anomalies. For this reason, we classified pipes and cables as linear anomalies and the other anomalies as volumetric anomalies.

Secondly, we need to model standard anomaly of volumetric and linear anomaly with a specific material. Since the purpose of a standard anomaly is for evaluation of GPR exploration, the standard anomaly should satisfy the following requirements:

a) Homogeneous medium
b) Simple shape
c) Resistance to deterioration

Considering these requirements and ease of manufacture we defined rectangular polystyrene foam as a standard volumetric anomaly and aluminum pipe as a standard linear anomaly.

1.3 Evaluation process of GPR

In this section, we will define an evaluation process which reveals how much information is correctly estimated by GPR exploration. We also define information level for a volumetric anomaly and a linear anomaly separately. Since this evaluation process is for GPR users, the information level is defined by considering a practical analysis process that we defined from user’s point of view.

1) Volumetric Anomaly

When we analyze a volumetric anomaly, first we search and localize the volumetric anomaly in a horizontal GPR slice (C-scan), and then estimate the depth of the anomaly using B-scan. After that we observe whether the anomaly has a horizontal spread or not using B-scan and transversal section images, and then observe its horizontal shape at C-scan. Finally, if the anomaly has a horizontal spread we measure its size using B-scan and transversal section images. Considering these analysis steps we defined information level for volumetric anomaly as shown in Fig.5 (a). Each process step of the evaluation method is explained below.

Once we detect a volumetric anomaly, a second step is the estimation of its depth using the B-scan image. Since GPR measures the arrival time of reflected wave (not the depth), the depth must be calculated using following equation:

\[ d = \frac{tc}{2\sqrt{\varepsilon}} \]

where \( d \) is the depth, \( t \) is the arrival time of reflected wave after electromagnetic wave radiation, \( c \) is the speed of light in a vacuum, \( \varepsilon \).
is the dielectric constant of medium. Because of the difficulty of knowing the dielectric constant of the background medium the accuracy of the depth measurement is strongly affected by constant value we use. After determination of the dielectric constant we calculate the depth by equation (1). If the error of calculated depth is smaller than 10% compared to actual one we consider the depth to be correctly estimated.

The third step is to judge whether the anomaly spreads horizontally or not. As shown in Fig.5 (a), if the reflected wave in B-scan has a flat area (left figure), the anomaly spreads horizontally. On the other hand, if we cannot see a flat area as shown in right figure, there are two possibilities. One possibility is that the anomaly is relatively small compared to the resolution of GPR system and then the anomaly looks like a point object. Another possibility is that the anomaly is like a sphere. In these cases, we cannot proceed to the next steps.

The fourth step is to observe the shape of the anomaly in the C-scan image. If we can estimate the actual shape of the anomaly we consider the information successfully estimated. For example, since our standard volumetric anomaly is rectangular the shape of reflected wave in the C-scan image also should be rectangular. The left figure shows a rectangular shape and the information is successfully extracted. On the other hand the shape in the right figure seems to be round in shape. In this case the information is not correctly estimated.

The final step is to measure the size of the anomaly in both inline and crossline direction. Here inline and crossline indicate the GPR survey direction and its transversal direction, respectively. If the measured size is close to the actual size (smaller than 10% error), the information is considered successfully estimated.

2) Linear Anomaly
As for linear anomalies we firstly need to evaluate presence and depth. We also need to know in which direction the anomaly extends. It is important to know its material and diameter in order to distinguish what may be many linear anomalies buried in an urban environment. According to these analysis steps, we defined the information level and evaluation process as shown in Fig.5 (b).

The evaluation process of the first and second steps is exactly the same as for a volumetric anomaly. For the third information level the direction of the linear anomaly must be estimated.

The fourth step is to estimate the material. The reflection coefficient \( R \) at a boundary of a surrounding medium and an anomaly can be
are the dielectric constant of the surrounding medium and that of the anomaly, respectively. If the dielectric constant of the anomaly is smaller than that of the surrounding medium the coefficient is positive, and as a result the polarity of reflected wave is the same as that of the transmitted wave. If the dielectric constant of the anomaly is larger, then the polarity of the reflected wave is opposite from that of the transmitted wave. Therefore we may estimate the magnitude relation of the dielectric constant by analyzing these waveforms, but cannot determine the dielectric constant or material itself. If we have background information of the exploration area such as a map the material may be determined in some cases using the magnitude relationship but in most of cases it may be quite difficult. Therefore we did not take into account the determination of the material in this evaluation method.

The final step is to estimate the diameter of the linear anomaly because this can be important information to determine the purpose of pipe (Alhasanat et al., 2011). Since this kind of estimation may depend on the algorithm used it is beyond the scope in this paper which is focused only on the exploration method.

**1.4 Experiment**

In the previous sections we have proposed the idea of a standard anomaly and an evaluation process for GPR. In this section an experimental approach to demonstrate the validity of the proposed method is described.

**1) Test field**

The experiment was carried out in our test field where standard anomalies of various shape, size and depth were buried. The test field mostly consists of soil and is covered with 5 cm thickness of asphalt pavement. The surface condition is smooth.

As we mentioned previously, there is a need for a reliable method to detect features such as cavities and pipe infrastructure in urban environments. In these cases, the depth of a cavity and the orientation of a pipe is important information. Therefore in this experiment, we chose the standard anomalies as follows. An object composed of polystyrene foam (50 cm*50 cm*10 cm) was used as the standard volumetric anomaly buried at depths of 20, 50, 150 and 200 cm. As for the standard linear anomaly, aluminum pipes having a diameter of 1.5 cm with orientation of 0, 30, 45, 60 and 90 degrees with respect to the GPR survey line were buried at a depth of 50 cm. Fig. 6 and 7 show the location of the standard anomalies in the test field.

**Fig. 6 Standard volumetric anomaly (50*50*10 cm) used in the experiment. The anomalies were buried in underground at depth of 20, 150 and 200 cm. The anomaly with depth of 50 cm was buried in other place.**

- **Fig. 7 Standard linear anomaly (1 m length, 1.5 cm diameter) used in the experiment. The anomalies were buried in underground at depth of 50 cm with different orientation, 0, 30, 45, 60 and 90 degree. The angle of 0 degree is parallel to inline direction.**
2) Data Acquisition

At first we determine the survey line of the GPR movement which corresponds to the inline direction. GPR was scanned two dimensionally along with survey lines in order to cover the all anomalies. In this experiment, we used two different array GPR instruments in terms of central frequency because it directly affects GPR image. The specifications of each system are listed in Table.1. GPR1 having 30 antenna pairs works with a central frequency of 200MHz, while GPR2 having 8 antenna pairs works with a central frequency of 2GHz. Generally, a GPR working with a higher central frequency has higher resolution but shallower penetration depth. Therefore, GPR2 can acquire a better quality image than GPR1 but only for shallow exploration depths.

3) Data Processing

Acquired GPR data was processed as follows. First a bandpass filter was applied then the time zero was adjusted to the ground surface. Background removal was applied to suppress undesirable horizontal signals such as antenna ringing. Gain control was applied to compensate for weak signals from deeper areas. According to equation (1), the conversion from arrival time to depth was applied by assuming the dielectric constant as 9, i.e., the propagation velocity of electromagnetic wave is 10 cm/nsec.

2. RESULTS

2.1 GPR Image

Fig.8 shows a GPR image of the volumetric anomalies acquired by GPR1. Fig.8 (a) shows C-scan image, i.e., horizontal GPR slice at depth of 20 cm. Here the horizontal axis and vertical axis of the image are the inline and crossline direction, respectively. The gray scale bar beside the figure represents amplitude value of reflected signal. The anomaly indicated by the arrow can be clearly seen in the image from its rectangular shape. Fig.8 (b) shows the B-scan image (i.e., vertical cross-section along inline). The horizontal axis and vertical axis of the image are inline direction and depth from the surface, respectively. Three anomalies shown in Fig.8 (b) can be seen in the image.

Fig.9 shows a GPR image of the linear anomalies acquired by GPR2. Fig.9 (a) shows C-scan image at depth of 52 cm. Four anomalies can be seen in the figure: 60, 45, 30 and 0 degree oriented linear anomalies from left to right. Fig.9 (b) shows B-scan image at the center of linear anomalies. Four anomalies corresponding to the image in C-scan also can be seen in B-scan image.

2.2 Evaluation of GPR

Using these acquired data we evaluated GPR exploration with the proposed method. Table.2 shows estimated depth of the standard anomalies by using equation (1). Gray cells indicate failure of depth calculation due to absence of clear reflection. Percentage represents the error of estimated depth. The depth is overestimated in deeper areas because actual dielectric constant of soil is smaller than the assumed one.

Fig.10 (a) and (b) show the evaluation results of the volumetric anomalies with GPR1 and GPR2, respectively. White cells indicate successful information estimation, while gray cells represent failure in information estimation. When we use GPR1 we can extract complete information of the anomaly at a depth of 20 cm while we can know only presence of that anomaly at a depth of 200 cm. Therefore the information level is high for shallow areas and is low for deep area. On the other hand, GPR2 can estimate detailed information up to 50 cm depth, but no farther due to the limitation of penetration depth.

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<th>Table. 1 GPR specification</th>
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<td>GPR 1</td>
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<tr>
<td>Frequency</td>
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<th>Table. 2 Actual and estimated depth of the standard anomalies</th>
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<td>Anomaly</td>
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<td>Volumetric Anomaly</td>
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<td>True Estimated by GPR1 Estimated by GPR2</td>
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<td>21.8</td>
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<td>22.0</td>
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<td>200 cm</td>
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<td>Linear Anomaly</td>
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<td>49.0</td>
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<td>52.0 (1.2%)</td>
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Fig. 8 GPR image of volumetric anomaly acquired by GPR1

Fig. 9 GPR image of linear anomaly acquired by GPR2

Fig. 10 Result of volumetric anomaly buried in 20, 50, 150 and 200 cm

Fig. 11 Result of linear anomaly oriented 0, 30, 45, 60 and 90 degree respect to inline
Fig. 11 (a) and (b) show the evaluation results of the linear anomalies with GPR1 and GPR2, respectively. Since the polarization of both GPR antenna is inline direction, anomalies at smaller angles are detected well with identifiable direction, while anomalies at larger angles (e.g. 90 degree) are not detected. The result of GPR1 and GPR2 are almost the same in this experiment.

3. DISCUSSION

According to the above results, GPR1 could be applied to a road cavity exploration given the following limitations, a) if a cavity is shallower than 50 cm a high information level can be attained (e.g. approximate size of the cavity could be estimated), b) if the cavity is deeper than 150 cm, the cavity could be detected but its horizontal spread, shape and size are not clear. A thin pipe of even a diameter as small as 1.5 cm could be detected by GPR1 and its direction could be identified up to a 60 degree oriented pipe with respect to the survey inline.

GPR2 could be successfully applied to road cavity exploration shallower than 50 cm depth with a high level of information obtained. But for road cavity exploration in deeper areas GPR2 may be less suitable than GPR1. GPR2 may be more suitable than GPR1 for a precise survey for a cavity shallower than 50 cm. GPR2 was able to detect and successfully determine direction of pipes up to a 60 degree orientation. Although this result is almost the same as GPR1, if the pipes are closely arranged in horizontal direction (e.g. rebar in concrete) GPR2 could yield a better result.

Above results and discussion may be somewhat expected considering the specification of GPR instrument such as frequency, antenna spacing, and so on. In other words, our proposed evaluation method is reasonable. Therefore, this method can be valuable to objectively evaluate a GPR instrument and investigate GPR applications in various fields.

In this paper, we only applied our method to volumetric anomalies at different buried depths, and for linear anomalies oriented different directions. Therefore further study is still necessary in order to validate the proposed method using other types anomalies of different size/shape and so on.

CONCLUSIONS

In this paper, we proposed the idea of standard underground anomaly and evaluation process based on practical analysis that we defined from user’s point of view, in order to establish reliable method for evaluation of array GPR instrument and its applicability to various fields of GPR exploration objectively. The proposed method was demonstrated through GPR measurement in a test field where various standard anomalies were buried. We conclude that the proposed method is valuable to objectively evaluate a GPR instrument and investigate GPR applications in various fields. However, we only demonstrated this method for a limited set of conditions. In future work we will demonstrate this method for anomalies of different size and shape for further validation of the proposed method.

REFERENCES


