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Technique for Detecting Subsurface Cavities of Urban Road Using Multichannel Ground-penetrating Radar Equipment

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As urban roads become more complicated and older, subsurface subsidence often occurs in underground utilities and spaces. The city of Seoul has been engaged in activities to prevent these problems since 2014. As one of the preventive activities, subsurface cavities that may cause road cave-ins have been mainly searched for using ground-penetrating radar (GPR) surveys. GPR has sensors for nondestructive survey. The purpose of this study was to analyze cavity signal patterns and compare them with cavities found by multichannel GPR equipment. Also, an optimal signal analysis method was proposed for multichannel GPR data. GPR tests were conducted on 204 road cavity test sections, and GPR signal patterns were analyzed to classify the signal shape, amplitude, and phase change. Four types of multichannel GPR equipment were used to detect subsurface cavities in a pilot road section in Seoul. Various types of filters were applied to time domain data to examine the optimal signal processing. GPR signals on cavity sections were mostly symmetric (or symmetric in some cases) hyperbola shapes in the longitudinal or transverse direction. The amplitude of GPR signals reflected from cavities was stronger than that from other media. No particular pattern of the amplitude was found because of non-uniform media and nearby utilities. In many cases where cavities reached the bottom of an asphalt concrete layer, the signal phase was reversed. However, no reversed signal was found in subbase, subgrade, or deeper locations. The time domain analysis of the raw data showed that the four types of GPR equipment produced reverse and strong signal reflection due to the low dielectric permittivity of air in the cavity compared with that in neighbor materials. Also, an asymmetric parabolic curve was commonly observed. An optimal signal-processing method for detecting road cavities was determined: zero-setting and background removal should be applied for all types of GPR equipment, and bandpass filtering can be optionally applied to remove high-frequency noise or direct waves. All types of evaluated multichannel GPR equipment were found to be suitable for detecting road cavities located at 1.0 and 1.5 m depths after a suitable filtering process. In general, GPR signals on

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road cavity sections had a symmetric hyperbola shape, relatively strong amplitude, and a reversed phase. However, because of the uncertainties of underground materials, utilities, and road cavities, GPR signal interpretation is still difficult. To perform quantitative analysis for road cavity detection, more GPR tests and signal pattern analysis need to be conducted.

1. Introduction

As cities have developed and their underground structure has become complicated with aging parts, accidents, such as a vehicle or pedestrian falling through roads, due to the subsidence or sinking of downtown road surfaces, have emerged as a significant social problem in recent years. With these phenomena continuing to occur and mass media reports, citizens' anxiety has grown, making this problem a social issue, and various measures have been taken. The Seoul Metropolitan Government prepared special management measures in August 2014 to prevent ground subsidence. As part of the measures to avoid subsidence in advance, equipment and technology have been developed and introduced to detect cavities below the road surface, with surveying for subsurface cavities carried out since July 2015. In general, such surveying in city centers is performed nondestructively using ground-penetrating radar (GPR).(1) GPR is widely used and established as a type of electromagnetic sensor. Its operating principle is the reflection and backscattering of radio-frequency (RF) waves from buried metallic or dielectric objects. GPR results appear as continuous analog signal patterns. These results rely on qualitative analysis methods based on academic knowledge and experience, so they depend on the capabilities of analytical experts. Therefore, to improve the reliability of the detection and analysis technology, it is necessary to improve the analysis technology based on quantitative analysis by acquiring a large amount of cavity data and analysis experience.

To increase the efficiency of surveys of subsurface cavities in city centers, multiple GPR transmission/reception antennas are connected in parallel, and vehicle-type multichannel GPR equipment that is attached to or towed by a vehicle is commonly used. Vehicle-type multichannel GPR equipment currently used for cavity detection in Seoul can be divided into four types, and each type has different hardware characteristics and analysis software. The analysis software of each type is not compatible with the others, so it is not easy to compare the results obtained from different equipment. In this study, for quantitative cavity signal analysis, GPR data obtained from Seoul roads were analyzed, and the characteristics of cavity signals were identified. Moreover, to optimize the cavity detection technology, the signal characteristics of the four types of multichannel GPR equipment and the optimal data-processing method for each material were compared and analyzed.

2. Materials and Methods

2.1 Principle of GPR investigation

GPR is a physical investigation method that obtains underground information from the propagation of electromagnetic waves by analyzing the shape and phase of electromagnetic waves that have returned from the medium after propagating underground in terms of their differences.[2] When electromagnetic waves propagate underground, the propagation speed changes according to the dielectric permittivity of the medium, and the propagation path changes as a result of reflection, refraction, and scattering. These characteristics can be used to determine the thickness of layers and the location and type of heterogeneous objects. In the road sector, GPR is mainly used to evaluate the thickness of pavement layers and the deterioration of concrete floor plates.[3–7]

GPR radiates electromagnetic waves in the frequency range of several MHz to several GHz into the primary medium, as shown in Fig. 1, through a transmission antenna that touches the surface, and the waves are reflected when they reach heterogeneous objects (stratum boundaries, buried materials, cavities, etc.) inside the primary medium. This nondestructive survey method, which irradiates the inside of strata and involves the analysis of reflected radio waves, is used to survey subsurface cavities in downtown areas owing to its short investigation time and high precision. In general, as the GPR frequency increases, the resolution increases but the propagation distance becomes shorter. Therefore, when high resolution is essential, GPR with a high frequency is used as much as possible. When the propagation distance is more important than the resolution, low-frequency GPR is used. However, in the transmission of actual electromagnetic waves, attenuation occurs depending on the site conditions, so even for the same frequency of wave, the actual transmission depth varies significantly with the type of equipment. Therefore, it is very important to select appropriate equipment according to the purpose of the investigation and environmental conditions.

2.2 Principle of multichannel GPR research

GPR survey results can be expressed as one-dimensional (A-scan) data indicating the magnitude of the reflected waves as a function of the travel time measured at one point and as

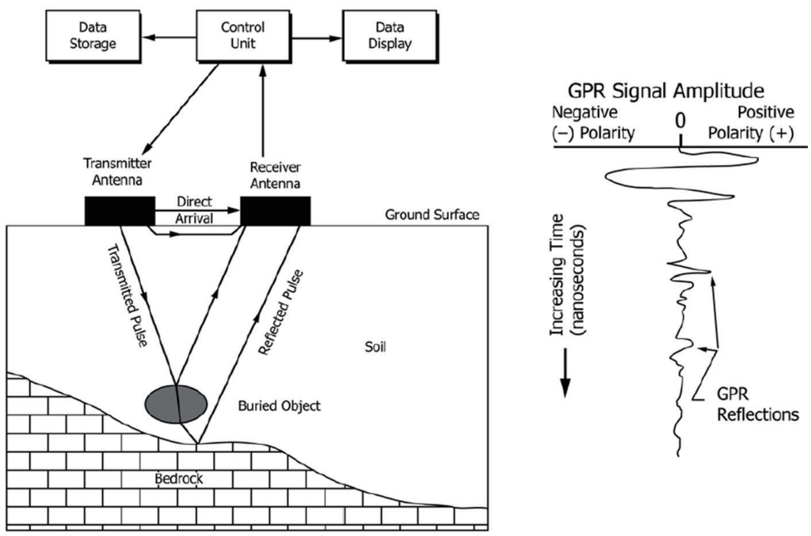


Fig. 1. Schematics of GPR system and trace.

two-dimensional (2D) (B-scan) data, which are aggregated by the measurement distance for one sideline. To find the location and determine the shape of underground objects by a GPR survey, 2D data obtained from signals are mainly used. However, in the case of cavity investigation for a general object buried underground such as sewage pipes, it is often difficult to confirm the object using 2D data because it is not a continuous form in a specific direction.[8] Therefore, to express three-dimensional (3D) shapes such as the longitudinal and transverse lengths and depths of cavities, scans are performed along multiple parallel lateral lines to obtain a 3D underground image from these data using software (Fig. 2).

There are two ways to image GPR data in three dimensions, namely, 1:1 transmission/reception and *N*:*N* transmission/reception. The 1:1 arrangement used in the former is a simple arrangement of transmitters and receivers, which is equivalent to repeating the 2D survey method at regular intervals [Fig. 3(a)]. The *N*:*N* arrangement is a staggered arrangement of several GPR transmitters and receivers [Fig. 3(b)].

For the *N*:*N* array, since a single transmitter transmits signals to two neighboring receivers, it has an advantage that the horizontal resolution can be increased to about twice that of the 1:1 array without increasing the number of transmitters. Therefore, to accurately detect even small cavities, the *N*:*N* arrangement is preferable to the 1:1 arrangement. The multichannel GPR equipment used in Seoul is based on the *N*:*N* arrangement.

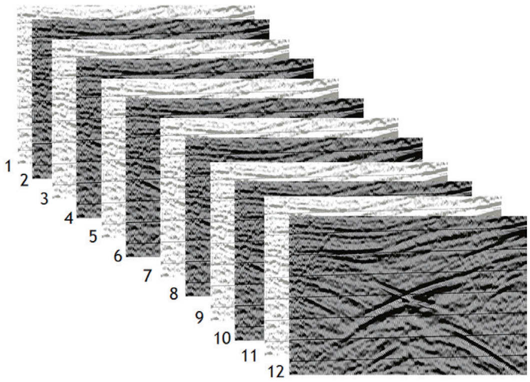
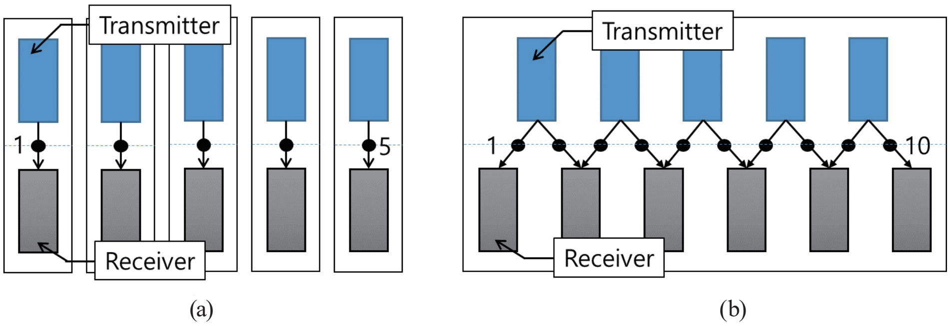


Fig. 2. Multichannel GPR section.



(a) (b)

Fig. 3. (Color online) Multichannel GPR antenna arrays: (a) 1:1 array type and (b) *N*:*N* array type.

2.3 GPR signal features

GPR can be used to check the thickness of urban pavement and for the presence of cavities. As shown in Fig. 4, the amplitude of the waveform on the GPR results screen changes when the medium of each layer changes. The phase (amplitude direction) may be reversed when a medium with a small dielectric constant is at the bottom.(9) For example, when there is a void inside concrete, phase reversal occurs.(10)

If the results of a mobile GPR test are continuously displayed over time (or distance), they are expressed in a parabolic form when there is an obstacle underground. As shown in Fig. 5, the arrival time from the measuring point to the object depends on the location. Such a parabola appears to have a lower slope for a material with a lower dielectric constant and a greater slope for a material with a higher dielectric constant.(11)

3. Results and Discussion

3.1 Experimental overview and data processing

In this study, the signal analysis was performed using GPR data obtained at 204 points where cavities were identified in Seoul, Korea, to understand the characteristics of the cavity signals.

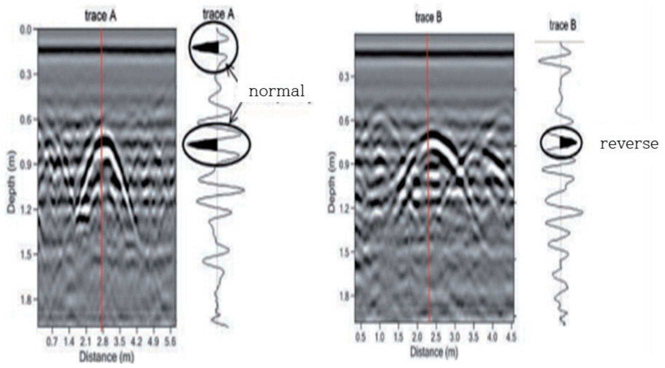


Fig. 4. (Color online) GPR data and reflection trace.(9)

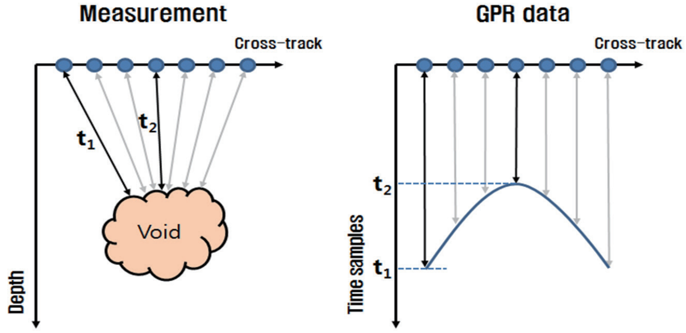


Fig. 5. (Color online) Parabolic signature of the GPR data.(11)

In addition, for a comparative analysis of the four types of multichannel GPR equipment used in Seoul, the same section was investigated with each type of equipment. For an objective comparison, data were processed using commercial software capable of integrated data processing.

Cavity investigation on a road is conducted in two stages or surveys. The first stage is to obtain underground data with vehicle-type multichannel GPR equipment and analyze the acquired GPR signal to estimate the cavity, buried object, and stratum boundaries. Among the various abnormal signals, a point estimated as a cavity is selected in the first stage. The second stage confirms the cavity by approving the final perforation point with handheld GPR equipment and conducting perforation. When the cavity is confirmed, it is photographed using an imager through a borehole to determine the pavement cross section, the depth of emergence, and the thickness of the cavity (Fig. 6).

If a cavity is found through this process, it is necessary to prepare a cavity survey report and notify the road management office to take safety measures or management before a sinking accident occurs. Then, after analyzing the specific cause of the cavity, a report of the results is prepared and the cavity data are updated (Fig. 7).

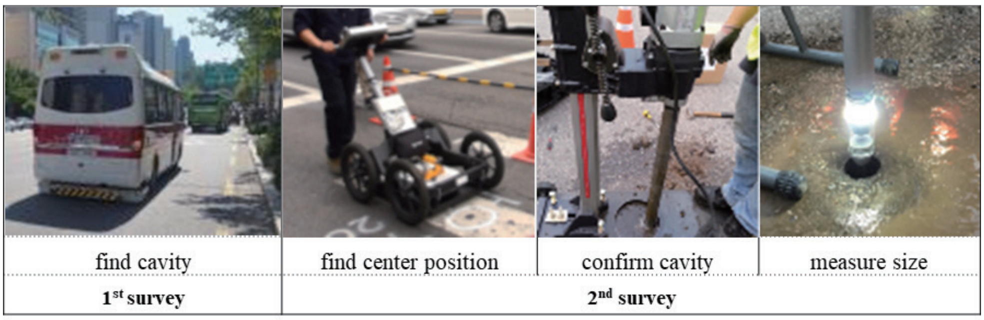


Fig. 6. (Color online) Method of road cavity investigation.

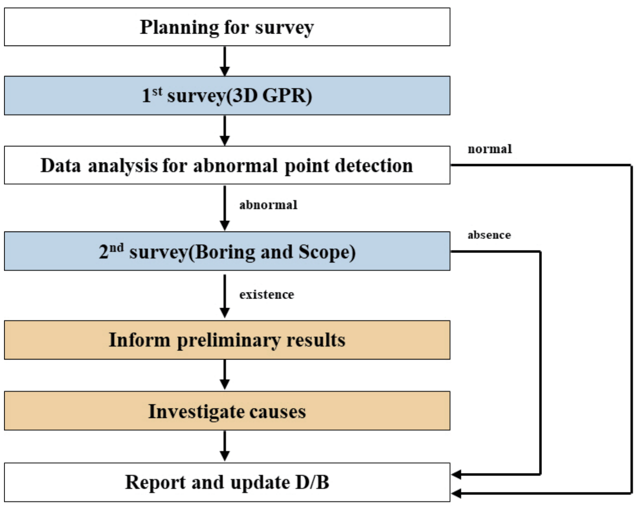


Fig. 7. (Color online) Flow chart of road cavity investigation.

After obtaining cavity signals for comparing the four types of multichannel GPR equipment, GPR surveys were conducted in the same way in one section of road (30 m long with an asphalt concrete paving thickness of 0.3 m). There is one cavity in the irradiation section, and as a result of field inspection, it was found that the cavity was 1.4 m in length, 1.4 m in width, and 0.5 m in thickness. All the multichannel GPR equipment compared in this study was ground-coupled with a center frequency of 200 to 3000 MHz, and the signal generation method involved three impulses, one step-frequency, and 20 to 38 channels (Table 1). Although each type of equipment has different characteristics, the measurement interval and the number of samples were set similarly to test the equipment under the same conditions as much as possible.

Data processing can be used for mathematical processing of the GPR survey data, the general digital signal-processing techniques, and the special techniques used in the elastic wave survey. Depending on the purpose of the data processing and the character of the input data, an optimal processing technique can be selected and applied.(3) The GPR survey data have a relatively high frequency and the irradiation depth is lower than that of other types of non-destructive tests. It has excellent resolution, so it is generally possible to perform data processing using only simple filters. However, to accurately analyze the data, specialized techniques such as background removal, bandpass filtering, regaining, Hilbert transform, deconvolution, and migration are required and performed. The commercially available GPR analysis software currently limits the integrated analysis of multichannel GPR data. In this study, multichannel GPR data were processed using GPR-SLICE©, the most widely known 3D GPR analysis software.

The following list summarizes the steps in the data processing in this study.

a) Create main track and individual channel profile information
b) Create navigation files for individual channels with offset information
c) Extract and convert multichannel radargram
d) Adjust zero level (0 ns) for start position of individual channel signals
e) Apply individual channel filtering (background removal, bandpass, regain, Hilbert transform, migration, etc.)

3.2 Cavity signal characteristic analysis

As a result of analyzing 204 cavities to identify the characteristics of the cavity signal, most of them were found to have topsoil cover of less than 0.6 m. As shown in Fig. 8, 15.2% of the

Table 1
Basic specifications of 3D multichannel GPR equipment.

Equipment	No. of channels	Frequency (MHz)	Signal generation	Width (m)	Resolution ($L \times W$) (cm)	Advantage	Disadvantage
A	24	800	Impulse	1.8	5.0 × 7.5	Easy maintenance Low cost	A few noise signals
B	24	400	Impulse	1.9	5.0 × 8.0	Easy to modify	Analysis difficult
C	20	200–3000	Step-frequency	1.5	5.0 × 7.5	Various applications	Difficult maintenance High cost
D	38	200, 600	Impulse	1.8	5.0 × 6.0	High accuracy	Large size Heavy weight

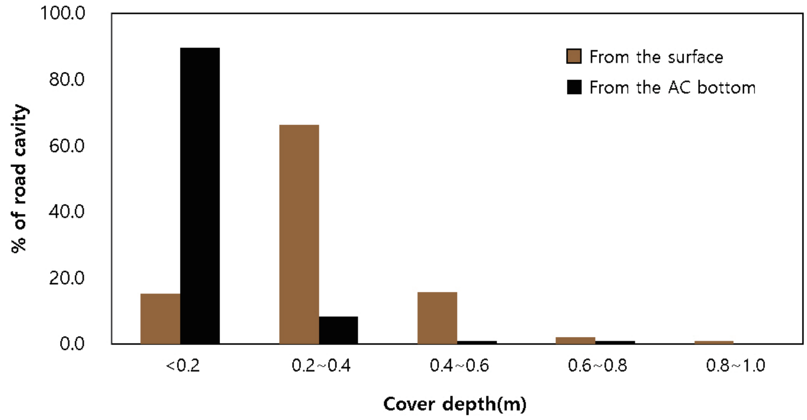


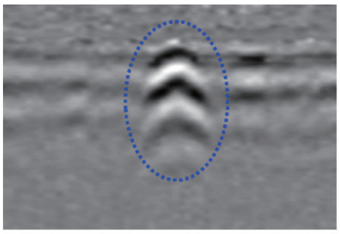
Fig. 8. (Color online) Cover depth distribution of road cavities.

cavities had topsoil cover of less than 0.2 m, 66.2% had topsoil cover from 0.2 to 0.4 m, and 15.7% had topsoil cover from 0.4 to 0.6 m; 89.7% of the cavities were less than 0.2 m from the bottom of the pavement layer. The depth of irradiation of the GPR equipment is up to about 1.5 m, but it is believed that this is because there are many cavities below the pavement. Moreover, it is relatively easy to analyze the cavities that have reached a uniform medium, such as a packaging layer (asphalt concrete). It is difficult to analyze a cavity existing in an auxiliary base layer (mixed aggregate), which is a relatively heterogeneous medium. For these reasons, many cavities are found at low depths.

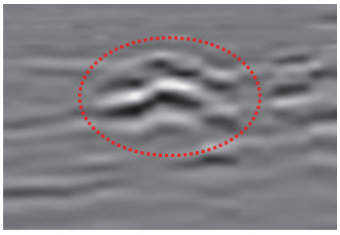
The GPR signal type in the cavities is parabolic in two directions, parabolic in only one direction, or has an irregular shape. The cavities appear in the longitudinal direction (direction of irradiation) or the transverse direction (perpendicular to direction of irradiation). Among the signals, 58.3% are parabolic in the longitudinal and transverse directions, 35.3% are parabolic in the longitudinal or transverse direction, and 6.4% have an irregular shape. Note that the left and right sides have a distorted parabolic shape rather than an asymmetrical parabolic shape (Fig. 9).

In general, in a downtown road, as the depth increases, a medium with a higher dielectric constant appears, so the phase of the reflected signal appears the same at the medium boundary, as shown in Fig. 10(a). However, if a cavity with a dielectric constant of 1 exists, a signal reflected from the upper portion of the cavity appears with the phase reversed from (+) to (–) as shown in Fig. 10(b).

As a result of analyzing the GPR signals applied in this study, we found that the ratio of cavities with phase reversal in the upper part of the cavity was 62% but there were also many exceptions. In particular, when the cavity occurred in the subgrade and subbase of the road, a phase change was often not observed. In addition, when the cavity thickness was small, a phase change did not appear in the cavity. The phase change could not be confirmed because the strong (+) direction signal generated in the lower part of the cavity interferes with the (–) direction signal generated in the upper part because the wavelength used for irradiation is longer than the

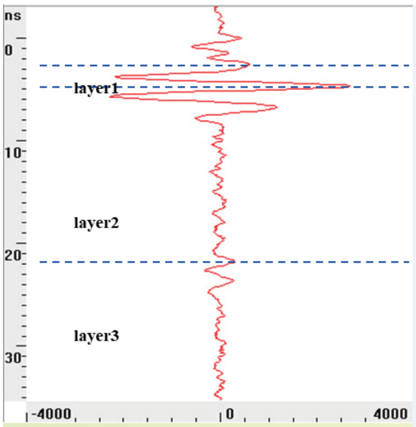


(a)

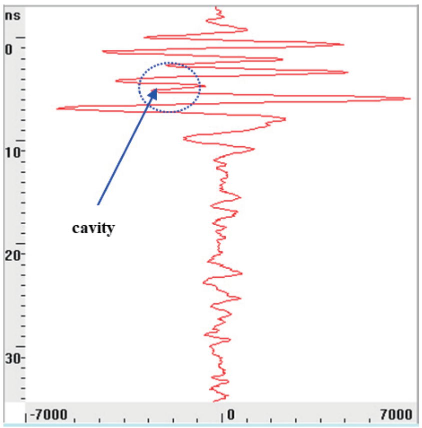


(b)

Fig. 9. (Color online) GPR signal pattern in subsurface cavity: (a) buried object and (b) subsurface cavity.



(a)



(b)

Fig. 10. (Color online) Signal phase between upper layer and road cavity: (a) road layer and (b) road cavity.

thickness of the cavity. Therefore, when determining the phase change of a small cavity using a GPR antenna with a shorter signal wavelength, because the wavelength at a higher frequency is shorter than the thickness of the cavity, the vertical resolution increases, so the phase change at the point where the cavity thickness is small will be detected. However, if an antenna with a high frequency is used, the detection depth is decreased.

A GPR signal is reflected at the boundary between two media having different permittivities, and the larger the difference in permittivity between the two media, the stronger the reflected wave. In general, the dielectric constant of the asphalt constituting a pavement ranges from 3 to 5, and that of the dry subbase and the road (sand, gravel) ranges from 4 to 6.(3) The space inside a cavity under a road contains air. Thus, the dielectric constant of the cavity is 1. Most of the cavities identified in this study exist within a depth of 0.7 m and are located between the asphalt pavement layer and the auxiliary base layer. Therefore, the GPR signal reflected from the cavity is usually strong because the relative permittivity difference is large.

Figure 11 shows the signal strength according to the depth of cavities. Overall, the greater the signal depth, the lower the signal strength. However, owing to differences in the dielectric constant of the medium where the cavity is located, the correlation with the depth did not appear to be statistically significant. When the soil layer is wet, the dielectric constant increases to 25, so the signal strength can be large in the lower part. In addition, when the cavity is small, the signals in the (+) and (–) directions partially overlap at the upper and lower boundaries of the cavity, so the signal strength may be small even at a low depth. Therefore, there is a limit to the ability to analyze the presence or absence of cavities from the signal strength.

3.3 Multichannel GPR signal analysis

The data obtained from the multichannel GPR test were compared with the raw data in terms of resolution and noise level to exclude the effects of the above-mentioned processing on the signal. Since there is no quantitative comparison standard, the comparison of the equipment was qualitatively performed using four grades: very good, good, normal, and poor, where "normal" means that the GPR data are in a state for which there is no problem in analysis and "poor" means that it is difficult to analyze the data.

The raw section results are as follows. Figure 12 shows 2D cross sections corresponding to the channel where a common signal appears among several channels that are not filtered.

The frequency band is most extensive for equipment B and mainly includes a high-frequency band (over 1000 MHz), and equipment B shows very high resolution. Compared with the other equipment, the vertical resolution is good but the horizontal resolution is relatively poor. In the cavity survey, the depth of penetration for setting the effective irradiation range was found to be relatively high for equipment D because its penetration depth is up to about 2.0 m. On the other hand, equipment B was shown to have a depth of penetration of about 1.5 m or less. It was shown that the penetration depth of equipment A was about 1.0 m, lower than that of other equipment, because the center frequency (800 MHz) is relatively high compared with that for the other equipment.

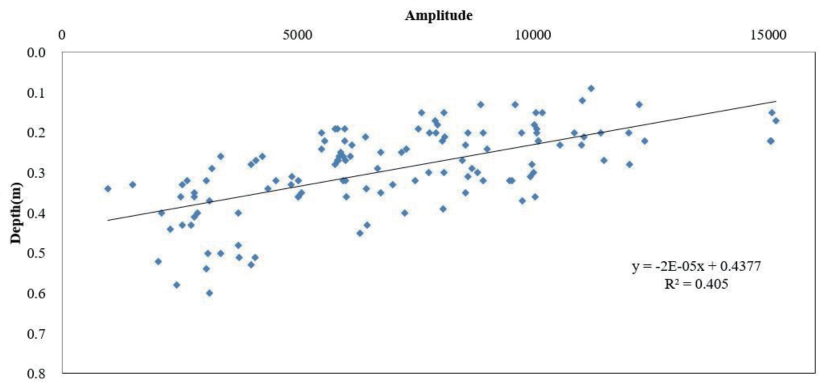


Fig. 11. (Color online) Relationship between signal strength and depth.

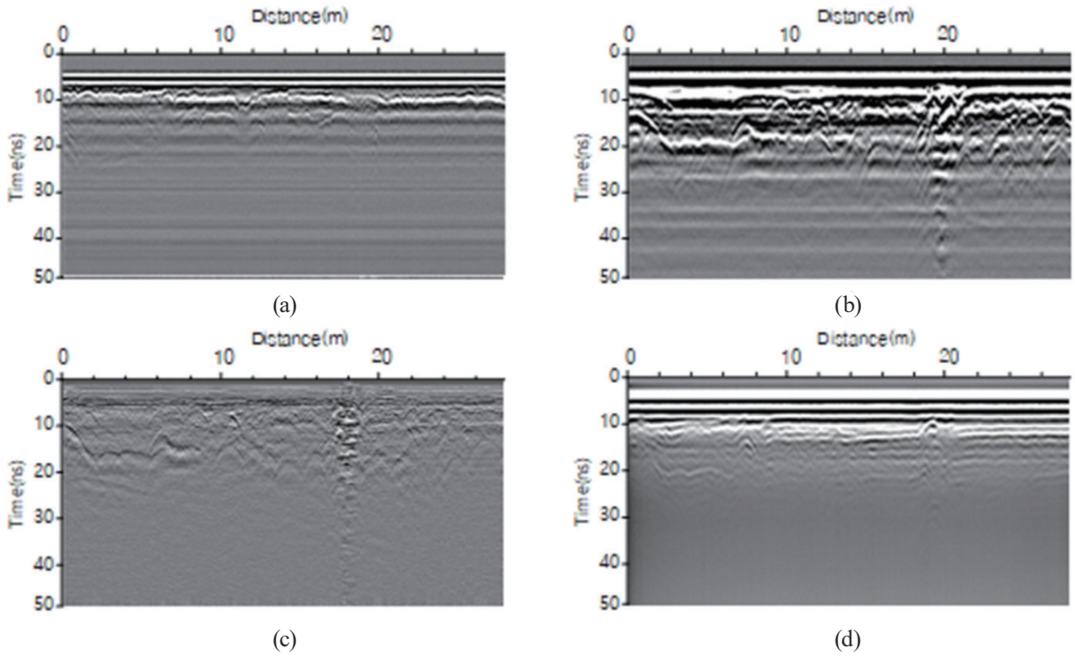


Fig. 12. Selected GPR raw data in time domain (B-scan): (a) equipment A, 12th channel, (b) equipment B, 12th channel, (c) equipment C, 11th channel, and (d) equipment D, 17th channel.

In the case of multichannel GPR data, it is generally necessary to adjust the zero point (0 ns) between channels to analyze the data acquired for each channel. In the case of equipment B, the zero points of each channel were slightly shifted, and equipment D showed a very different zero point from the other equipment, making it necessary to adjust the zero point. On the other hand, when data were acquired with equipment A and C, it was found that the zero points of each channel were the same.

To identify a common signal, the signal should be clear with low noise. Equipment A shows little ringing. Equipment B showed almost no signal deviation or low-frequency noise or ringing. Equipment C exhibited some high-frequency noise, but there was no signal deviation of the antenna, and low-frequency noise or ringing was rare. In the case of equipment D, signal deviation, low-frequency noise, or ringing was hardly observed for most antennas. Since it was difficult to identify a cavity with only the original signal, it is considered that appropriate signal processing is necessary.

3.4 Optimal data processing by equipment

To process multichannel GPR data into an optimal state, several signal-processing steps are required. In this study, zero-point adjustment, background removal, and bandpass filtering were mainly applied. On the other hand, as a result of applying migration and the Hilbert transform, it was found that it is unnecessary to confirm the cavity signal. Table 2 shows the quality of raw data for each equipment and Table 3 shows the optimal signal processing for each equipment applied for cavity signal identification.

Table 2
Results from GPR raw data.

Equipment	Vertical Resolution	Horizontal Resolution	Penetrating Depth	Zero Level	Noise Level	Cavity Signal
A	Normal	Normal	Good	Very good	Normal	Normal
B	Good	Good	Normal	Good	Very good	Very good
C	Very good	Good	Good	Very good	Very good	Very good
D	Normal	Very good	Very good	Normal	Good	Good

Table 3
Optimal GPR data processing.

Equipment	Optimal processing	Function
A	0 ns setting, background removal	Remove ringing
B	0 ns setting, background removal, bandpass filtering	—
C	0 ns setting, background removal, bandpass filtering	Remove high-frequency noise
D	0 ns setting, background removal	Remove direct wave

In the case of equipment with relatively strong ringing in the raw data, processing is necessary to remove the background. In addition, bandpass filtering had a smoothing effect on the data owing to the effect of removing noise (mainly high-frequency signal noise) outside the center frequency signal band. In the case of equipment C, background removal was applied to remove the direct coupling, and bandpass filtering was applied to identify the optimal cavity signal. No significant effect was observed after applying other types of signal processing. In the case of equipment C, even after background removal, the processed signal did not appear significantly different from the original signal. On the other hand, when bandpass filtering was applied, a clearer cavity signal was obtained. This is considered to be because part of the signal in the high-frequency band that affects the cavity signal is removed by bandpass filtering. In the case of equipment D, it was possible to obtain a reasonably satisfactory cavity signal by simply applying background removal to remove direct waves. In addition, when bandpass filtering was applied, a smoothed signal was clearly observed.

The cavity signal exhibits a similar shape to a typical underground buried object, such as a sewer pipe, but shows some unique characteristics.[12–16] First, in a 2D cross section, the inverse phenomenon (phase change), a change in reflection intensity, and an asymmetric parabola appear in the cavity signal. Secondly, the cavity signal, which appears as a distorted circle or oval in the flat cross section, is diffused with increased depth. In this study, we compared how the characteristics of the cavity signal appear for each device.

A comparison of GPR signals in the same 2D section obtained with a different equipment is shown in Fig. 13. Commonly, the GPR signal displayed at the cavity occurrence position appears with a parabolic shape. It can be seen that the (+) and (–) signals are reversed to (–) and (+). The cavity signal in the cavity is stronger than in the other sections. The difference in dielectric constant between the medium above the cavity and the cavity filled with air is larger than that between other sections. The strength and shape of the signal are slightly different for each equipment, but the five characteristics of the cavity signal mentioned above were confirmed for all four types of equipment. Here, the signal strength may vary among the equipment

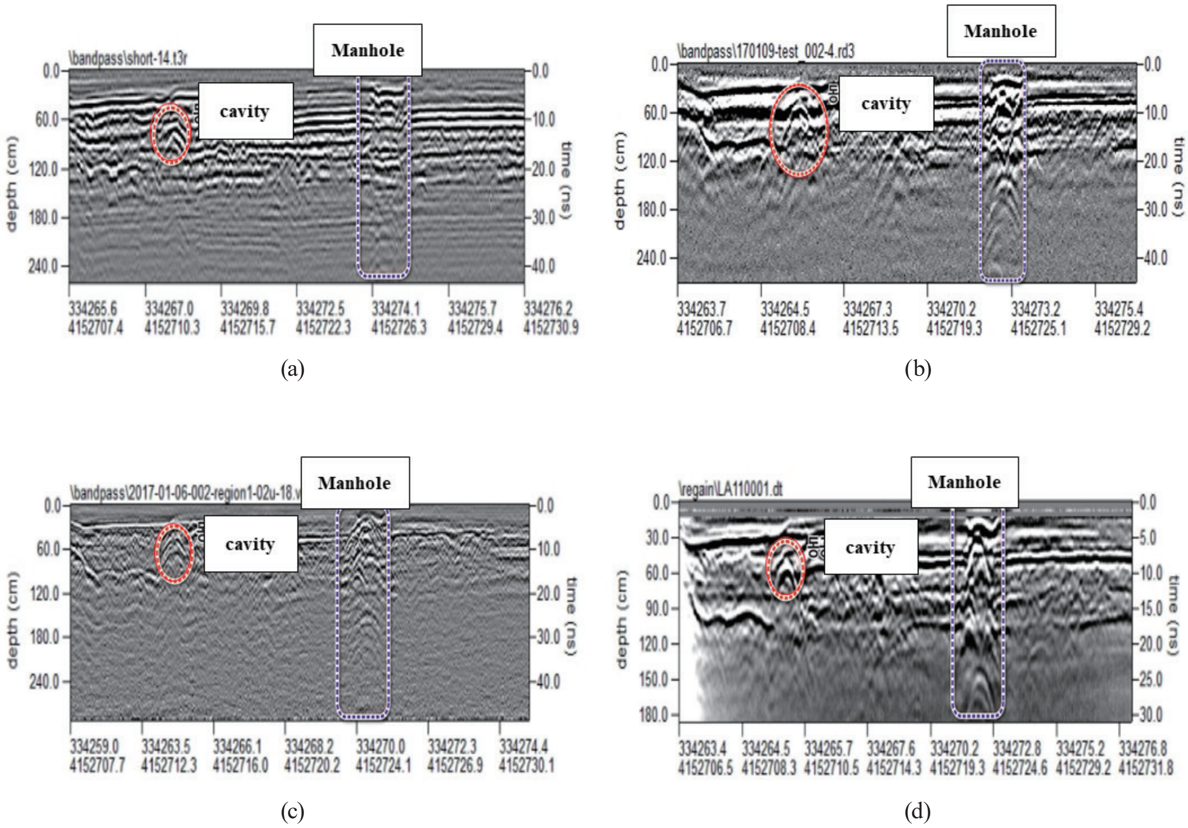


Fig. 13. (Color online) B-scan section of 3D GPR data: (a) equipment A, (b) equipment B, (c) equipment C, and (d) equipment D.

depending on the degree of overlap of the signal. Also, the signals of all equipment were inverted at the upper portion of the cavity, with normal signals at the lower portion. Therefore, the reflection intensity in a cavity with the same thickness may be different for each equipment, so it is considered that the accuracy of cavity analysis can be improved by considering this point.

4. Conclusions

In this study, the acquired GPR signal characteristics were analyzed for 204 cavities found in Seoul to identify common characteristics. GPR is an available electromagnetic sensor for detecting cavities rapidly. The results of analyzing cavity signals using four types of multichannel GPR equipment employed in Seoul are as follows.

1. The GPR signal generated in the cavity appears as a circular or elliptical shape on a plane with a distorted parabolic shape in the longitudinal section. It is distorted in one or both directions owing to the heterogeneity of the medium or the direction of the cavity.
2. The GPR signal is relatively strong at the upper cavity position. However, since the GPR signal is strong even at the pavement boundary or around the buried material, there is a limit to determining whether a cavity exists simply from the signal strength.

3. Most (62%) of the cavities that developed up to the asphalt concrete layer showed a phase change of the GPR signal. However, when a cavity exists in a heterogeneous medium such as a subbase layer or a roadway, a phase change does not usually occur, so it is necessary to perform a precise and additional analysis.
4. To determine the presence or absence of a cavity from a GPR signal, the shape, strength, and phase change of the signal and the conditions of the surrounding medium conditions must be considered.

In addition, it was found that all the types of multichannel GPR equipment examined in this study are suitable for all cavity surveys. However, since the data-processing method is different for different equipment, it is considered desirable to use specialized software for equipment rather than general-purpose software for optimal data analysis. In this study, it was important to simultaneously analyze the raw data and the optimized filtering data. All four types of equipment showed clear reflected signals and characteristics in the cavity. Therefore, the multichannel GPR equipment used in this study is suitable for performing cavity surveys. If single-channel GPR equipment is used, since only one 2D section is acquired in one operation, the efficiency of use decreases and the horizontal resolution is lower than that of multichannel GPR equipment. Therefore, multichannel GPR equipment must be used for efficient and accurate surveying. The advantage that can be derived from using a variety of equipment is the increased reliability of analysis, confirming the general sequence of analysis and identifying the characteristics of equipment. In addition, in a cavity survey, not only the standardized data but also the data processing and the final judgment ability of the analyst interpreting the data are important. Hence, the performance of the equipment is not necessarily directly related to its ability to carry out a cavity survey. Therefore, it is necessary to increase the accuracy of analysis by continuously constructing a database for the common signals of each equipment.

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