International Journal of Technology and Engineering Studies
volume 4 issue 4 pp. 143-149 doi: https://dx.doi.org/10.20469/ijtes.4.10003-4

A Study on the Limitations of Geophysical Surveying Techniques to Survey Underground Cavities and Areas Affected by Loosened Grounds

YUSHIK HAN*
Geotechnical Engineering Research Institute of Korean Geotechnical Society, South Korea

KI-CHEONG YOO
Geotechnical Engineering Research Institute of Korean Geotechnical Society, South Korea

Abstract: The current study aims to analyze the effects of factors such as the properties of the earth or soil on geophysical surveying techniques upon understanding the engineering properties of the ground earth. A testbed was built and used to analyze survey limitations undertaken via Ground Penetrating Radar (GRP) surveying and electrical resistivity surveying to consider the various and complex factors from actual complex grounds. As a result of the surveying, this study found that a GPR survey at a frequency of 250 MHz in clay sand medium was capable of accurately identifying underground cavities 0.1 m in diameter at a depth of up to 3.7 m. By measuring the distorted potential, the anomaly's location, size, shape, and physical properties can be acquired. In addition, while an electrical resistivity survey was found to present low resresistivity in areas affected by loosened grounds, the survey technique was limited in its ability to pinpoint the location.

Keywords: *Underground cavities, geophysical surveying, GPR, electrical resistivity*

Received: 01 April 2018; ***Accepted:*** 21 June 2018; ***Published:*** 22 August 2018

I. INTRODUCTION

Research regarding the surveying and detection of underground cavities to detect ground subsidence in South Korea has been actively pursued [1, 2, 3, 4, 5, 6]. Non-destructive survey methods used to survey subsurface grounds largely include techniques such as GPR surveying, electrical resistivity surveying and surface wave surveying. Of such methods, GPR surveys are known to be highly applicable to the surveying of underground cavities and facilities, bedrock, and the discontinued surfaces of fragmented fault zones in addition to being highly applicable to the non-destructive surveying of concrete. However, depending on the factors that affect the GPR signal (permittivity, electric conductivity, transmission rates, etc.), the energy of the electromagnetic waves can become relatively weakened. Despite electrical resistivity surveys being capable of providing geotechnical information regarding the geological structures of fragmented fault zones and alteration zones [7, 8, 9], the distribution of groundwater, and rock classifications, the method is known to be largely affected by saturation rates, porosity, pore water conductivity, clay content, and temperature [10, 11]. As such, non-destructive geophysical surveying methods are largely affected by the properties of underground media, and in the case of earth, a type of discontinuous underground media in which the particles of earth can easily be separated, relative displacement of the particles may easily take place upon the introduction of external forces. In addition, considering that the engineering properties of earth are heterogeneous and anisotropic, various and complex factors come into play according to ground depths. It is thus difficult for GPR surveys to be used to penetrate deep underground locations as signif-

*Correspondence concerning this article should be addressed to YUSHIK HAN, Geotechnical Engineering Research Institute of Korean Geotechnical Society, South Korea. E-mail: shikrush@naver.com

icant loss of electromagnetic energy occurs in cases in which a penetrated medium has high conductivity. The depth at which the electromagnetic waves can penetrate may differ depending on the frequency of the waves and is affected by the dielectric constant and conductivity of the penetrated earth [12].

For the purpose of considering the various and complex factors from actual complex grounds, a testbed was built and used to analyze survey limitations undertaken via GPR surveying and electrical resistivity surveying.

II. THEORETICAL BACKGROUND

A. *GPR Surveying*

GPR surveying is used to examine shallow underground structures using an electromagnetic pulse at frequencies between 10 MHz - 1 GHz. This method makes use of electromagnetic waves that are relatively shorter than those used in other survey methods, resulting in a high resolution. In doing so, this method regards measuring and interpreting the reflections and diffractions of the electromagnetic waves according to differences in permittivity of the concerned media to understand geological structures. GRP surveys, in particular, have a relatively higher applicability in dry sandstone or conglomerate as such structures allow electromagnetic waves to easily penetrate. On the other hand, this method is subject to large energy losses of the electromagnetic waves when penetrating clay layers due to high conductivity and is not suited to survey such grounds.

The 10 MHz -1 GHz high-frequency band used in GPR surveys concerns a band in which the displacement current is dominant over the conduction current. In this case, the behavior of the electromagnetic field is governed by the wave equation. The variables of interest with respect to the behavioral properties of the GPR wave concern the rate of attenuation and speed. Assuming a plane electromagnetic wave, the attenuation constant (“a” , [dB/m]) and location constant (β, [rad/m]) for the waveband is shown in Eq. (1) and (2).

$$a = \frac{\sigma}{2} \frac{\mu}{\varepsilon} \tag{1}$$

$$\beta = \omega\mu\varepsilon \tag{2}$$

Where, σ is conductivity (S/m), ε is permittivity (F/m), μ is permeability (H/m), and ω is each frequency. Thus, if the conductivity of the medium is larger or permittivity of the medium becomes smaller, the GPR wave is subject to greater losses irrespective of frequency. However, in the case of high-frequency bands of 100 MHz or higher, due to the relaxation effect, the attenuation constant quickly rises, and in turn, rapidly lowers the capable survey depth at which the GPR surveying equipment using frequencies of 100 MHz or higher operate.

Assuming that the permeability of the underground rock is the same as that of a vacuum ($\mu = \mu_(0)$), the velocity of the GPR wave ($v, [m/ns]$) can be defined as Eq. 3 shown below.

$$v = \frac{c}{\sqrt{\varepsilon r}} = \frac{0.3}{\sqrt{\varepsilon r}} \tag{3}$$

As indicated, the transmission velocity of the GPR wave is unaffected by frequency and depends on permittivity. In this case, where $\varepsilon_r = \varepsilon/\varepsilon_o$ is relative permittivity, c is the velocity of the electromagnetic wave, 0.3 m/ns, and the wavelength of the GPR wave is shown in Eq. (4).

$$\lambda = \frac{v}{f} = \frac{300}{\varepsilon_r f} \tag{4}$$

Where, the unit used in f is MHz. Due to the relative permittivity of the underground rock being 3 $\sim$ 30, the transmission velocity of the GPR wave is 0.01 m/ns $\sim$ 0.175 m/ns. In addition, the relative permittivity of water is 80, which is dramatically larger than that of other substances. Thus, the amount of water content within an underground medium has a dramatic effect on the behavior of radar waves.

There are approximately three factors that drive the attenuation of GPR waves. First, due to the transmission antenna used in GPR surveys being a point source, the waves are transmitted at a 90-degree angle in the form of a cone from its transmission source. Therefore, as the distance from the transmission antenna increases, the size of the signal attenuates at a rate of 1/r. Second, as some energy converts to heat according to the attenuation constant, the signal attenuates. This is called absorption. Third, energy loss occurs at boundaries as the GPR waves reflect and penetrate. Assuming vertical propagation, the reflection coefficient is shown in Eq. (5).

$$k = \varepsilon_1 - \frac{\varepsilon_2}{\varepsilon_1} + \varepsilon_2 \tag{5}$$

Where, $\varepsilon_1, \varepsilon_2$ is the relative permittivity of both sides of the boundaries. Thus, in locations where a large amount of various geological noises is present (including micro-inhomogeneities), the applicable depths of GPR surveying become reduced.

GPR resolution regards the capacity to distinguish between two reflected signals that are temporally adjacent. Therefore, resolution is a function of frequency.

The transmitting and receiving antenna used in GPR surveys are created to emit signals within a certain frequency band and this frequency band is known as the bandwidth of the antenna. In addition, the frequency that presents the greatest reaction is known as the center frequency. In light of this, it is thus the case that antennas have a unique center frequency and that most GPR surveying equipment are designed to have the same bandwidth as the center frequency.

The minimal detectable object size is referred to as the 'resolution,' and differs according to the earth. Resolution also refers to half of the length of one wave. The center frequency must become larger to enhance resolution. Despite resolution enhancement as a result of increasing center frequencies, this results in greater attenuation in GPR surveys and lowered applicable survey depths. Therefore, it is advantageous to prioritize applicable survey depths when selecting antennas rather than focusing on resolution. This is recommended if there is no information regarding the approximate depth or permittivity of the object to be surveyed. Due to the velocity of the GPR wave being a function of permittivity, resolution changes according to media must be considered. The lower limit of the frequency is determined by resolution and the upper limit is determined according to the applicable survey depth and geological noise.

TABLE 1
RELATIONSHIP WITH VARIABLES OF UNDERGROUND ELECTRICAL CHARACTERISTICS, GPR EXPLORATION, AND FREQUENCY

Measurement Variable	Permittivity	Conductivity	Frequency
	low → high	low →high	low →high
Velocity of electromagnetic wave	fast → slow		
Attenuation	high → low	low → high	low → high
Depth of investigation	shallow → deep	deep → shallow	deep → shallow
Wavelength	long → short		long → short
Resolution	low → high		low → high

III. ELECTRICAL RESISTIVITY SURVEYING

Electrical resistivity concerns the properties of a substance in terms of its resistance to electrical currents. Electrical resistivity surveys involve the use of current electrodes on a ground surface to generate an induced current upon which potential differences are measured from a potential electrode. The process entails the acquisition of a resistivity distribution cross-section of a concerned medium. Although the objective of electrical resistivity surveying is to realize a true resistivity model of geological significance, actual geological conditions are not homogeneous, rendering impossible the realization of true resistivity. Therefore, apparent resistivity is first calculated and thereafter true resistivity is determined. The passing of a current through an electrode through an underground media having homogeneous electrical resistance presents a homogeneous isoelectric line. Should an electrical resistance anomaly exist underground, the effects of the surface charge of the surface of the anomaly distort the isoelectric line. This affects the potential difference measured by the potential electrode on the ground surface (Fig 1). By measuring the distorted potential as presented above, the location, size, shape, and physical properties of the anomaly can be acquired.

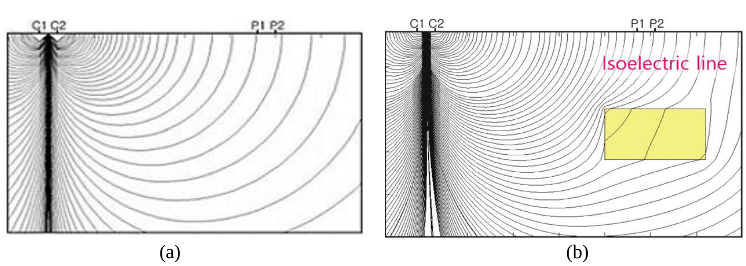


Fig. 1. (a) Isoelectric lines under the surface in the homogeneous model when a current is given current electrodes (C1, C2) (b) Isoelectric lines under the surface in the heterogeneous model having a different resistivity region when a current is given current electrodes (C1, C2)

In the case of electrical resistivity surveying, a number of current electrodes and potential electrode configurations can be applied according to the ground characteristics. However, the dipole array configuration (Fig 2) is capable of acquiring a precise response and is thus widely used. Potential differences are measured by installing multiple potential electrode pairs to a single current electrode pair. The measurement of apparent resistivity at deep depths is possible according to the number of potential electrode pair configurations (Figures 2 and 3). Due to electrical resistivity surveying being the most widely used survey method to analyze the electrical properties of a ground medium, a relatively large amount of empirical data is available. However, it is difficult to understand the precise location or structure of underground anomalies using this method.

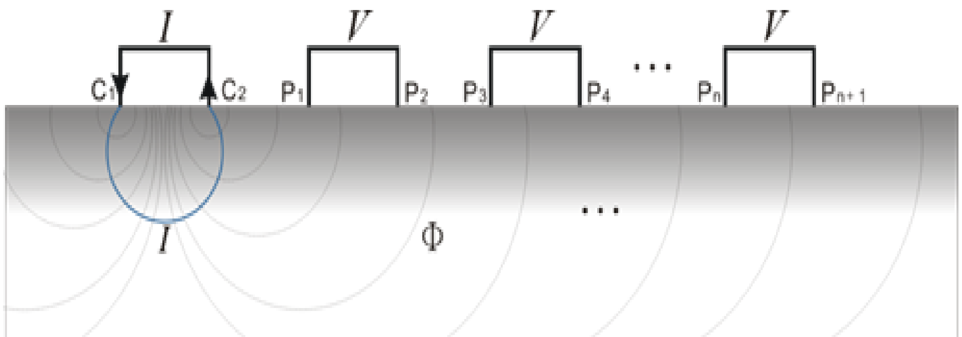


Fig. 2. Dipole-dipole array

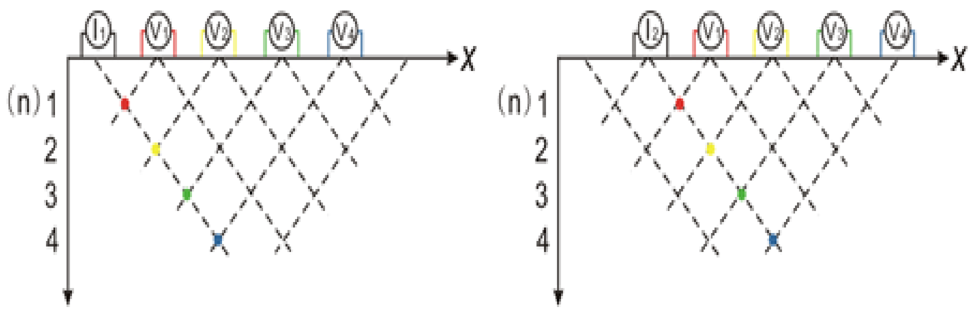


Fig. 3. Apparent resistivity measurement in dipole-dipole array

IV. ANALYSIS OF THE LIMITATIONS OF GEOPHSICAL SURVEYING

A. *Establishment of a Testbed for Validation Purposes*

The ground conditions of the testbed site, which comprised clayey sand down to a depth of 4.8 m from the ground surface, were presented as consisting of a brittle sedimentary layer with high clay content. Silty sand below this layer was present up to a depth of 10.7 m in the form of very dense weather soil, and beneath this, a layer of weather rock was present. The groundwater level was found to exist at a depth of 6.0 m from the ground surface.

To measure the electrical properties of the ground layers, bed excavation to a depth of 2.0 m was performed. The electrical properties of the top layers were measured at depths of 0.5 m, 1.25 m, and 2.0 m locations from the ground surface. The TDR sensor used for the measurements was a GS3. The GS3 sensor was manufactured by Decagon of the United States and was capable of simultaneously measuring volumetric water content and conductivity (Fig 4).

Fig. 4. Measuring the electrical properties of clayey sand

The dielectric constant was found by applying the relation between the dielectric constant and volumetric water content as proposed by [13] in an experiment to equation (1).

$$VWC(\frac{m^3}{m^3}) = 5.89 \times 10^{-6} \times \varepsilon^3 \times -7.62 \times 10^{-4} \times \varepsilon^2 + 3.67 \times 10^{-2} \times \varepsilon - 7.53 \times 10^{-2} \quad (6)$$

The subsurface electrical properties were measured as shown in Table 1. The #1 location of the measured clayey sand compared to the #2 and #3 locations had low clay content and thus presented a large dielectric constant.

With respect to the same clayey sand, the #2 location compared to the #3 location was found to have a relatively increased double layer thickness of clay particles and thus a lower dielectric constant [14].

To simulate areas affected by loosened grounds, a crawler drill as shown in Fig 5 was used to drill a hole 150 mm in diameter at a 30-degree angle and a depth of 14.4 m. Upon doing so, high pressure was applied to the hole to perturb the ground. In addition, to form underground cavities, a crawler drill was used to drill a hole at a 30-degree angle and a depth of 7.3 m. Upon doing so, 100 mm diameter PVC pipes were inserted into the hole.

TABLE 2
ELECTRICAL PROPERTIES OF CLAYEY SAND

Ground Layer Properties	No.	Depth	Dielectric Constant	Volumetric Water Content (%)t	Conductivity (mS/m)
Clayey sand	#1	0.5m	12.2	27.0	1.2
	#2	1.25m	10.3	22.8	2.7
	#3	2.0m	11.5	25.5	3.0

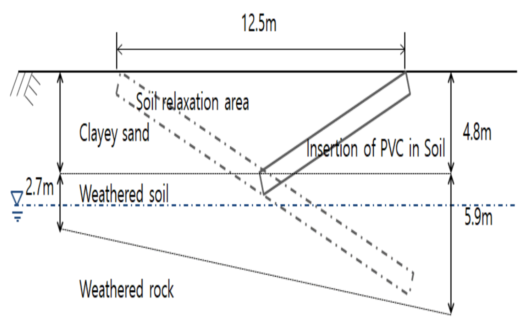


Fig. 5. Establishment of the testbed to analyze the limitations of geophysical surveying

B. Analysis of the Limitations of GPR Surveying

The GPR survey was undertaken by applying a frequency of 250 MHz to the reflection mode. Reflection mode, as shown in Fig 6, involves a method of surveying upon fixing the transmitter and receiver at certain distances and moving them by certain distances (X) during the survey process.

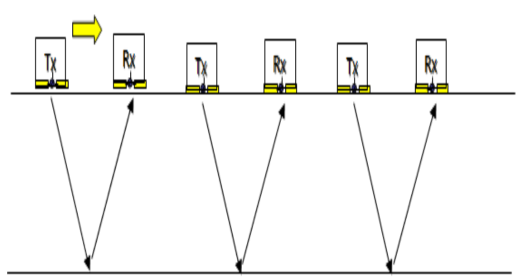
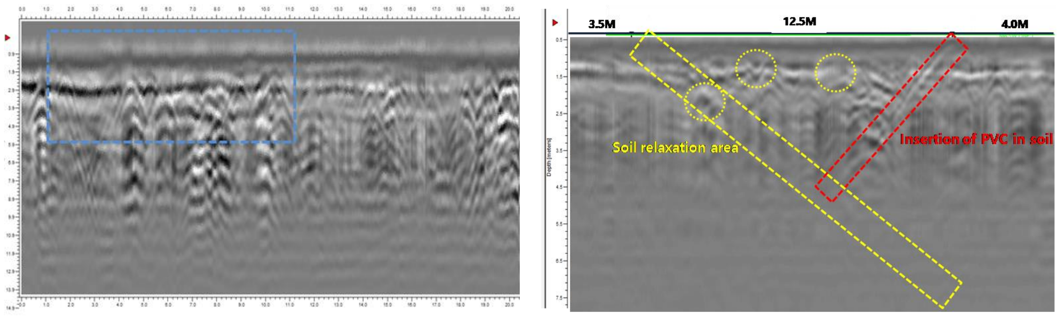


Fig. 6. GPR exploration mode (Reflection mode)

The lower the pitch and the higher the electrical non-conductivity of the ground, the deeper it becomes possible to undertake GPR surveys. In the case of using an antenna having a center frequency of 250 MHz, it was possible to survey up to a depth of 3.7 m. In addition, this method was found to be capable of accurately identifying the 0.1

m diameter PVC pipe. It was also possible to ascertain the range of the perturbed area affected by loosened grounds by applying this method. However, at depths having high water content due to the capillary suction of the groundwater level, dramatic attenuation of the electromagnetic waves was observed, which made it difficult to undertake GPR surveying.

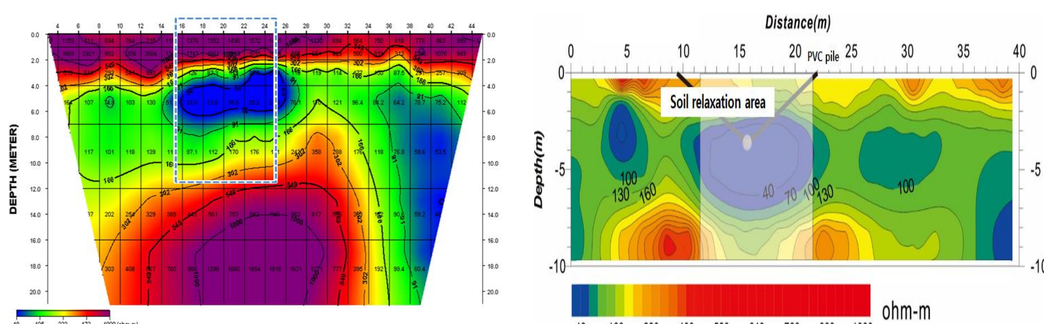


(a) Prior to Survey (b) Post Survey

Fig. 7. GPR exploration mode (Reflection mode)

V. ANALYSIS OF THE LIMITATIONS OF ELECTRICAL RESISTIVITY SURVEYING

In the case of the electrical resistivity survey, a dipole-dipole configuration having 2.0 m and 4.0 m electrode distances was applied in the survey. The results of the electrical resistivity survey indicated a distribution of overall resistivity distributions of 50 ohm-m ∼ 1000 ohm-m in which the higher distributions of resistivity were found to exist in lower depths. A relatively low resistivity value of 40 ohm-m was present at the 6.0 m depth of the groundwater level. In addition, despite the areas affected by loosened grounds that presented low resistivity, this method was limited in its ability to pinpoint the location of the affected area.



(a) Prior to Survey (b) Post Survey

Fig. 8. Electrical resistivity surveying results

VI. CONCLUSION AND RECOMMENDATIONS

Upon simulating an actual area affected by loosened grounds and underground cavities and undertaking geophysical surveying, the following conclusions regarding the limitations of geophysical surveying were reached.

1. The results of the GPR survey indicated that an antenna transmitting at a center frequency of 250 MHz was capable of surveying at an applicable depth of 3.7 m and identifying cavities of a diameter no less than 0.1 m.

2. Despite the results of an electrical resistivity survey presenting low resistivity in areas affected by loosened grounds, the survey method was found to be limited in its ability to pinpoint the location of the loosened ground.

In the case of GPR, the location of the anomaly can be identified by checking the diffraction phenomena occurring in the underground cavity. If the composite analysis is performed using the signal values and the electrical vision terms of GPR, it will be possible to confirm the accurate ground relaxation area and the result of exploration of the underground cavity.

Declaration of Conflicting Interests

No conflicts of interest.

Acknowledgments

This research was supported by the Korea Agency for Infrastructure Technology Advancement under the Ministry of Land, Infrastructure and Transport of the Korean government. (Project Number: 18SCIP-B108153-04)

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