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Measurements of dielectric constants of soil to develop a landslide prediction system

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Abstract. In this study, the measurements of the dielectric constants of soil at 900 MHz and 1 GHz were made to relate those properties to the moisture content of the soil. This study's intention was to use the relationship between the dielectric constant and the moisture content to develop a landslide prediction system. By monitoring the change of the moisture content within the soil using ground penetrating radar (GPR) systems in the field, the possibility of a landslide is expected to be detected. To establish a database for the dielectric constants and the moisture content, the measurements of soil samples were made using both an open-ended dielectric coaxial probe and the GPR. Based on the measurement results, correlations between the GPR and reflector for each frequency at 900 MHz and 1 GHz were found for the dielectric constants and the moisture content. Finally, the mechanism of the measurement device to be implemented in the field is suggested.

Keywords: dielectric constant; electromagnetic; soil; open-ended probe; radar; landslide; moisture.

1. Introduction

Landslides involve ground movement, rock falls and debris flows. One of the causes of a landslide is increasing moisture levels inside the ground. As global warming progresses, unusually heavy rainfall has been more frequently observed and is expected to increase around the world. Especially during a rainy season, rapid buildup of moisture can cause catastrophic results from an abrupt landslide. Such landslides result in human casualties, the loss of properties and traffic blocks in roads. Thus, a landslide is a complex natural phenomenon that constitutes a serious hazard in many countries (Fang *et al*. 2005). The Federal Emergency Management Agency (FEMA) in the U.S.A. designates landslides and slope failures as one of many hazards to be prepared for, in terms of public safety (FEMA, 2009). According to the statistics provided by the National Emergency Management Agency (NEMA) in Korea, landslides consist of 22% of the total casualties that have occurred in the last ten years in Korea. The death toll dramatically increases especially when there is a typhoon.

Because the build-up of moisture levels inside soil can be one of the reasons that triggers a landslide, it is necessary to monitor the moisture change in order to predict a possible landslide in an effective way. Soil and other materials have dielectric constants as a material property representing its characteristic in response to incoming electromagnetic waves (Rhim and Buyukozturk, 1998, Laurens *et al*. 2005). The dielectric constant varies as a function of frequency, moisture content, density and

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many other factors (Lunt *et al*. 2005). Thus, by measuring the dielectric constants, it is possible to relate the constants to the corresponding moisture level inside the soil.

In this study, the dielectric constants of soil were measured at 900 MHz and 1 GHz, at which a typical commercial ground penetrating radar (GPR) system operates. The dielectric constants were first measured using the GPR with varying moisture levels. Then, the same soil samples were measured again using an open-ended dielectric coaxial probe to check the accuracy of the measurements by GPR. The results showed that GPR could provide acceptable data for measuring dielectric constants of soil with up to 35% moisture content. Findings from this study can be used for developing a landslide prediction system using GPR in the field to alert of any imminent moisture buildup prior to a possible landslide.

2. Electromagnetic properties of soil to monitor moisture change

In general, dielectric materials such as concrete and soil can be characterized by two electromagnetic properties: the permittivity ε (Farads/meter, F/m) and the permeability μ (Henry/meter, H/m). The permittivity is the measure of how much resistance is encountered when forming an electric field in a medium. The permittivity relates to a material's ability to transmit or permit an electric field. This permittivity can be expressed in terms of a relative number with respect to the permittivity of a vacuum, ε_0.

$$\varepsilon = \varepsilon_r \varepsilon_0$$

where ε_r is the relative permittivity of the material, and $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m is the vacuum permittivity. ε_r is also called the dielectric constant of the material, which represents the degree of polarization within that material (Wang, 1980). The second material constant of permeability μ can be expressed again in terms of a relative number with respect to the permeability of a vacuum, μ_0.

$$\mu = \mu_r \mu_0$$

where μ_r is the relative permeability of the material, and -$\mu_0 = 4\pi \times 10^{-7}$ H/m is the vacuum permeability. Most common dielectric materials including concrete and soil, however, are nonmagnetic, which make the permeability -μ very close to the permeability of free-space -μ_0, thus, making $\mu_r = 1$. Therefore, it becomes a matter of measuring the relative permittivity or the dielectric constant of the material, ε_r, -to characterize the electromagnetic properties of the material.

For example, in Fig. 1, the measured dielectric constant of water is shown over the wide frequency range from 100 MHz to 20 GHz. The typical known value for the largest dielectric constant for water is about 80, which decreases as frequency increases. It is also observed that the dielectric constant of air (or vacuum) remains constant at the value of 1 over the frequency spectrum in Fig. 1. The change of the dielectric constant in concrete follows the trend seen in pure water as the moisture content within concrete increases, as shown in Fig. 2. Efforts have been made to establish a database for concrete as a function of moisture level (Rhim and Buyukozturk 1998). An experimental investigation of monitoring concrete dams using the moisture level variation inside the dam has also been reported (Rhim 2001). Also, measurement and modeling of moisture movement in the ground are concerns for remote sensing and monitoring (Galagedare *et al.* 2005).

The concept of the landslide prediction system is to monitor the moisture buildup inside soil using a GPR, as shown in Fig. 3. By placing a metal reflector at a distance, the electromagnetic waves

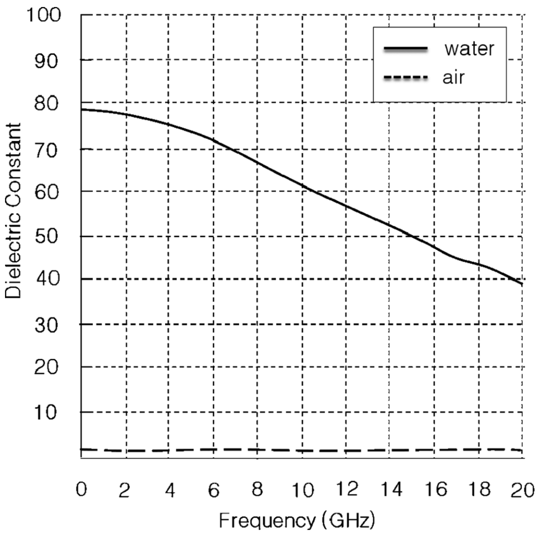


Fig. 1 Dielectric constant of water

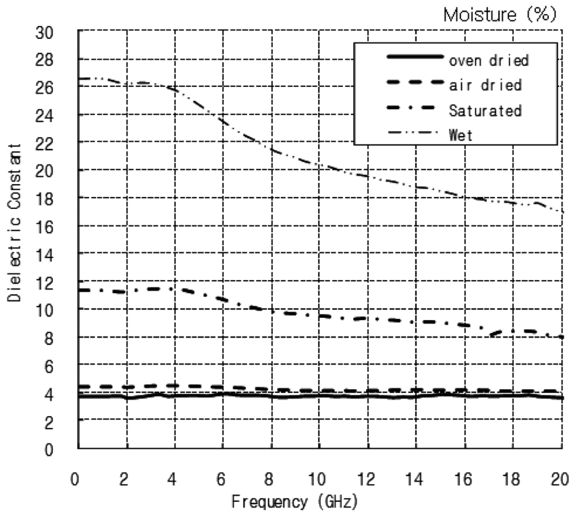


Fig. 2 Moisture variation and dielectric constants in concrete

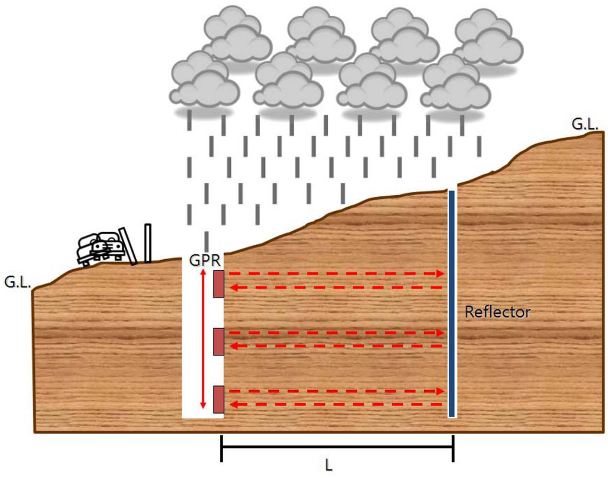


Fig. 3 Concept of *in-situ* moisture measurement system

from the GPR are reflected back with a different velocity based on the moisture level during that travel. The higher moisture content within the soil results in a slower returned signal due to the increased dielectric constant as in Eq. (3).

$$v = \frac{c}{\sqrt{\varepsilon_r}} \tag{3}$$

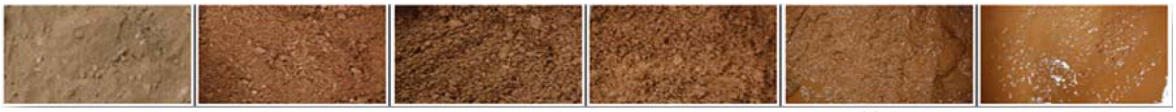
where v = velocity of wave (meter/second), c = speed of light = 3×10^8 m/s and ε_r = dielectric constant (unitless).

3. Electromagnetic property measurements using an open-ended coaxial probe

To establish a database for the dielectric constants of soil at various moisture levels, soil samples were first oven-dried. Starting with the oven-dried samples, which had zero moisture content, an exact amount of pure water was added to obtain the expected moisture content, from 5% to 35% in 5% increments. A total of eight soil samples were prepared for the measurements. The appearance of the samples is shown in Fig. 4.

An open-ended coaxial dielectric probe kit was used for the measurements of the dielectric constants of the soil samples. This method has been proven to be effective in measuring constants with accuracy (Topp *et al.* 1980). The probe was placed on the top of soil samples in a container, as shown in Fig. 5. A network analyzer was connected to the probe. As the electromagnetic signals were transmitted from the analyzer and reflected back, the dielectric constants were recorded at the measured frequency. At each frequency, a set of measurements were made 15 times to get an average value of the dielectric constant.

The results of the measurements at 900 MHz and 1 GHz are tabulated in Table 1. The change of the dielectric constants as the moisture content increases was clearly noticed and quantified. This makes it possible to apply this technique of correlating dielectric constants to different levels of moisture content. As shown in Fig. 1 for the dielectric constants of water, the constants increased in soil with increased amounts of water inside the soil. This database serves as a basis for verifying the measurements by GPR in the following experiment.



(a) 5% (b) 10% (c) 15% (d) 20% (e) 25% (f) 30%

Fig. 4 Condition of soil samples change as moisture contents increase

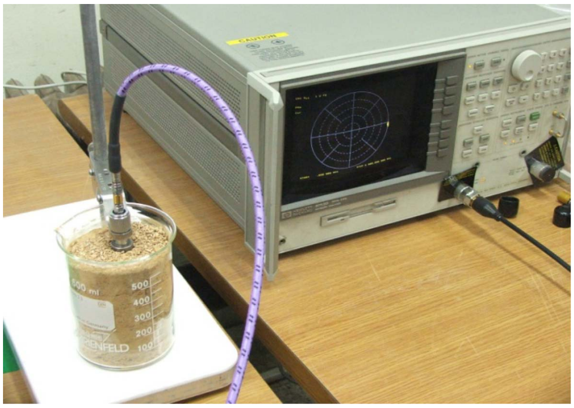


Fig. 5 Network analyzer and dielectric probe kit

Table 1 Measure dielectric constants (ε_r) over moisture variation

Moisture Content	0%	5%	10%	15%	20%	25%	30%	35%
900 MHz	2.23	3.99	5.06	13.53	29.33	37.61	44.96	65.01
1 GHz	2.28	4.02	5.10	13.56	29.31	37.59	44.95	64.96

4. Electromagnetic property measurements using ground penetrating radar

Ground penetrating radar (GPR) systems have been widely and effectively used for probing underground objects and in nondestructive testing of various structural members. Due to its ability to penetrate into any dielectric material, it is possible to detect objects embedded in another material (Weihermüller 2007, Singh 2003, Turesson 2006). In this study, a radar measurement system was proposed to measure the moisture content of soil so that the possibility of a landslide can be predicted (Galagedare *et al.* 2005, Stoffregen *et al.* 2002).

The travel time of a radar wave is determined by the velocity of the wave in a given distance. The velocity is then based on the velocity of light and the dielectric constant of the medium that the wave is travelling through. As the moisture level of soil increases, the dielectric constant becomes a larger value, which results in the slow-down of the velocity of the wave, as seen in Eq. (3). A schematic diagram of the proposed system is shown in Fig. 6. A metal plate was embedded into the soil as a reflector. At a given distance, the GPR system rolled down while sending and receiving the signal from the transmitter and reflector. By obtaining the imagery from the reflector, the round-trip travel time is calculated and the velocity is determined as shown in Eq. (4). Finally, using the relationship in Eq. (3), the dielectric constant is decided.

$$v = \frac{s}{t} = \frac{c}{\sqrt{\varepsilon_r}} \tag{4}$$

where s = round-trip distance, and t = time for the reflection. With the known values of s and c, ε_r can be determined by measuring t.

A commercial GPR system was used for the measurements. Two different antennas with 900 MHz and 1 GHz were connected to the main system, one at a time. As shown in Fig. 6, a box full of soil was measured along its side to obtain the travel time to the reflector. The metal detector was placed at different locations to examine the effect of the loss of waves as the moisture level went up. The distance for the reflector varied from 100 to 500 mm in 100 mm increment. A total of 5 different distances was used in the measurements. Sample measurement results are shown in Fig. 7. For both 900 MHz and 1 GHz measurements, returned signals are shown as a one-dimensional presentation of the results.

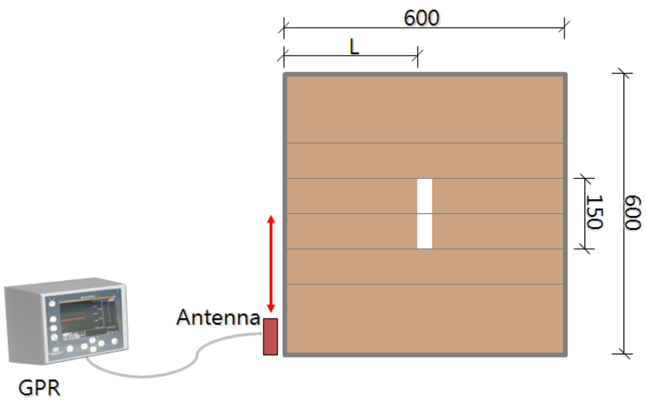


Fig. 6 A box of 600×600×150 mm with a reflector of 150×150×3 mm inside

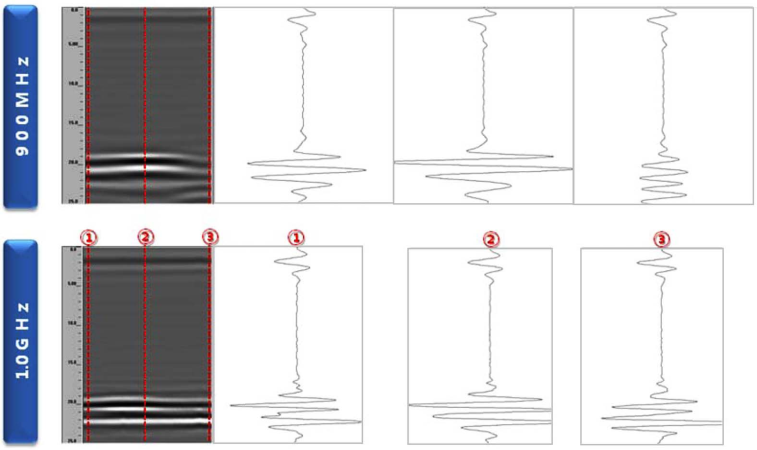


Fig. 7 Reflected signal for measurements at 900 MHz and 1 GHz

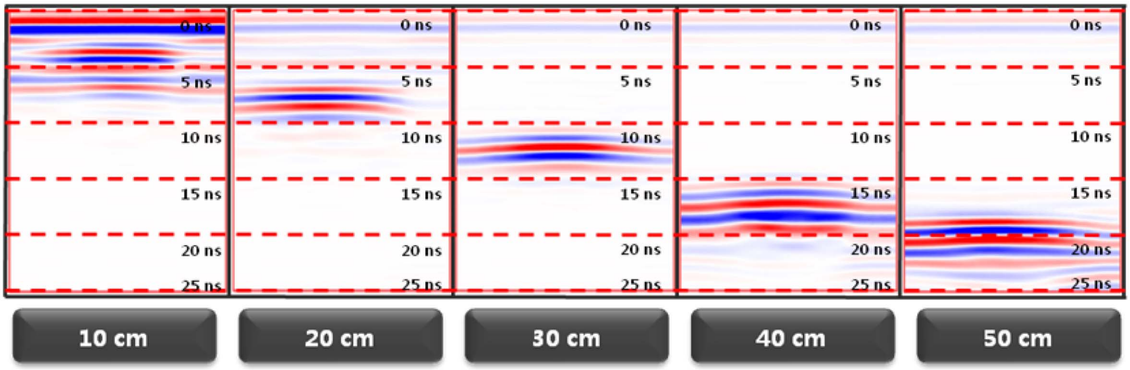


Fig. 8 A sample reflected signal showing delayed return due to both distance and moisture level

In Fig. 8, it can be clearly seen that the returned signal was further away as the distance to the metal reflector increased, in 10 cm increments. The travel time was used to calculate the dielectric constant using Eq. (4). With the presence of different levels of moisture content, the location of the reflected signal changed.

5. Measurement results and discussion

Measured data using both an open-ended coaxial dielectric probe and ground penetrating radar method are presented in Figs. 9 and 10. In Fig. 9, 900 MHz data are shown. Dielectric constants were measured at different moisture contents of 10, 15, 20 and 25%. The coaxial probe measurements (denoted as “probe” in Fig. 9) and the GPR measurements were supposed to be the same, theoretically. However, differences existed, as shown in Fig. 9. GPR measurements varied more than with the probe method. Due to the nature of the measurements, the probe method is regarded as a more exact method than GPR. In the field, on the other hand, the probe method cannot work because of its limitation in penetration capability. GPR has more power to transmit signals and to receive reflected waves.

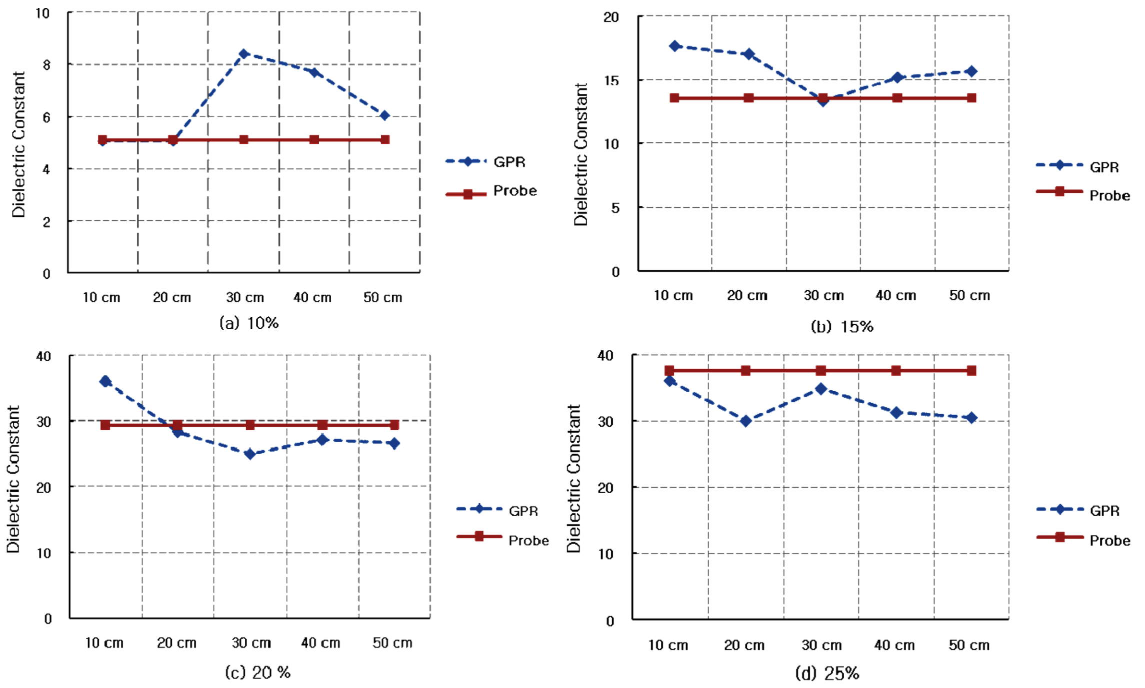


Fig. 9 Electromagnetic properties measured at 900 MHz

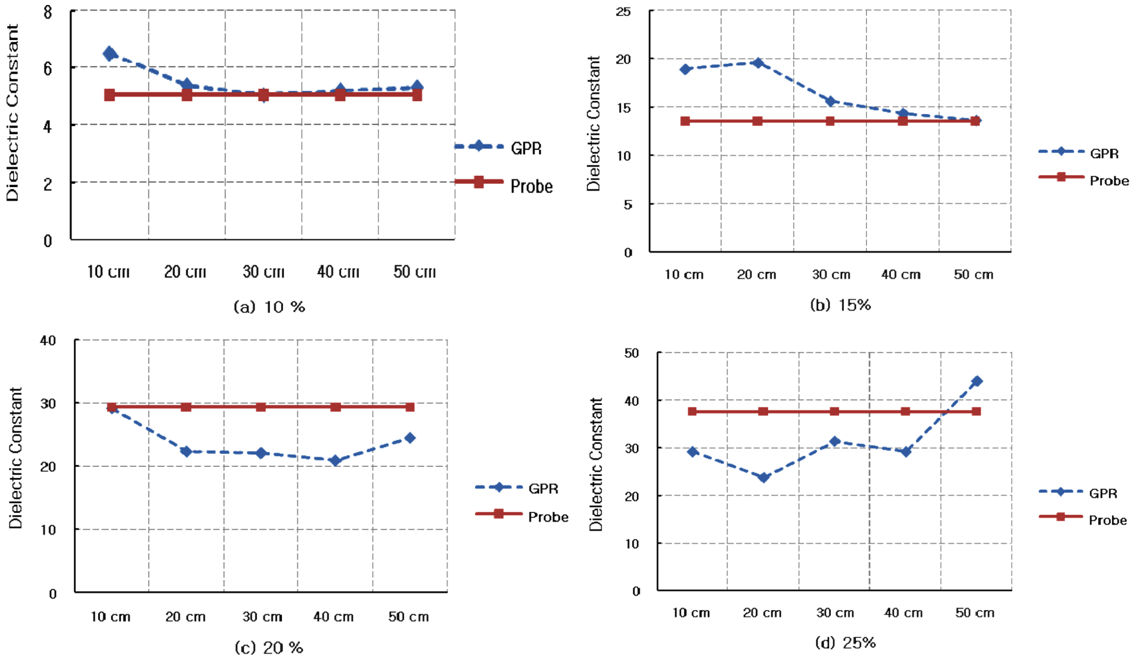
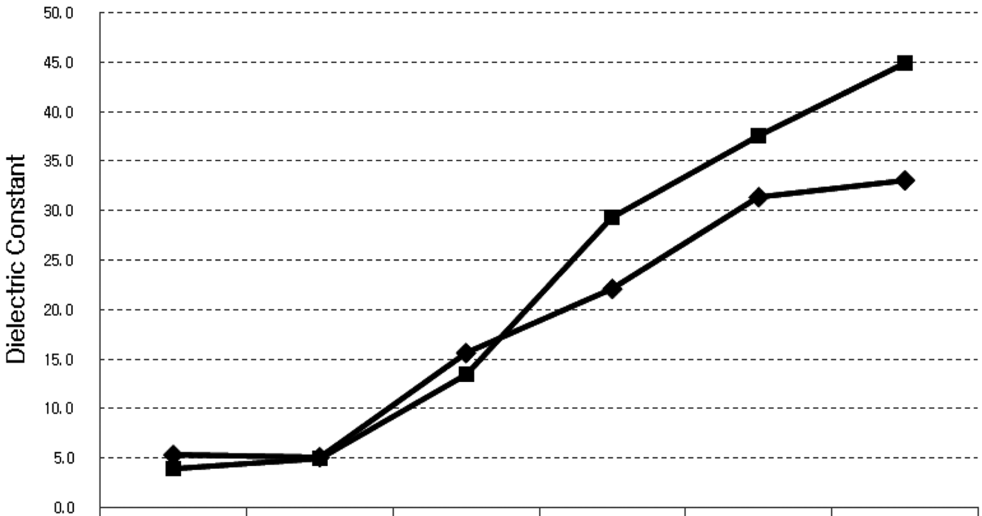


Fig. 10 Electromagnetic properties measured at 1 GHz

Measurements at 1 GHz are shown in Fig. 10. A similar phenomenon to the one found at 900 MHz can be seen. The probe method gave more consistent results than with GPR for the same



	5%	10%	15%	20%	25%	30%
GPR	5.29	5.06	15.60	22.09	31.36	33.06
EMP	3.99	5.06	13.53	29.33	37.61	44.96

Fig. 11 Electromagnetic properties vs. moisture content at 900 MHz

reason. If the difference is small, it is believed that a certain frequency works better than the other for the given condition.

In Fig. 11, the final result is presented in the graph with dielectric constant versus moisture content. The values are averaged from Fig. 9 for the different distances to the reflector. The GPR values were checked with probe measurements so that the GPR could be used for actual measurements in the field. Rainfall increases the moisture content in the slope and consequently, dielectric constants go up and are measured by GPR.

6. Development of measurement system prototype

The developed database for the electromagnetic properties of soil will eventually be used in developing a measurement system in the field. As a GPR is moving along the pre-bored hole in the slope as shown in Fig. 3, the reflected signal gives a total travel time required for the waves to complete a round-trip to the reflector. Then, based on the known distance between the GPR and the reflector, the dielectric constant is calculated, which gives the moisture content from the experimentally obtained results in the laboratory.

Once the data is secured from the measurements, eventually, a profile of moisture variations can be drawn and can be processed as an image. It can be either sent out with a digitized signal or processed internally. The developed system has now been checked for its possible deployment in the field. As the structural health monitoring techniques are being developed and readily available, it is also expected that advanced features can be added to the system (Chan *et al.* 2004, Pinelli *et al.* 2005, Chrysostomou *et al.* 2008, Shrive 2009, Fujino *et al.* 2009).

7. Conclusions

Microwave methods are used for the measurements of the dielectric constants of soil and a dielectric probe kit is used for measurements from 600 MHz to 2 GHz. The GPR system used in this study was for measurements at 900 MHz and 1 GHz. Results showed that the dielectric constants increased as the moisture level in soil increased, with the moisture level varying from 0 to 35%. The relationship between the dielectric constants and moisture content can become a basis for the development of a microwave system for the early detection of landslides.

The microwave method proposed in this study was for the detection of change in moisture in a sloped hillside area. Preliminary experiments show that the change in the location of the reflected signal helps in determining the dielectric constant of soil. This property can then be related to the moisture level of the ground. This system is for the purpose of early detection of a landslide during a rainy season. The 900 MHz results proved to be effective through the measurements. Further research will complete the system to be used in the field for practical applications.

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