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An Investigation on the Frequency Dependence of Soil Electrical Parameters

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Abstract

This paper presents the results of an investigation into the frequency-dependent electrical parameters for different types of soil as a function of moisture content. The frequency dependence of soil electrical parameters is very important in the design of grounding systems. In fact, the performance of grounding systems is greatly dependent upon various factors such as soil type, particle size, water content, temperature, frequency, and the like. The resistivity and relative permittivity for four different soils were measured and analyzed in the frequency range of 1kHz - 1MHz. Soil resistivity declined as moisture content and frequency increased. In particular, the frequency dependence of soil resistivity was significant as the moisture content was low. In contrast, the relative permittivity of soil dramatically declined at the frequency of 10kHz or below as the moisture content increased, showing the opposite pattern in terms of variation patterns, compared to resistivity.

Key Words : Soil, Resistivity, Permittivity, Frequency-Dependent Soil Parameter, Grounding System

1. Introduction

The frequency dependence of soil electrical parameters has a significant impact on the performance of grounding systems and the ground potential rises. In design and installation of grounding systems, it is very important to determine accurate electrical parameters for the soil. Because ground resistance is proportional to soil resistivity, the type of soil and moisture content are critical determinants of ground resistance[1-4]. Generally, in the design of grounding systems for low-frequency signals, soil resistivity is assumed constant and identical to the value measured at low frequency. However, the performance of grounding systems on earth current, which includes high-frequency components reaching up to several hundred kHz such as lightning surge, should be evaluated at high frequency. The frequency dependence of soil parameters such as resistivity and relative permittivity plays a key role in determining the high-frequency performance of grounding systems. Recently, many studies of the frequency dependence of soil electrical parameters have been performed by experimental approaches

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and computational simulations[5-11]. Also, it is known that electrical parameters such as soil resistivity and relative permittivity are highly dependent on the amount of water in the soil and the considered frequency. The dependence of soil parameters on moisture content is a basic factor that determines the performance of grounding systems. In addition, the frequency dependence of soil resistivity and relative permittivity can affect the transient behavior of grounding systems[12]. To assess the high frequency performance of grounding systems, an analysis of variation by the frequency of soil parameters is very important. The soil resistivity value is an essential factor in the design of grounding systems[13].

With an aim of analyzing influential factors of the high-frequency performances of grounding systems, this study measured soil resistivity and relative permittivity by frequency and investigated their characteristics. For this analysis, the measurements of the soil resistivity and relative permittivity were made as a function of the moisture content for four different soils. Then, the factors influencing the frequency dependence of soil electrical parameters were analyzed. Basic data for use in analyzing the high-frequency performances of grounding systems were obtained.

2. Experiments

2.1 Experimental Arrangement

To measure the frequency-dependent characteristics of soil resistivity and relative permittivity by moisture content, the experimental arrangement was configured as shown in Fig. 1. For the measurement of soil parameters, a two-electrode method was used [14-15]. Copper electrodes were attached to the top and bottom of the cylindrical container. The measurement chamber was 230mm in diameter with 50mm of electrode spacing. At measurement, 5kg of pressure was applied to the upper electrode.

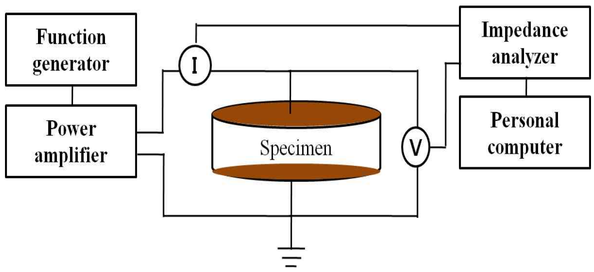


Fig. 1. Schematic diagram of the experimental setup

A sinusoidal current is supplied to both plates by a function generator and power amplifier. The test current and voltage are detected by using the active current probe and differential voltage probe. The impedance of sample soils is measured as a function of frequency and the soil resistivity and relative permittivity are calculated from the amplitude and phase angle of the impedance with a PC-based impedance analyzer. The moisture content in soil refers to percentage water content by weight[13]. The line filter and isolating transformer were installed on the power lines of the instruments to reduce noise and disturbances. The specifications of

Table 1. Specifications of main equipment used in this work

Items		Specifications
Power amplifier	Frequency	DC~1MHz, 40W
		10kHz~250MHz, 75W
Function generator	Frequency	DC~80MHz
Oscilloscope	Frequency	4 Channels, 500MHz
Voltage probe	Voltage	0~2.2kV
Current probe	Current	0.6~60kA
	Frequency	0.1Hz~16MHz

power sources and measuring instruments employed in this work was tabulated in Table 1.

2.2 Samples and Method

In terms of samples, the following four soils were examined: sand, loess, silt and gravel. Using a standard sieve, the particles of target soils were classified by size. The classification of soil by the size of particles is summarized in Table 2.

Table 2. Types of soil employed in this work

Type of soil	Size of particle (mm)
Sand	2 or less
Loess	2 or less
Silt	3 or less
Gravel	4 - 7

When considering saturated moisture, the moisture content was measured within 1-15%. For the adjustment of moisture content in soil, 70Ω · m of tap water was used. The test current and voltage were measured by adjusting the frequency from 1kHz to 1MHz, and the impedance was directly calculated in a detected voltage-current ratio. The electrical equivalent circuit of the measuring system is shown in Fig. 2, and soil resistivity and relative permittivity can be determined as follows[16]:

$$\rho = \frac{AZ^2}{lR_e} \tag{1}$$

$$\epsilon_s = \frac{lI_m}{\epsilon_0 \omega A Z^2} \tag{2}$$

Where, A is an electrode area, and l is electrode gap distance. In equation (1), the impedance consists of actual-part and imaginary-part components and is expressed in resistance, capacitance, and frequency. Because the electrode area and electrode gap distance are constant, the soil resistivity ρ in Ω · m and relative permittivity ϵ_s can be calculated from the equations (1) and (2).

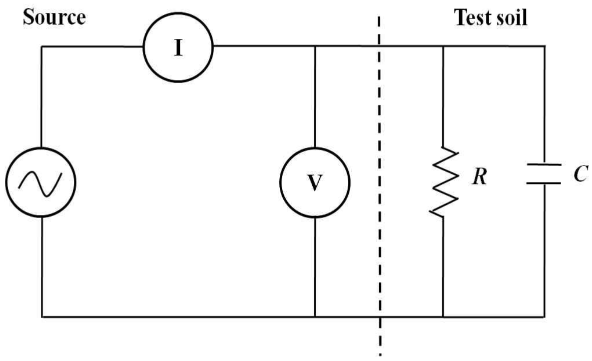


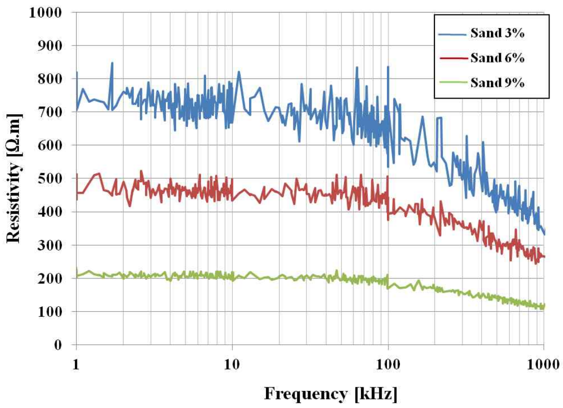
Fig. 2. Electrical equivalent circuit of the experimental setup

3. Results and Discussion

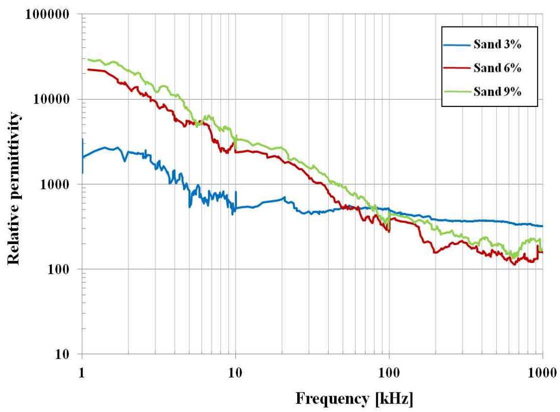
3.1 Sand

The analysis of the frequency dependence of soil electrical parameters is very important when grounding systems are subjected to lightning currents[12-13]. Thus the changes of soil resistivity and relative permittivity are examined in the range of lightning current frequency components. The measured results are quite impressive. The frequency dependence of electrical parameters of sand measured at 3, 6 and 9% of moisture content is illustrated in Fig. 3.

As the moisture content increased, the resistivity declined almost proportionally. The resistivity values at 1kHz decrease to around 60% at 1MHz and frequency dependence is pronounced at low moisture contents. However, relative permittivity increases with moisture content. At low moisture content, the frequency dependence of soil resistivity leads to a smooth change, but the frequency dependence of relative permittivity is loose. At 100kHz or below, the frequency dependence of the resistivity was weak. When the frequency exceeded 100kHz, however, it declined. As the moisture content increased, the frequency dependence of resistivity decreased.



(a) Resistivity

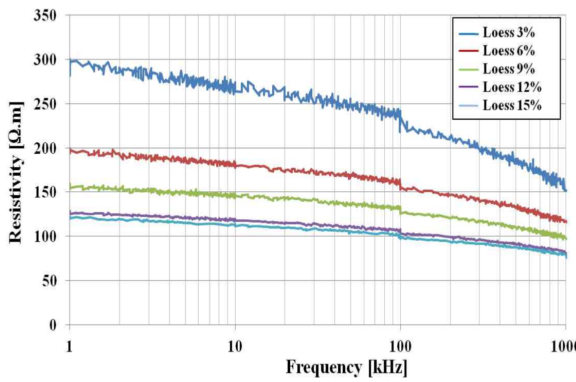


(b) Permittivity

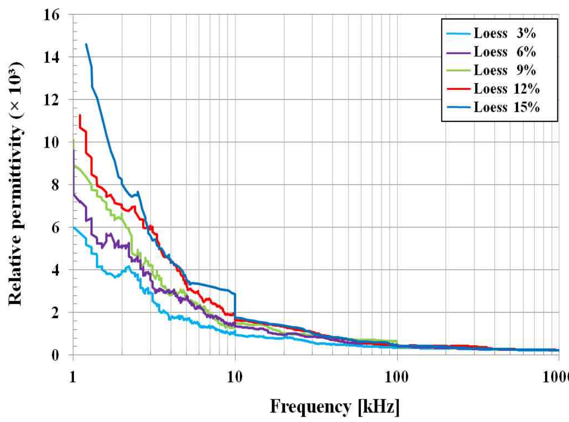
Fig. 3. Frequency-dependent electrical parameters of sand as a function of moisture content

Over a frequency range of 10kHz or above with 3% of moisture content, the frequency dependence of relative permittivity was weak. When the moisture content was 6% or greater, it gradually declined as the frequency increased. However, the variation caused by the moisture content was slight. In terms of the variation trends of electrical parameters by frequency, current was most resistive at 100kHz or below. When the frequency exceeded 100kHz, the dominant capacitive aspect was observed.

3.2 Loess



(a) Resistivity



(b) Permittivity

Fig. 4. Frequency dependent-electrical parameters of loess as a function of moisture content

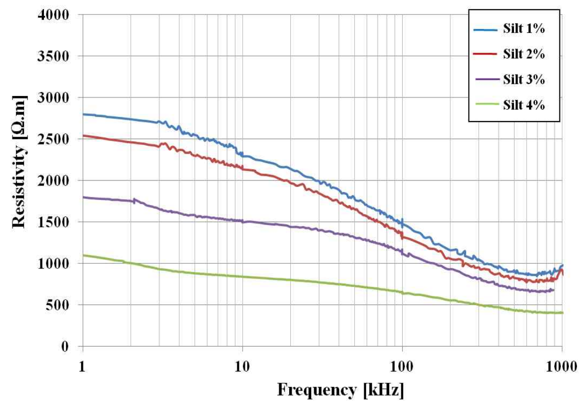
Soil resistivity and relative permittivity by the size and type of particles and moisture content are critical factors in determining the electrical characteristics of soil. Therefore, it is necessary to analyze the effects on electrical parameters. The detailed results for the frequency dependence of resistivity and relative permittivity of loess with moisture content as the parameter were described in [13]. Fig. 4 indicates the resistivity and relative permittivity behavior as a function of frequency at each moisture content level.

The frequency dependence of electrical parameters in loess is significantly changed in relation to the moisture content. The reduction of soil resistivity is more pronounced at lower moisture contents. When the moisture content of loess was 3%, the resistivity was 320Ω·m at the frequency of 1kHz. It gradually declined as moisture content increased, and peaked at 130Ω·m at 15%. As moisture content increased, in addition, relative permittivity decreased. This aspect of variation took place because the resistive current component was active at high frequency as the moisture content increased[13]. The relative permittivity drastically declined at the frequency of 10kHz or below. It decreased further as moisture content increased. The decrease in resistivity slowed down at a frequency of 10kHz or above. The frequency dependence of relative permittivity was minor at the frequency of 100kHz or above with almost no effect by moisture content.

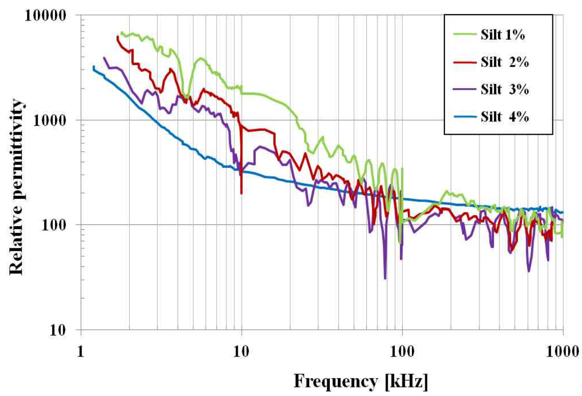
3.3 Silt

In silt, which is relatively small in terms of soil particle size, the frequency dependence of electrical parameters was measured in the range of 1-4% of moisture content. The results in the frequency range from 1kHz to 1MHz are shown in Fig. 5.

There is a significant frequency dependence of resistivity and permittivity in the frequency range of 1kHz - 1MHz, which is the typical frequency component of lightning currents[17]. The soil resistivity almost linearly declined in inverse proportion to an increase in moisture content. The frequency dependence of resistivity was strong as moisture content decreased[18].



(a) Resistivity



(b) Permittivity

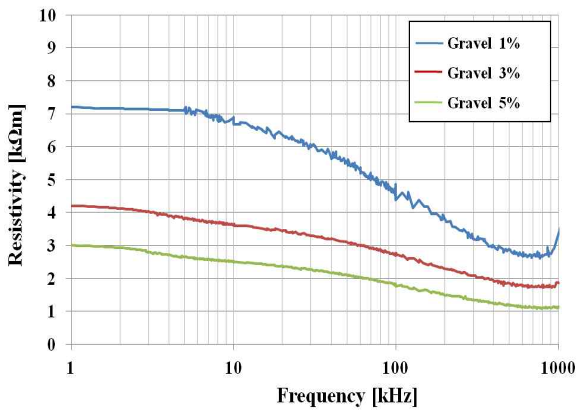
Fig. 5. Frequency dependent electrical parameters of silt as a function of moisture content

The relative permittivity of silt increased as the moisture content increased at the frequency of 100kHz or below. When the considered frequency exceeded 100kHz, however, the effects of moisture content were negligible. In the frequency range of 10kHz - 1MHz, relative permittivity by moisture content ranged from around hundreds to several thousands. In general, the relative permittivity of soil only is 10 or less. As the soil contained water, the effects of the water caused by water polarization became far stronger than the relative permittivity of the soil itself.

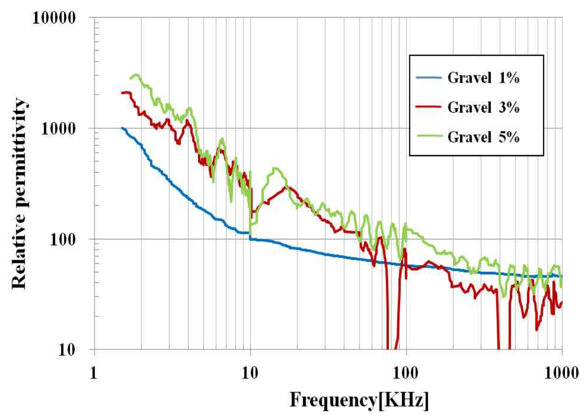
3.4 Gravel

The frequency dependence of electrical parameters was measured as a function of the moisture content of gravel, which is known to have dominant electronic conduction under dry conditions. The measurements were made for three different moisture content levels. Fig. 6 shows the experimental results over the frequency range of interest for different values of moisture content. The moisture content is responsible for decreasing the values of resistivity throughout the frequency range measured, while relative permittivity is influenced reversely. In particular, at low moisture content, the frequency dependence of soil resistivity becomes more dominant.

At the frequency of 1kHz, resistivity was about 7,200Ω·m when the moisture content was 1%. It dropped to 3,000Ω·m at 5% of moisture content. As the considered frequency increased, resistivity declined[18]. When the moisture content was 1%, the frequency dependence of resistivity was significant at a frequency of 10kHz or above. As moisture content increased, the frequency dependence of resistivity tended to slow. On the other hand, the relative permittivity drastically decreased at the frequency of 10kHz or below.



a) Resistivity

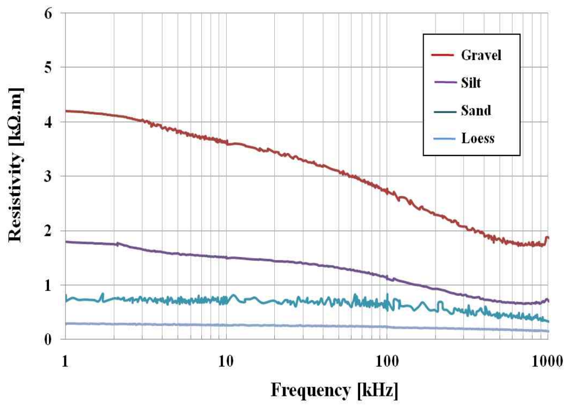


(b) Permittivity

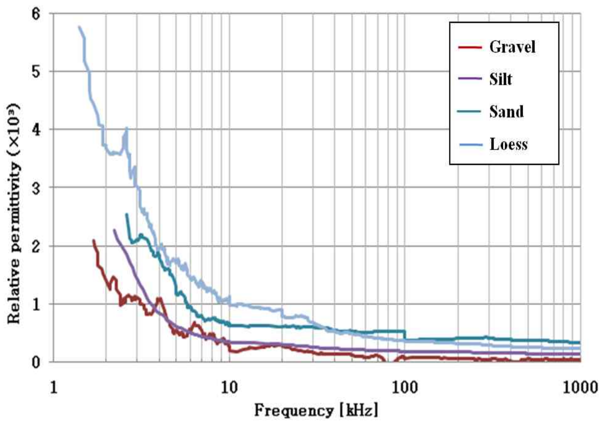
Fig. 6. Frequency dependent electrical parameters of gravel as a function of moisture content

3.5 Comparison of the frequency-dependent electrical parameters for different soils

The characteristics of soil resistivity and relative permittivity by frequency at a moisture content of 3% were compared, and the results are illustrated in Fig. 7 for different types of soil. When soil resistivity was low, as with loess and silt, no significant variation by frequency was observed. As the soil resistivity increased, frequency dependence became significant because the capacitive current increased as the frequency increased. In terms of relative permittivity, a great difference was found in reverse order of resistivity depending on the type of soil[18]. At a frequency of 10kHz or below, the soil relative permittivity dramatically declined. As the frequency increased, the relative permittivity decreased almost exponentially. When the frequency exceeded 10kHz, the variation declined considerably.



(a) Resistivity



(b) Permittivity

Fig. 7. Comparison of frequency-dependent soil parameters at a moisture content of 3%

Similar results were found in previous studies[10,19]. In the frequency range of 1kHz - 1MHz, the variation of resistivity was about 30% in loess, which has low resistivity. In the high resistivity of gravel, on the contrary, the variation was 60% or more. The frequency dependence of the resistivity leads to a smooth variation for low resistivity soils, while the frequency dependence of relative permittivity is more significant for high resistivity soils. The experiments showed that the frequency dependence of the soil resistivity and relative permittivity are closely related with moisture content. The effect of moisture content on the frequency dependence of the soil resistivity is more pronounced for high resistivity soil. Therefore, it appears that the analysis of the frequency dependence of soil resistivity and permittivity would make a contribution to the improvement of the high frequency performances of grounding systems. It is expected that the results presented in this paper will be useful for understanding and estimating high frequency performance of grounding systems for lightning protection.

4. Conclusion

Through experimentation, this study analyzed the frequency dependence of soil electrical parameters, which are essential in determining the high-frequency performances and transient characteristics of grounding systems, and found the following:

1) The soil resistivity declined as moisture content and frequency increased.
2) Unlike the frequency dependence of soil resistivity, the relative permittivity of soil revealed great variation by frequency when resistivity was low. In the frequency range of 10kHz or below, it drastically declined as frequency increased.
3) The frequency dependence of soil resistivity was significant as resistivity increased because of low moisture content.

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