Chapter 5 Instruments for Electromagnetic Property Measurements

5.1 Introduction

An electromagnetic property measurement system is usually composed of a probe, a signal generator, a signal receiver, a signal analyzer, and the cables connecting them. The signal generator, receiver, and analyzer are usually integrated and can be divided into two categories – network analyzer and cable tester. The network analyzers, although having superior frequency domain capabilities, are more expensive and not particularly suitable for field use. The cable testers are rugged, portable and battery-powered and therefore suitable for practical field measurements. The probe refers to the part that guides the generated EM waves through a soil. It has various forms, including two-terminal electrodes, four-terminal electrodes, coaxial chamber, single-head dielectric probe and multi-wire electrodes. A time domain reflectometry (TDR) system is composed of a cable tester in connection with a coaxial chamber or a multi-wire probe. Commonly used signal analyzers and probes are listed in Table 5.1.

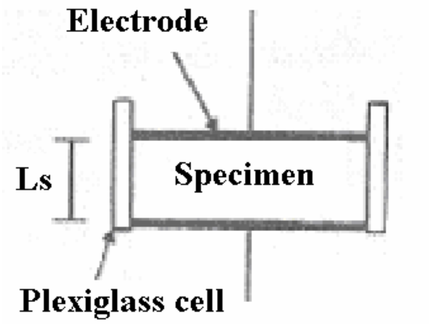
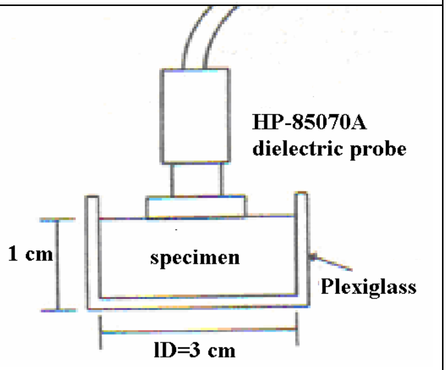
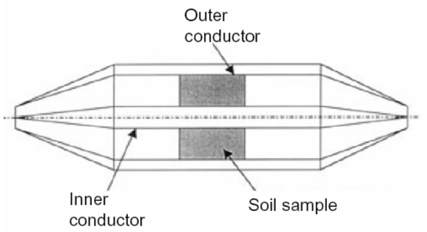
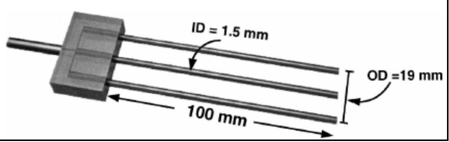
A significant drawback of the two or four terminal electrode probe is electrode polarization. In the lower MHz frequency range, electrode polarization usually makes the measured real permittivity higher than the actual real permittivity of a soil. This effect is especially significant when the electric conductivity of a soil is high. The cylindrical chamber developed by Shang, et al. (1999) can be used to measure soil electromagnetic properties in the lab but is not suitable for in-situ testing. Moreover, the EM measurements using the cylindrical chamber are subjected to the influences of the longitudinal resonance and circumferential resonance, which are detrimental to correctly measure soil EM properties. The single-head dielectric probe used by Klein and

Santamarina (1997) can provide good measurements for the dielectric spectra of soils from about 20 MHz to 1 GHz. It is a convenient and reliable apparatus to measure soil dielectric spectra in the lab but is not suitable for in-situ testing because the volume of a soil that can be measured by this type of probe is very small. The time domain reflectometry is less susceptible to electrode polarization, relatively cheaper and adaptable for in-situ measurements. However, numerical transformation is needed to convert the TDR signals from time domain to frequency domain.

After a comparison of various apparatuses, the Hewlett-Packard HP-8752A network analyzer in conjunction with the HP-85070A dielectric coaxial termination probe were chosen to measure soil electromagnetic properties in the lab to verify the theory developed in Chapter 3. The tests were performed at Georgia Institute of Technology under the direction of Prof. Santamarina.

To make the in-situ dielectric spectrum measurement possible, the time domain reflectometry system (TDR100 in conjunction of a three-rod probe CS605 from Campbell Scientific) was used to measure the electromagnetic properties of natural soils in this study. The TDR100 system and the principle of the time-domain waveform analysis will be introduced in this chapter. The time domain to frequency domain transformation will be discussed in Chapter 7.

Table 5.1 Commonly used electromagnetic property measurement system

	Type	Probe	Measuring frequency range	Probe configuration
Network analyzer	HP4191A	Two terminal electrodes	Usually less than 100 MHz	
	HP8752A	Single-head dielectric probe HP85070A	20 MHz – 1.3 GHz	
	HP8753D or HP 8714B	Cylindrical chamber	Low MHz – 3 GHz;	
Cable tester	Tektronix 1502 B/C	Coaxial chamber or multi-wire probe	Time domain (transformable to 20 MHz to 1.5 GHz)	

Sources: (Arulanandan and Yogachandran (2000), Klein and Santamarina (1997), Shang, et al. (1999), Friel and Or (1999)

5.2 Network analyzer

The network analyzer system used in this study is shown in Figure 5.1. The system is composed of the network analyzer HP8752 A, a coaxial cable and a computer to operate the system. The soil samples are placed in a plastic container with a diameter of about 0.8 inch (2 cm) and a depth of about 0.6 inch (1.5 cm). The diameter of the probe head is slightly smaller than that of the plastic container. The network analyzer HP8752A was designed to measure the equivalent dielectric permittivity over the 300 kHz to 4 GHz frequency range. The actual frequency band that the system can measure is limited by the coaxial cable HP85070A, which was designed to measure the EM properties over the 200 MHz to 1.3 GHz. However, the system is still able to correctly measure soil EM properties at a frequency 20 MHz. At frequencies lower than 20 MHz, the measured EM properties are unreliable.

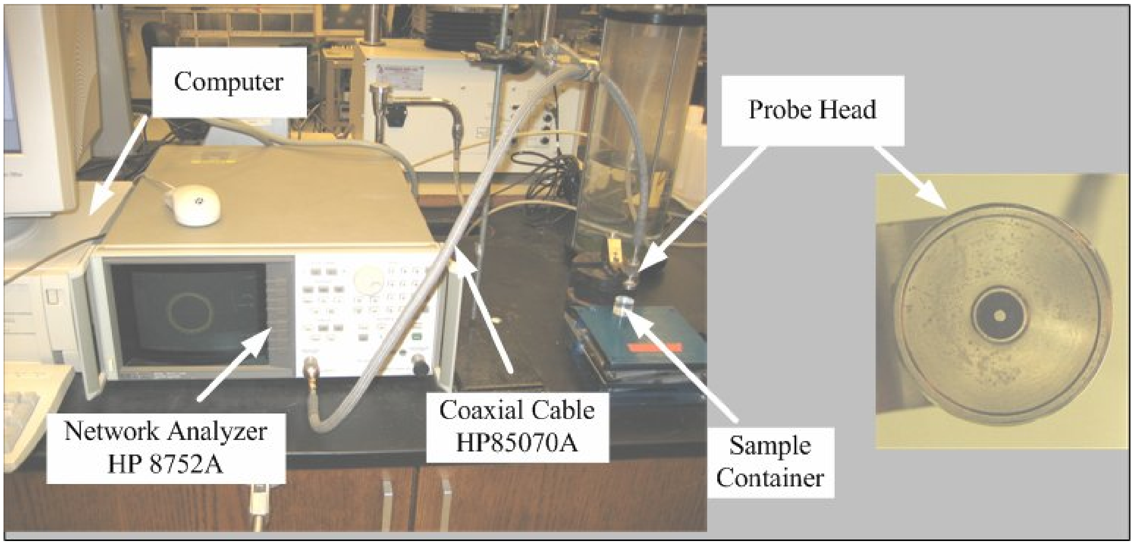


Figure 5.1 Network Analyzer HP8752A in conjunction with coaxial cable HP85070A

Before measuring the EM properties of soils, the system needs to be calibrated by measuring the impedances of air (open circuit), metallic shorting block (short circuit), and deionized water. The system is very sensitive to the deformation of the coaxial cable. Therefore, recalibration is necessary whenever the coaxial cable is moved.

The EM waves generated by the network analyzer propagate through the coaxial cable to the probe head, where they are partially reflected. Then, the EM properties of the material in contact with the probe head can be determined from the reflected EM waves because the magnitude and phase delay of the reflected waves are determined by the electromagnetic properties of the material in contact with the probe head. The principles of the EM wave propagation in the coaxial cable are exactly the same as the time domain reflectometry system, which will be discussed in Chapter 7.

In this study, the frequency dependent dielectric spectra of the kaolinite-water mixture, bentonite-water mixture and mixtures of bentonite, silicon flour and water were measured using the network analyzer. The dielectric spectra of these soils have been presented in Chapters 3 and 4 to verify the theoretical model and investigate the influences of compositional and structural factors.

5.3 Time Domain Reflectometry System

Firstly developed in the 1950s to locate and identify cable faults in the power and telecommunication industries, time domain reflectometry (TDR) technology began to be applied for geomaterials in the 1970s (O'Conner 1999). To date, the most popular application of the TDR in geotechnical engineering is for the volumetric water content and soil bulk electrical conductivity measurements. TDR has been proved to be a reliable, fast and safe technology for monitoring in-situ water contents of many soils (Benson 1999; Noborio 2001). The TDR100 system used in this study is produced by the Campbell Scientific Co. Its configuration is shown in Figure 5.2.

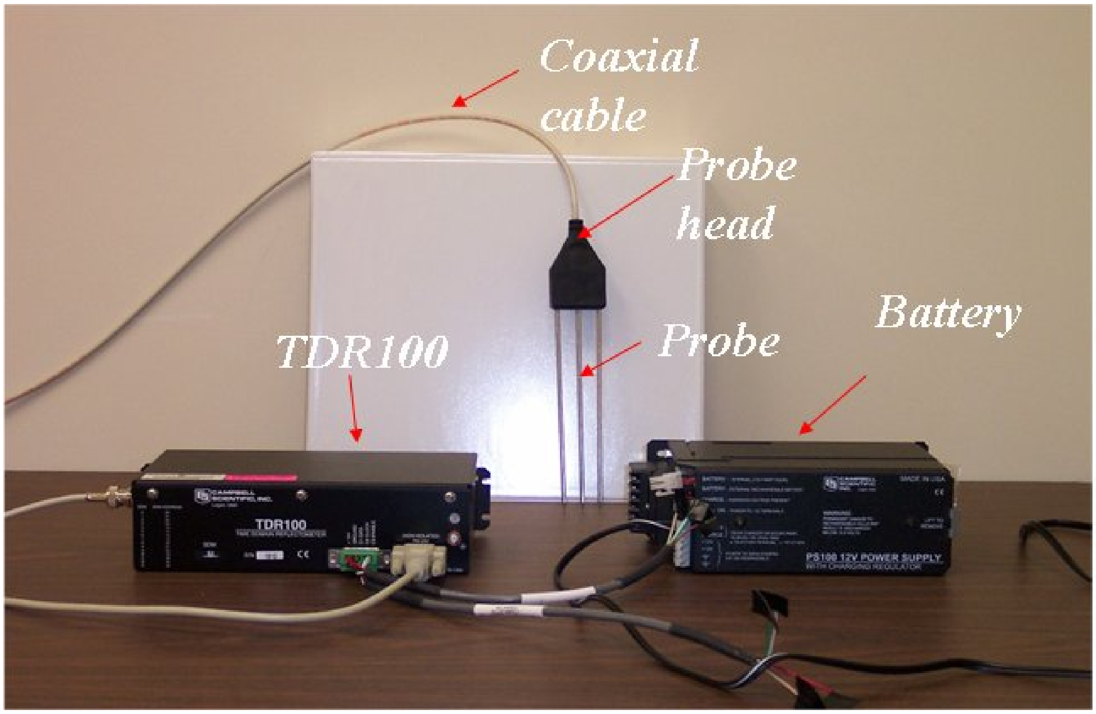


Figure 5.2 TDR100 system (including a three-rod probe and battery)

The mechanism of using TDR for soil electromagnetic property measurements is to analyze how the input step voltage generated by the TDR is affected by the soil through which it travels. The input and reflected voltages are digitized and plotted as a function of time, which is referred to as the time domain waveform, or simply the TDR waveform as illustrated in Figure 5.3. By measuring the travel time of the pulse in the TDR probe, an apparent dielectric permittivity can be determined, from which the volumetric water content can be estimated because the apparent dielectric permittivity was found to be closely related to the volumetric water content of a soil (Roth et al. 1992; Topp et al. 1980).

The TDR waveform is obtained by superimposing the reflected voltages from the probe on the step voltage generated by the TDR signal generator. After all the reflections from the probe are superimposed, the recorded voltage reaches a stable value (V_f) and the time-domain dielectric spectrum becomes leveled.

As illustrated by Figure 5.3, the speed at which the voltage travels in the probe is calculated using v=2L/t, where L is the length of the probe and t is the time for the voltage to complete a round trip in the probe.

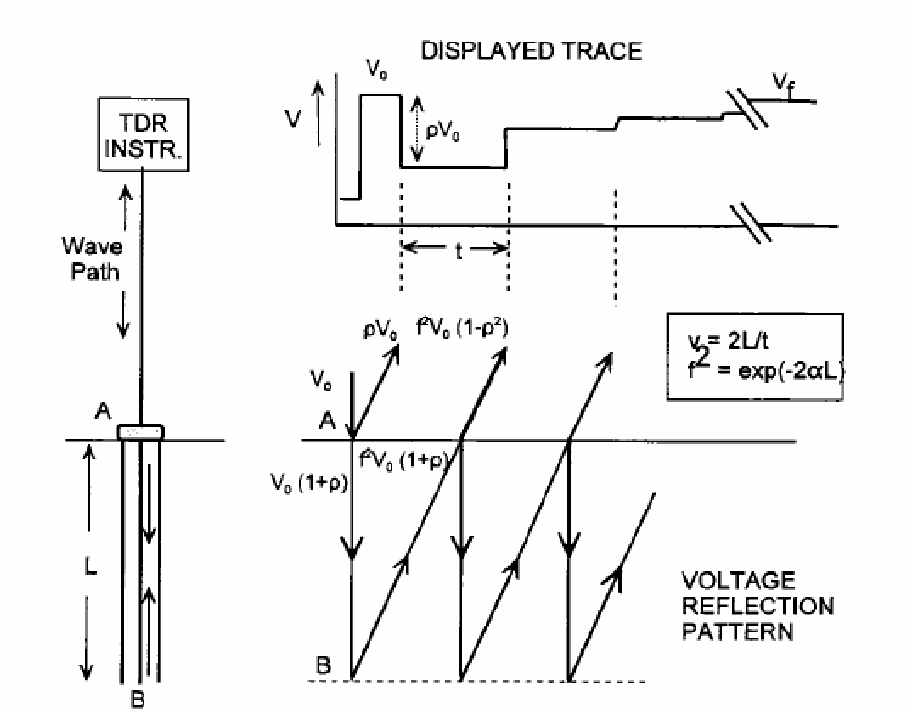


Figure 5.3 Schematic diagram of time domain reflectometry system (left), idealized trace (upper right), and voltage reflection pattern (lower right) (from Topp et al. 2000)

The step voltage generated by the pulser contains EM waves with frequencies over a wide frequency range. The demonstrated waveform assumes that the EM waves at different frequencies propagate at the same speed in the probe, which is only true when the probe section is lossless, e.g. probe in the air. When the probe is inserted into a conductive soil, the EM waves at different frequencies propagate at different speed and the time for them to complete one round trip is different.

5.3.1 Apparent dielectric permittivity and its physical meaning

The time domain waveform of a saturated sand-water mixture was measured by TDR as shown Figure 5.4. Here, the vertical axis is plotted as the coefficient of reflection ρ, which is the recorded voltage normalized by the voltage before the first reflection from the TDR probe is detected by the signal receiver V_0:

$$\rho = \frac{V(t) - V_0}{V_0} \qquad [5.1]$$

Correspondingly, ρ_∞ is the coefficient of reflection at infinite time:

$$\rho_\infty = \frac{V_f - V_0}{V_0} \qquad [5.2]$$

where V_f is the voltage after all reflections from the probe are finished as illustrated in Figure 5.3. The time interval *t* is the time for the pulse to finish a round trip in the probe. Point A corresponds to the time when the signal reaches the interface between the probe head and the soil. Point B corresponds to the time when the signal finishes one round trip in the probe.

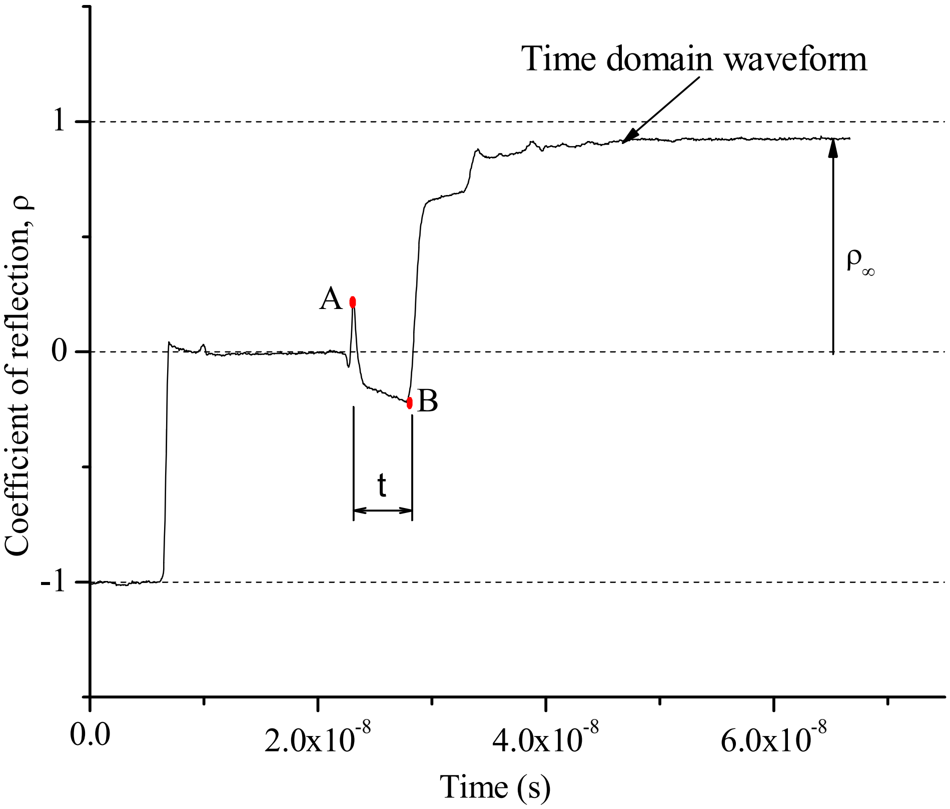


Figure 5.4 TDR waveform of the saturated sand

The actual velocity at which EM waves travel in the probe is frequency-dependent:

$$v = c / \sqrt{\kappa * (f)} \qquad [5.3]$$

Where c is the velocity of light ($3*10^8$ m/s) and $\kappa * (f)$ is the equivalent dielectric permittivity of the soil.

$$\kappa^* = \kappa' - j\kappa^{ii} = \kappa' - j\left(\kappa'' + \frac{\sigma_{dc}}{2\pi f \varepsilon_0}\right) \qquad [5.4]$$

in which, k' and k'' are the real and imaginary components of the dielectric permittivity; σ_{dc} is the DC electrical conductivity of the soil.

Since the dielectric permittivity of plastic soils is not a constant, the EM waves generated by the TDR signal generator have different time-delay in the probe. Theoretically, the calculated apparent dielectric permittivity corresponds to the EM wave component that travels fastest in the soil, which is also the EM wave component with the highest frequency. However, the higher frequency component of the TDR signal is of much less energy than the lower frequency component of the signal, and they may be attenuated in the propagation process without being detected by the cable tester. Therefore, the calculated apparent dielectric permittivity, obtained by picking up two points where voltage changes abruptly, has an undetermined frequency.

Even though the actual frequency of the TDR measurement is unknown, a correlation between the apparent dielectric permittivity and the volumetric water content was established by Topp et al. (1980):

$$\theta = 4.3\times10^{-6}\kappa_a{}^3 - 5.5\times10^{-4}\kappa_a{}^2 + 2.92\times10^{-2}\kappa_a - 5.3\times10^{-2} \qquad [5.5]$$

The correlation works well for saturated non-plastic or low-plasticity soils because the dielectric permittivities of those soils do not change much with frequency. Since the real permittivity of the water ($\kappa_w^{'} \approx 80$) is much higher than that of the solid soil particles ($\kappa_s^{'} \approx 5$) and air ($\kappa_a^{'} = 1$), the measured apparent dielectric permittivity is largely determined by the amount of water in the soil. Thus, the volumetric water content is approximately determined by the apparent dielectric permittivity.

5.3.2 Determination of soil bulk electrical conductivity from TDR waveform

The bulk soil electrical conductivity can be calculated from the reflection coefficient of the TDR waveform after all reflections from the probe are finished. The resistance measured by TDR is equivalent to the low-frequency resistance of the soil between the probe rods.

$$\sigma_{dc} = \frac{K}{Z_c} \cdot \frac{1-\rho_\infty}{1+\rho_\infty} \qquad [5.6]$$

in which K is probe constant, which is only related to the geometry of the probe. Z_c is the impedance of the coaxial cable (= 50 ohm). The DC electrical conductivity can be reliably measured using time domain reflectometry if the probe constant K is correctly calibrated.

5.4 Problems in Measuring the EM Properties of Soils

Many types of apparatuses can be used to measure the electromagnetic properties of soils. However, the measured dielectric permittivity may differ from the true values of the tested soil because of measuring system effects. Factors that may lead to the differences between the measured and true EM properties of soils include: oxidation-reduction reactions at the electrode-material interface, ionic diffusion within the diffuse layer, the cable conductance, fringe/edge effects, and most significantly, electrode polarization.

5.4.1 Electrode polarization

Electrode polarization is due to the migration of some electrons from the metal probe into the conductive fluid. The migration is caused by the difference in electronegativity between the ions in solution and the metal of the probe (Lyons 1967). As a result, ions in the specimen migrate towards the metal probe, creating a cation layer between the metal probe and the specimen. This cation layer acts as a capacitor in series connection with the specimen.

The influences of electrode polarization on dielectric property measurements were studied by Klein and Santamarina (1997) for a two-terminal system consisting of two parallel disk electrodes as shown in Table 5.1. It was found that the limiting frequency at which electrode polarization begins to manifest itself increases as the specimen conductivity increases. Below the limiting frequency, electrode polarization may overwhelm the material behavior and the experimental data become unreliable. The minimum frequency above which electrode polarization does not significantly affect the measurement $f_{\mathrm{lim}it}$ (the limiting frequency) was derived by Klein and Santamarina (1997) as:

$$f_{\mathrm{lim}it} = \frac{1}{2\pi}\frac{\sigma_s}{\varepsilon_0}\sqrt{\frac{1}{\kappa'_s\, e_\kappa}\frac{L_e}{L_s}} \qquad [5.7]$$

where L_s = specimen thickness, L_e = the equivalent thickness of the ion layer at the electrode, κ'_s = the real permittivity of the specimen, σ_s = the DC electrical conductivity of the specimen, e_κ = the acceptable error in the real permittivity measurement.

The thickness of the equivalent thickness of the ion layer L_e is much smaller than the specimen thickness L_s. A value of $L_e / L_s = 10^{-7}$ was assumed by Klein and Santamarina (1997). The relationship between the limiting frequency (Hz) and the electrical conductivity (S/m) is shown in Figure 5.5 when the real permittivity of the soil κ'_s equals to 10, 20, 30. An acceptable error e_κ of 10 percent was assumed in the calculation. It was found that, at frequencies lower than 1MHz, an error of more than 10% can be caused by electrode polarization if the DC electrical conductivity of the specimen is higher than about 0.1 S/m.

Several methods had been proposed to eliminate or minimize deviations due to electrode polarization, such as using reversible electrodes (Scott et al. 1967), adding an insulation layer (McGehee 1988), measuring at two different sample lengths (Schwan 1962; Hill 1969), and substitution techniques (Schwan 1962; Hill et al. 1969). However, the effectiveness and reliability of these methods are still questionable.

For a coaxial termination probe, the limiting frequency above which reliable measurements can be made is also related to the DC electrical conductivity of a soil (Klein 2004).

$$f_{\lim it} = -6.4\sigma_s^{\ 2} + 135\sigma_s + 20 \ \text{[MHz]} \qquad [5.8]$$

It can be seen from Figure 5.5 that the limiting frequency of coaxial termination cable is much higher than that of the two-terminal system. As a result, the coaxial termination cable should be used to measure the soil electromagnetic properties at frequencies higher than 20 MHz.

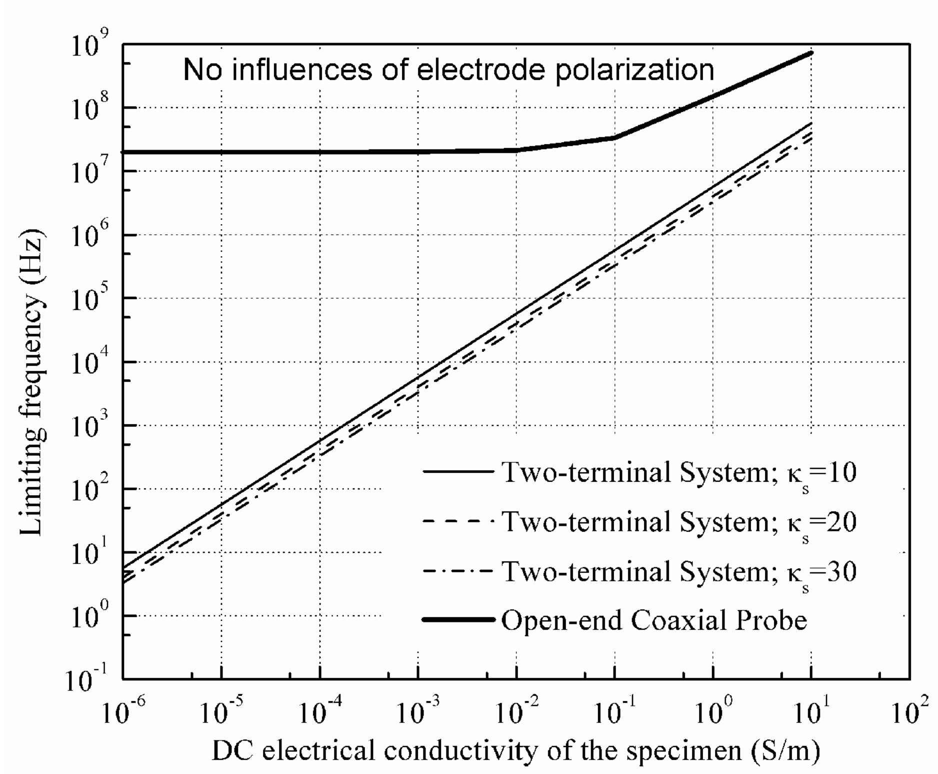


Figure 5.5 Limiting frequencies for the open-end coaxial probe and the two-terminal electrode system corresponding to an error of 10%

5.4.2 Penetration depth

The attenuation of electromagnetic waves in conductive soils is one of the obstacles that hinder the applications of EM measurements for soil and site characterization. The attenuation of EM waves is usually characterized by the penetration depth of EM waves. The penetration depth z of an EM wave is defined as the distance through which the amplitude of the EM wave is reduced by e^{-1} ($\approx$ 37%). The penetration depth z is dependent on the magnetic permeability μ, real permittivity κ' and effective electrical conductivity σ_{eff} of the soil:

$$z=\left[2\pi f\sqrt{\frac{\mu\kappa'\varepsilon_0}{2}}\left[\sqrt{1+\left(\frac{\sigma_{eff}}{2\pi f\kappa'\varepsilon_0}\right)^2}-1\right]^{1/2}\right]^{-1} \qquad [5.9]$$

where ε_0 is the dielectric permittivity of vacuum = $8.854\times10^{-12}F/m$; the effective electrical conductivity is defined by equation [2.2], which includes the polarization loss and the losses caused by the DC electrical conductivity. The magnetic permeability can be assumed as $\mu=\mu_0=4\pi\times10^{-7}H/m$ because most soils are non-ferromagnetic, where μ_0 is the magnetic permeability of the vacuum. Then, the penetration depth of an EM wave at a specific frequency is primarily controlled by the effective electrical conductivity of the soil. The maximum electrical conductivity of a soil above which a required penetration depth z can not be achieved can be derived from equation [5.9] as:

$$\sigma_{\max}=\frac{\sqrt{4\kappa'\varepsilon_0\mu_0+\dfrac{4}{z^2\left(2\pi f\right)^2}}}{z\mu_0} \qquad [5.10]$$

where $\varepsilon_0=8.854\times10^{-12}F/m$. For dry soils, $\kappa=$ 4 to 6.

The maximum electrical conductivities corresponding to penetration depths of 20 cm and 50 cm are plotted in Figure 5.6 as a function of frequency. The real permittivity is set to be 3 and 80 in the calculation as the lower and higher bounds for most soils. The electrical conductivity of natural soils is usually in the range of 0.01 to 1 S/m (Mitchell and Soga, 2005). Figure 5.6 shows that, at a frequency of 1 GHz, the penetration depth of the EM wave is approximately 10 cm to 60 cm in natural soils.

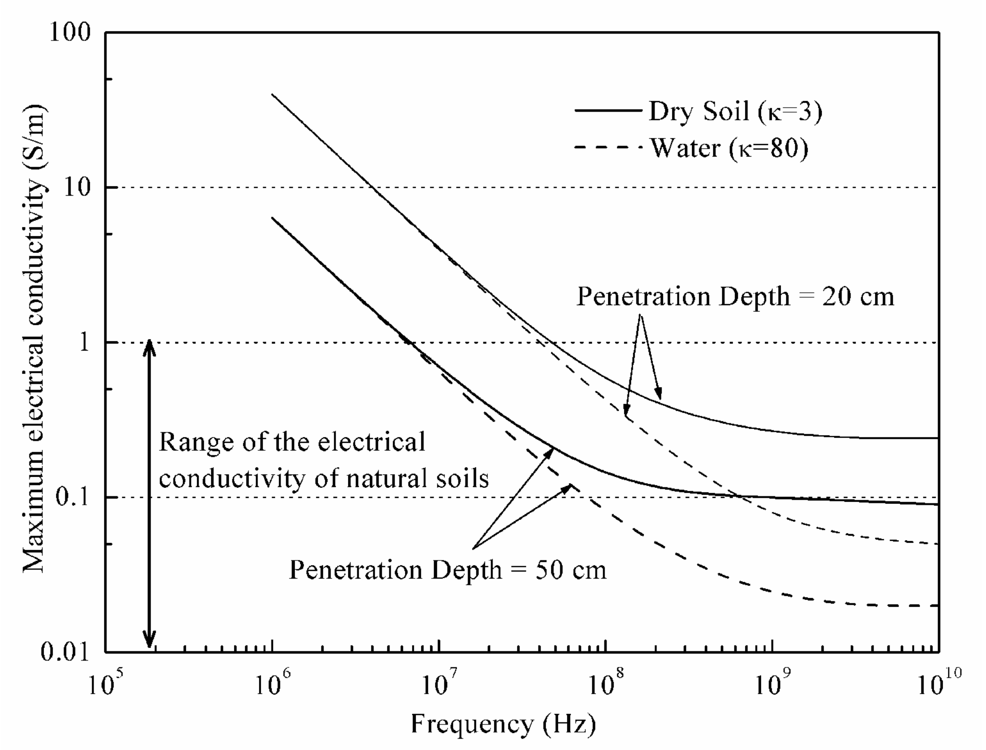


Figure 5.6 Maximum electrical conductivity of a soil for the required penetration depth

5.5 Conclusions

Several types of electromagnetic measurement systems are introduced and compared. The network analyzer HP 8752A in conjunction of a coaxial termination probe HP 85070A is a convenient instrument to reliably measure the dielectric spectrum of soils over the 20 MHz to 1.3 GHz frequency range in the lab. However, it is not suitable for in-situ testing. Time domain reflectometry is a practical method that can be readily used in the field to measure soil electromagnetic properties. The configuration and mechanisms of the network analyzer system and TDR100 system are emphasized because they are used in this study to measure soil EM properties. Two possible problems with soil electromagnetic measurements-electrode polarization and penetration depth-are discussed, and the limiting conditions for their satisfactory use are determined.