# Skin Depth And Wavelength In Soil

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As radio waves penetrate into soil the wavelength is shortened and the amplitude rapidly attenuated. The depth at which the amplitude of the wave is reduced to 1/e ( about 0.37) compared to the amplitude at the surface is called the "skin depth". Skin depth and wavelength will depend on frequency and soil parameters, $\sigma$ = soil conductivity and $\varepsilon$ = permitivity or dielectric constant. In general for the design of antenna ground systems we are interested in the soil characteristics down to a skin depth.

## Skin depth

Skin depth in an arbitrary material is given by:

$$\delta = \left( \frac{\sqrt{2}}{\omega\sqrt{\mu\varepsilon}} \right) \left[ \sqrt{1 + \left( \frac{\sigma}{\omega\varepsilon} \right)^2} - 1 \right]^{-1/2} \qquad (1)$$

Where:

$\delta$ = skin or penetration depth

$\omega = 2\pi f$, f = frequency

$\sigma$= conductivity [Siemens/meter, S/m]

$\mu = \mu_r \mu_o$=permeability

$\mu_o$= permeability of vacuum = $4\pi 10^{-7}$ [Henry/meter]

$\mu_r$ = relative permeability

$\varepsilon = \varepsilon_r \varepsilon_o$ = permitivity

$\varepsilon_o$ = permittivity of vacuum = $8.854\text{x}10^{-12}$ [Farad/meter]

$\varepsilon_r$ = relative permitivity

A graph of equation (1) for some typical ground types is given in figure 1.

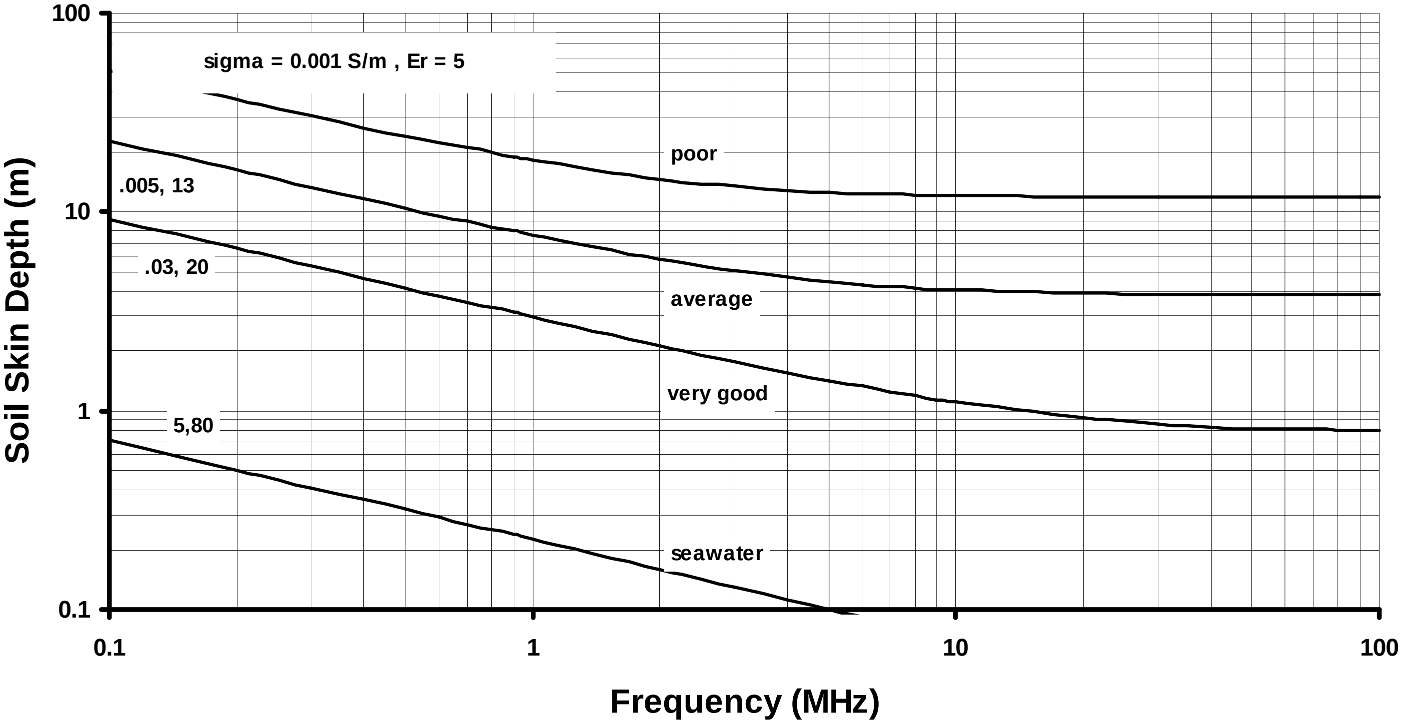

Figure 1, Skin depth in typical soils.

The skin depth varies with frequency and soil type. For example, at 1.8 MHz δ varies from about 16 cm in seawater to 15 m in poor soil. As we go up in frequency the skin depth decreases, roughly proportional to 1/ square root of f, until at some point it flattens out.

The soil types used in figure 1 represent the typical values used in antenna modeling. However, real soils seldom have the same pairs of σ and $\varepsilon_r$. For a given value of σ , $\varepsilon_r$ can vary widely. Both σ and $\varepsilon_r$ increase with soil moisture content so it is normal to have higher $\varepsilon_r$ when you have higher σ. However, it is also possible in some soils to have moderate values of σ but quite high values for $\varepsilon_r$. Clay soils or soils with clay particles very often have high $\varepsilon_r$ even though σ may be moderate. An example of the effect of differing $\varepsilon_r$ for soil of average conductivity ( $\sigma = 0.005$ S/m) is given in figure 2. Higher values of $\varepsilon_r$ result in larger values for δ. For fresh water at 23° C, $\varepsilon_r = 78$. You may wonder how soil can have an $\varepsilon_r$ higher than water. The higher values are the result of polarization effects which can occur in clay soils. It is quite possible to have a soil with $\varepsilon_r > 100$ at least at lower frequencies.

Looking at figure 2, we can see a couple of interesting points. At low frequencies the values for δ converge and $\varepsilon_r$ makes little difference. At high frequencies the curves are flat with a value that depends on $\varepsilon_r$. This can be used to illustrate the differences between ground behavior at low frequencies and at HF.

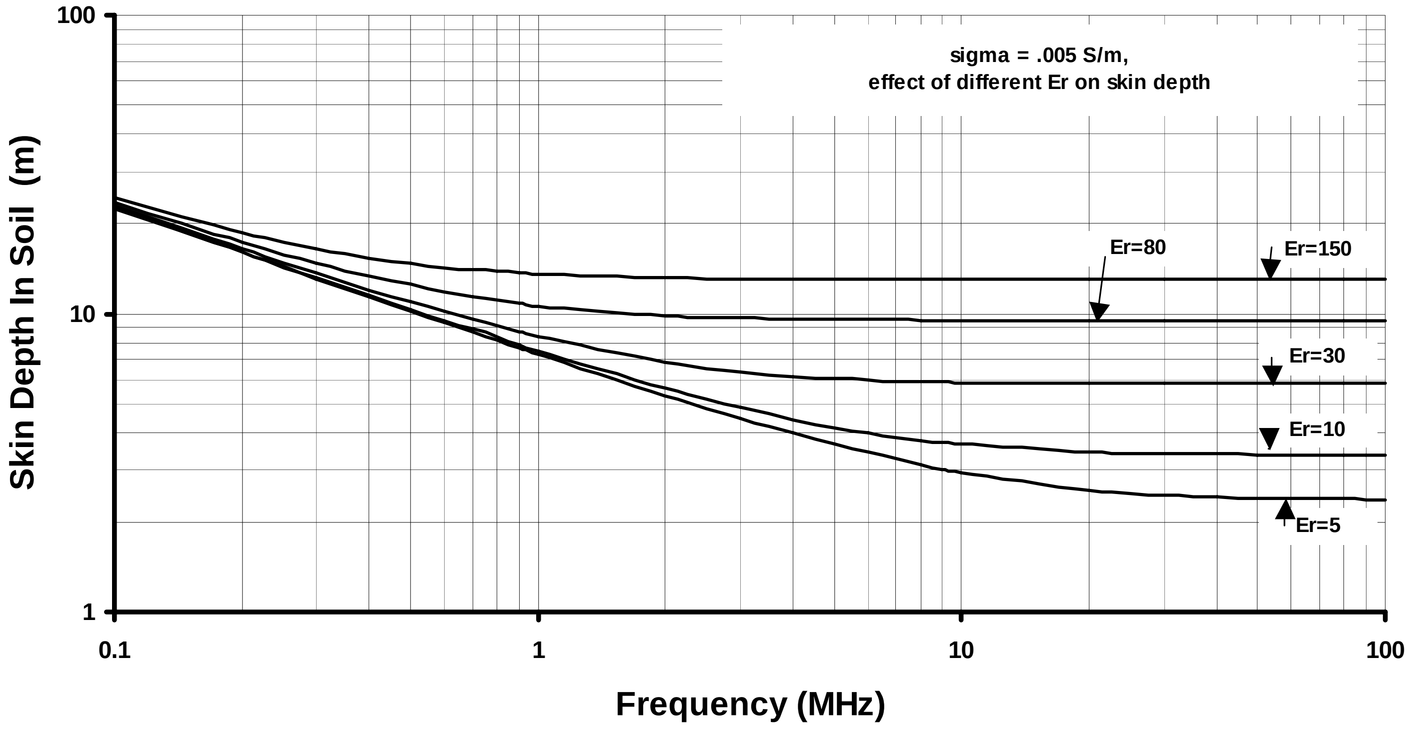

Figure 2, effect of different values of $\varepsilon_r$ on skin depth.

For high conductivity materials like metals or sea water where $\sigma$ dominates or a low frequencies:

$$\frac{\sigma}{\omega\varepsilon_o\varepsilon_r} >> 1 \quad (2)$$

and we can use the simpler approximation for $\delta$:

$$\delta = \frac{1}{\sqrt{\pi\sigma\mu f}} \quad (3)$$

Equation (3) represents the low frequency asymptote for equation (1). We can also derive the high frequency asymptote for equation (1) which is:

$$\delta = \frac{2}{\sigma}\sqrt{\frac{\varepsilon}{\mu}} \quad (4)$$

These two asymptotes will intersect at the frequency where they are equal:

$$f = \frac{\sigma}{4\pi\varepsilon} \qquad (5)$$

All of this can be summarized in a single graph as shown in figure 3 which is for $\sigma$ = 0.005 S/m and $\varepsilon_r$ = 10.

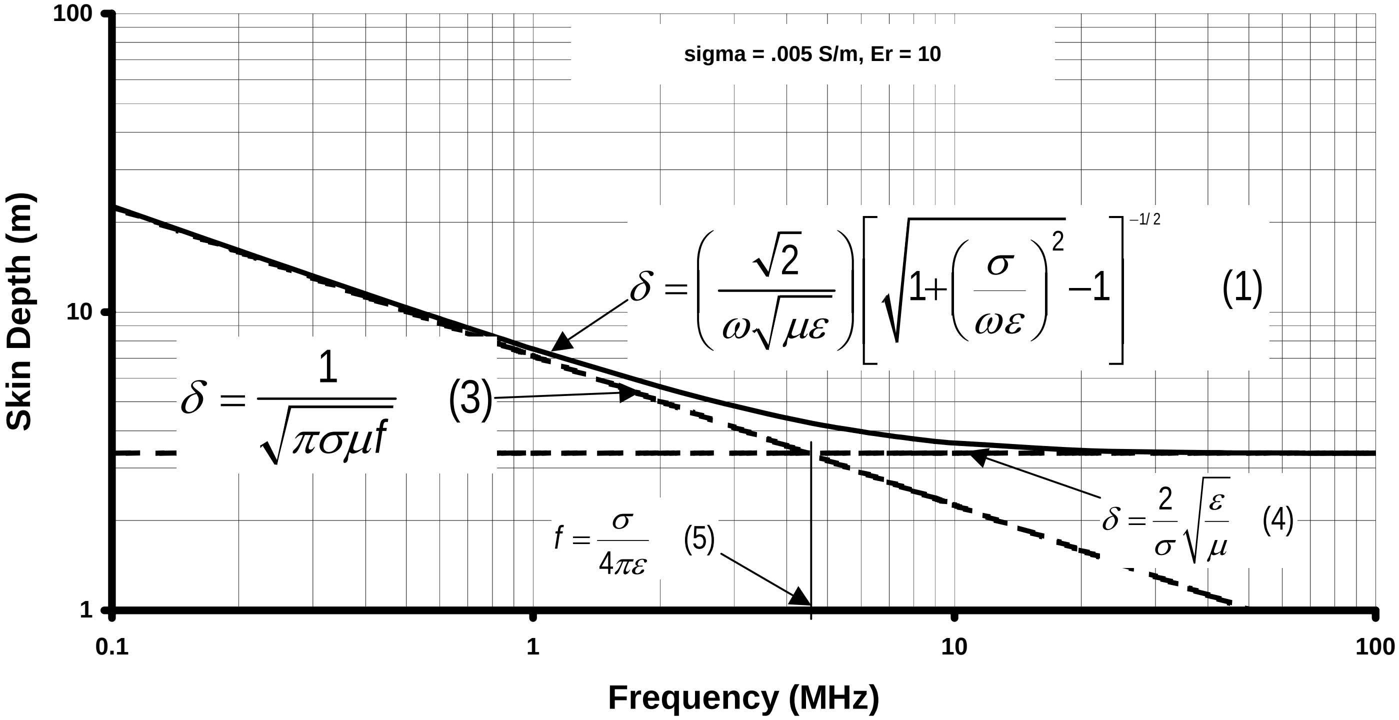

Figure 3, Relationships between the exact skin depth expression (1) and the high (4) and low frequency (3) approximations. The frequency of intersection (5) is also shown at 4.49 MHz.

Unfortunately things are a bit more complicated than this. In real soil at HF both $\sigma$ and $\varepsilon_r$ will vary with frequency. Figures 4 and 5 show a typical example of the variation of $\sigma$ and $\varepsilon_r$ with frequency. The data is derived from actual soil measurements at my QTH.

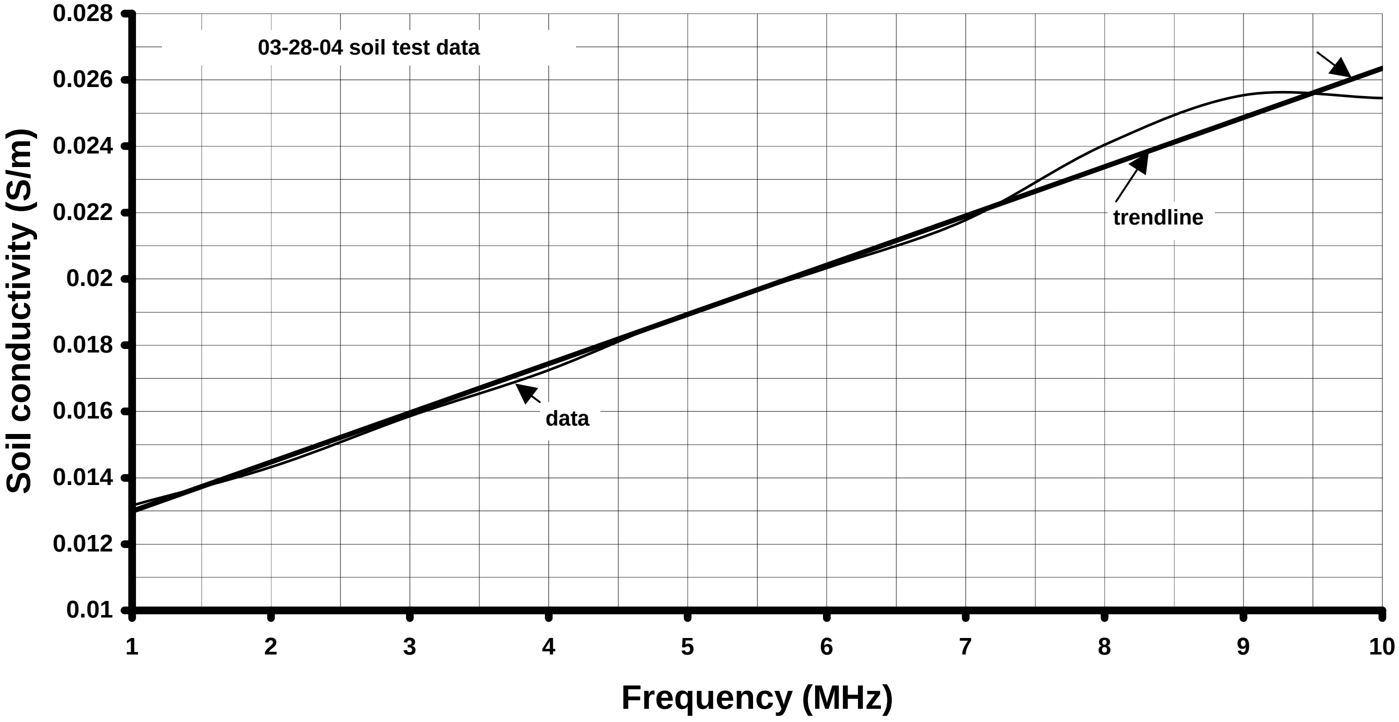

Figure 4, soil conductivity variation with frequency. From actual soil measurements.

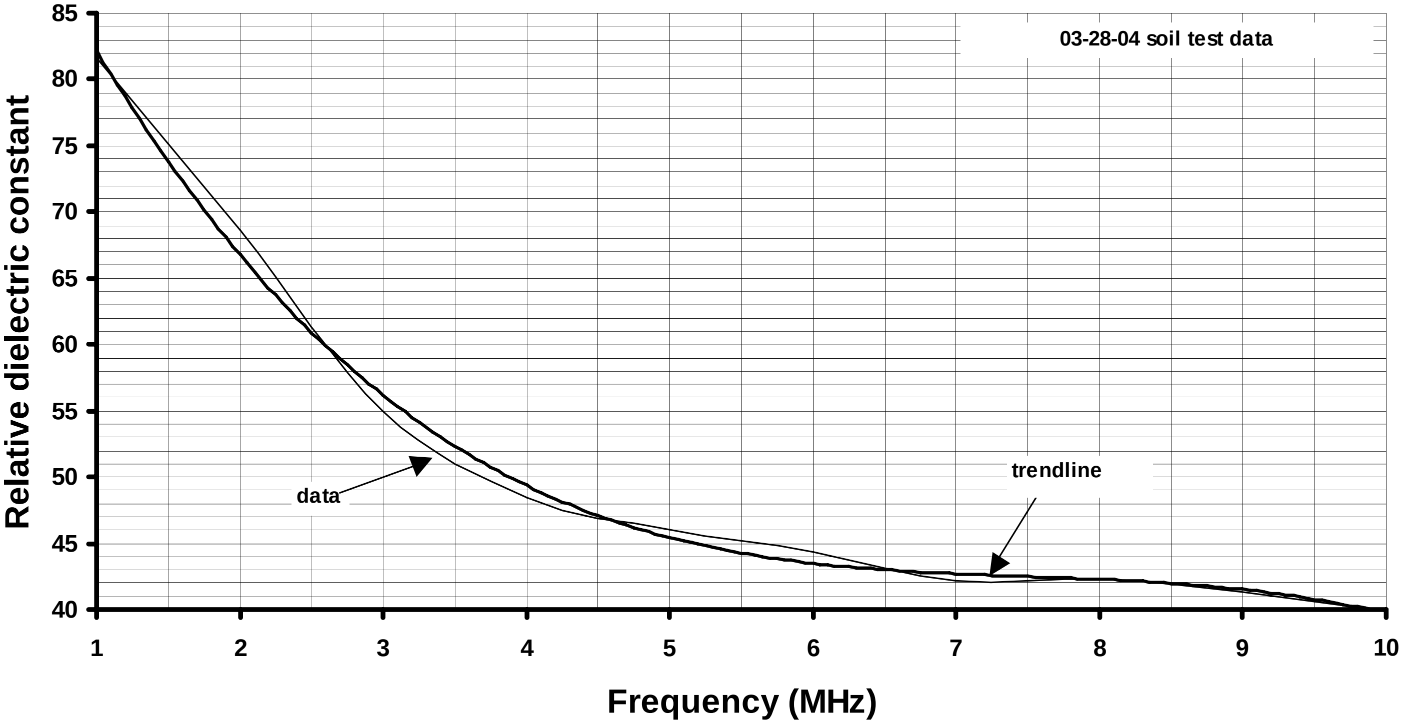

Figure 5, permitivity variation with frequency from actual soil measurements.

From figures 4 and 5 we can plot the associated skin depth as a function of frequency. This is shown in figure 6.

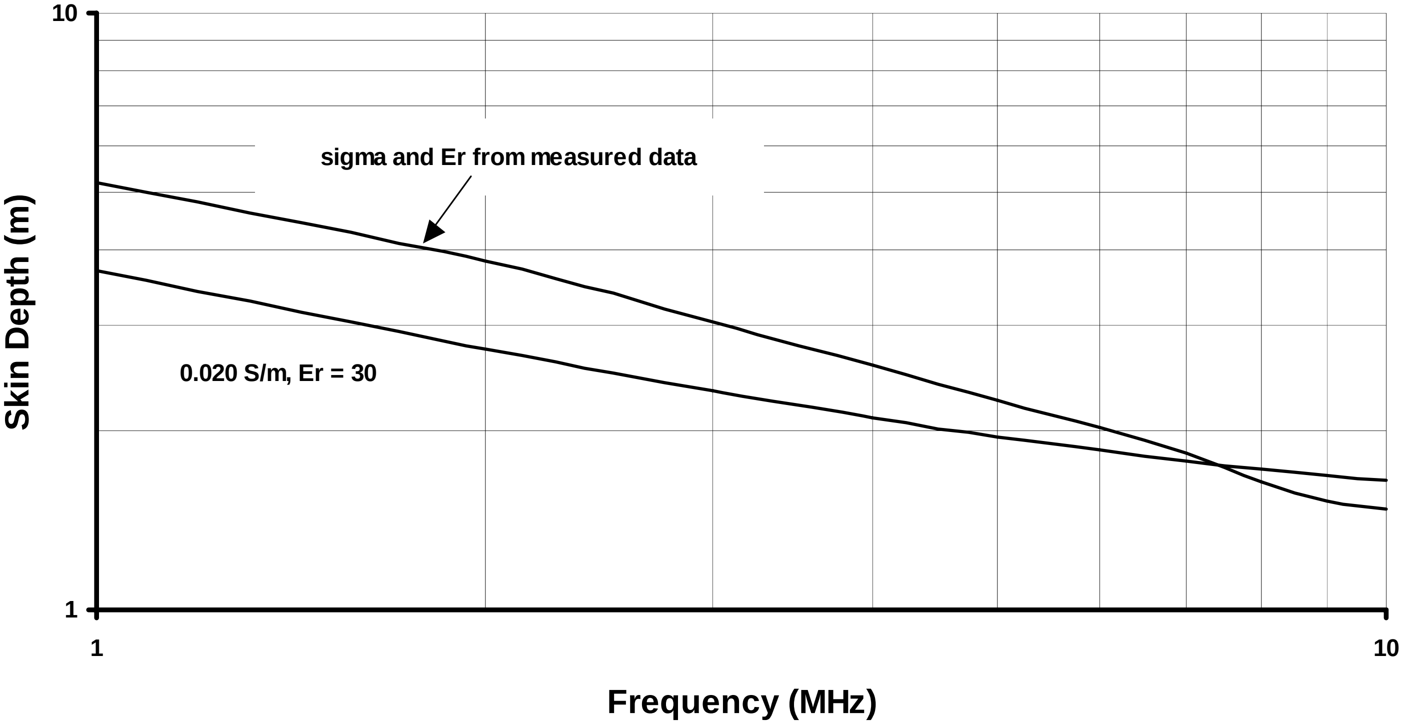

Figure 6, skin depth versus frequency for soil with the values shown in figures 4 and 5. There is also a line of data for $\sigma = 0.020$ and $\varepsilon_r = 30$, which represents good soil with constant parameters.

Wavelength in soil

Just as the skin depth varies with frequency and soil characteristics, the wavelength will also vary. It turns out that this is important when modeling buried radials where shorter segments must be used than what is normal in free space.

Wavelength in free space is:

$$\lambda_o = \text{ wavelength in free space}$$

$$\lambda_o = \frac{c}{f} = \frac{299.79}{f_{MHz}} \quad [m]$$

c = speed of light 299.79E6 m/s

f = frequency

$f_{MHz}$ = frequency in MHz

The wavelength in soil (λ) will depend on σ and $\varepsilon_r$:

$$\lambda = \frac{\lambda_o}{\left[\varepsilon_r^2 + \left(\frac{\sigma}{\omega\varepsilon_o}\right)^2\right]^{1/4}}$$

A graph of wavelength versus frequency for typical soils is given in figure 7.

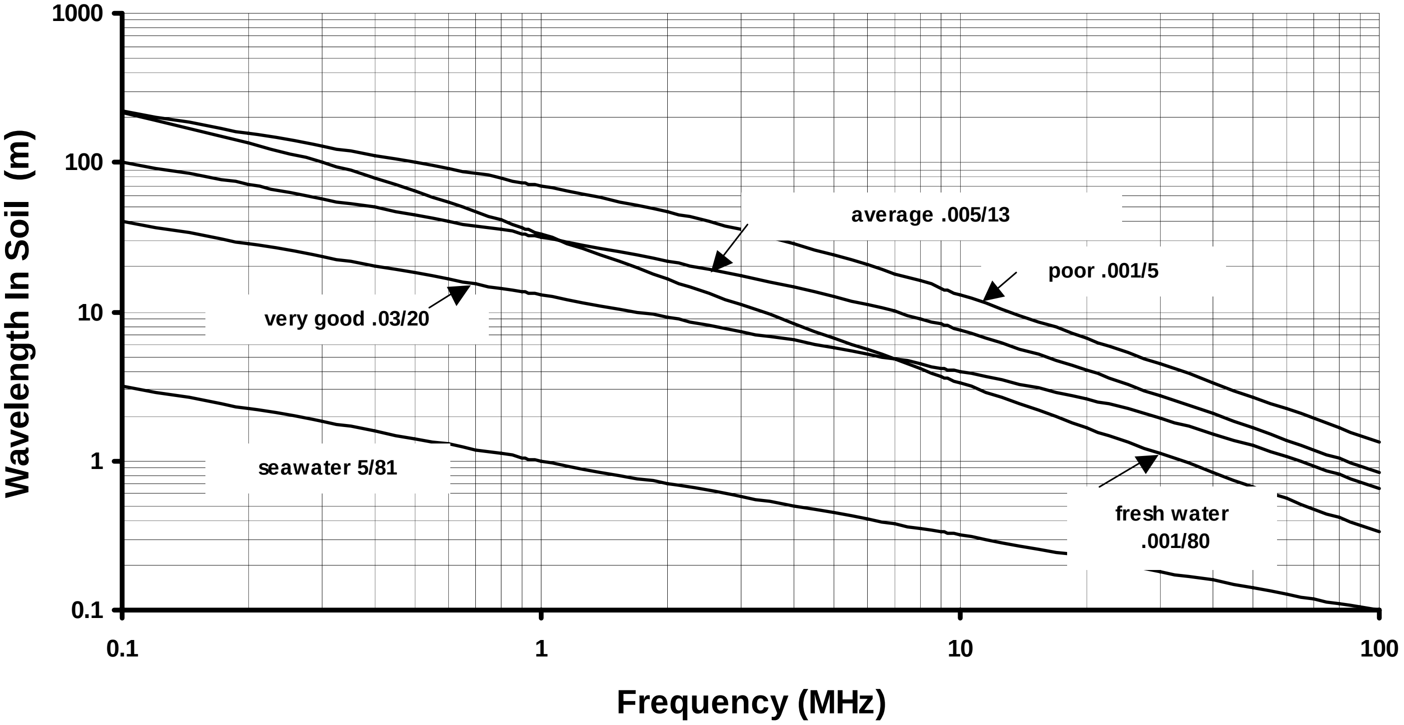

Figure 7, wavelengths in typical soils.