Effects of Soil Properties on Microwave Dielectric Constants

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The electrical properties of soils can be used to estimate soil characteristics such as moisture content and density. Relationships between the dielectric properties and soil moisture are the basis for the microwave remote sensing of soil moisture and some in situ soil moisture instruments. Several soil characteristics can produce the same set of dielectric properties and only through system design can any one be isolated with complete confidence. In recent years, investigations have been conducted to isolate the effects of specific characteristics through laboratory and field experiments. A review of the results of these studies is presented, and the following soil characteristics are included: soil moisture, soil texture, bulk density, structure, salinity, organic matter content, and temperature. Of these factors, the most significant and easiest to isolate is soil moisture. Of secondary importance are texture, density, and structure, depending on local conditions. Salinity, temperature, and organic matter content are of limited significance.

The microwave region of the electromagnetic spectrum has great potential for measuring soil water conditions using both remote sensing and in situ techniques. Large contrasts in the electrical properties, primarily the dielectric constant at these wavelengths, of dry soil and water are the primary reason for exploring this region.

Early investigators had reported some limited results dealing primarily with laboratory and in situ devices. Recently, there has been a renewed interest in this area as it applies to remote sensing, particularly at wavelengths between 5 and 21 cm. These investigations have led to expanded data bases and a better understanding of the fundamental relationships. Studies have also revealed that other soil properties, in addition to soil water, affect the dielectric properties of the mixture.

In this paper the effects of soil moisture, soil texture, bulk density, organic matter content, salinity, temperature, and structure on the dielectric properties are reviewed. When possible, the effects of these properties are illustrated using recently developed dielectric simulation models. The presentation will be limited to a wavelength of 21 cm because this is the primary frequency being considered for remote sensing.

SOIL WATER EFFECTS

Soil, as measured by a dielectric device, is a mixture of air, water, and soil particles. Several studies have shown that at 21 cm the dielectric constant of a dry soil is nearly constant

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regardless of variations in any of the factors that will be discussed here. The real part of the dielectric constant (k') is about 2 to 4 and the imaginary part (k'') is about 0.05 (1).

When water with a k' of 80 is introduced in relatively large proportions, significant changes in the k' of the mixture occur. One of the key developments of recent years has been the concept introduced by Schmugge (2) and refined in Wang and Schmugge (3). Laboratory studies had shown that k' was a nonlinear function of volumetric soil moisture; simple mixture formulas did not explain this phenomenon, as illustrated in Figure 1. Schmugge (2) proposed that water in the soil could be divided into two types that had different dielectric properties. Part of the water close to the surface of the soil particles was considered bound. Under such conditions the water molecules were not free and behaved more like ice. The k' of this portion of the water is small. In their model, Wang and Schmugge (3) assumed that water added to dry soil was bound until it reached a transition point beyond which it had the properties of free water.

Dobson et al. (4) developed on the basic concept of bound and free water by offering a more physically based explanation and a complete procedure for estimating the bound water capacity of a soil, which will be discussed in the next section.

On the basis of the concept just described, the dielectric constant of a soil can be determined from the proportions of air, bound water, free water, and soil particles present. A wide variety of models has been developed for soil-water-air mixtures (1, 5). Each of these models has some conceptual basis; however, the predictions can vary widely. Dobson et al. (4) used the basic approach proposed by Polder and van Santen (6) and de Loor (7), which considered the volume fraction, shape, and dielectric constant of the components. The mixing equation is

$$k_m = [3k_s + 2V_B(k_B - k_s) + 2V_F(k_F - k_s) + 2V_a(k_a - k_s)]$$

$$\div \left[3 + V_B\left(\frac{k_s}{k_B} - 1\right) + V_F\left(\frac{k_s}{k_F} - 1\right) + V_a\left(\frac{k_s}{k_a} - 1\right) \right] \quad (1)$$

where

$\quad k_m$ = dielectric constant of the mixture,
$\quad k_s$ = dielectric constant of the soil,
$\quad k_B$ = dielectric constant of the bound water,
$\quad k_F$ = dielectric constant of the free water,
$\quad k_a$ = dielectric constant of the air,
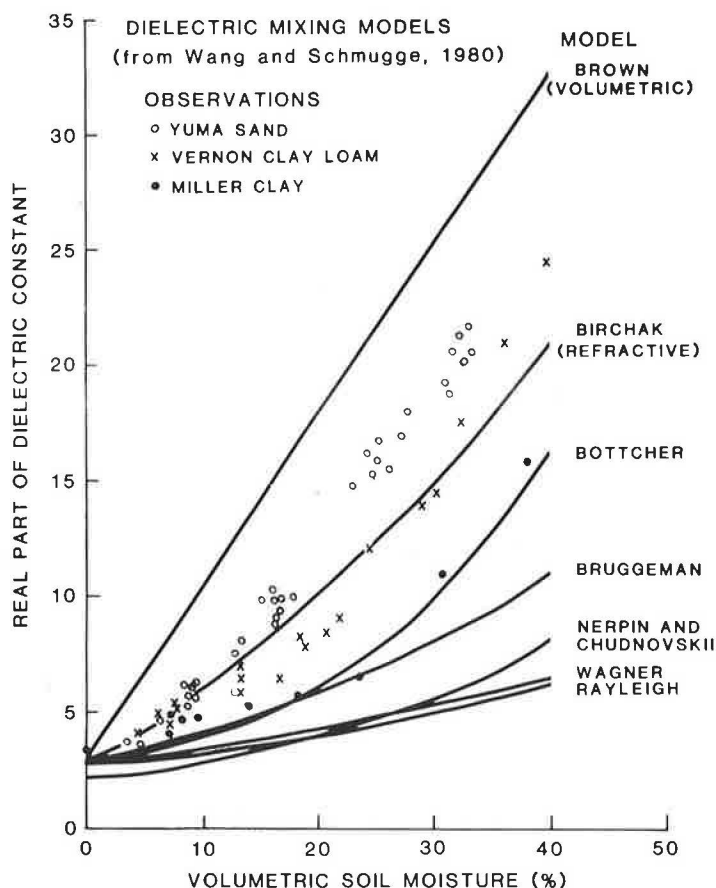$\quad V_B$ = volume fraction of the bound water,

FIGURE 1 Observed and predicted relationships between volumetric soil moisture and the real component of the soil dielectric constant, adapted from Wang and Schmugge *(3)*.

V_F = volume fraction of the free water, and

V_a = volume fraction of the air.

Figure 2 shows the general relationship between the real and imaginary parts of the dielectric constant of a moist soil and the volumetric soil moisture. It should be noted that there are other approaches to mixture modeling that can explain the general relationship and that the model of Dobson et al. *(4)* was developed for a homogeneous soil-water-air mixture. This model has been tested using laboratory measurements of the dielectric constant, which can differ from actual field conditions.

SOIL TEXTURE EFFECTS

The importance of soil texture or particle size distribution, or both, on the dielectric constant of a soil-water-air mixture is easily understood using the concepts introduced by Schmugge *(2)*, Wang and Schmugge *(3)*, and Dobson et al. *(4)*. The bound water fraction of the mixture is determined by the amount of water that is close to the surface of the soil particles. Two factors determine this. The first is the number of layers of water molecules that are actually bound. Dobson et al. *(4)* assume that three layers are involved. This point could be argued, but it appears to be an adequate approximation based on their results.
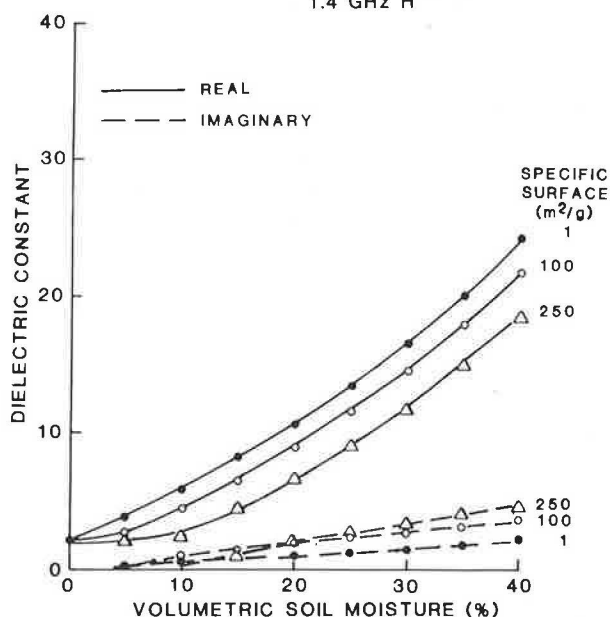

FIGURE 2 Effects of soil specific surface area on the relationship between k' and k'' and volumetric soil moisture.

The second factor that determines the bound water in the dielectric mixing models is the total surface area of the soil available to the water molecules. A sand with a specific soil surface of 1 m²/g would have a much smaller bound water fraction than a clay with a value of 300 m²/g. In the Dobson et al. (4) approach, the specific surface area of the soil is used to calculate the bound water fraction and, therefore, the bound water fraction is a function of soil texture (actually particle sizes and shapes).

The specific surface can be measured or estimated from particle size distribution data. The estimation approach presented by Dobson et al. (4) is based on a procedure developed by Ayra and Paris (8). A number of assumptions are involved in this estimation technique that make it unreliable.

Figure 2 shows the relationship between volumetric soil moisture and the dielectric constant for three soil textures, as determined by their specific surfaces. The variability in k'' is quite small; however, the effects of the specific surface on k' are large. For the same volumetric soil moisture, the k' of a sand will be larger than that of a clay because there is more free water in the sand mixture. Dobson et al. (4) tested this model using laboratory measurements of various soils and found that it worked quite well.

BULK DENSITY EFFECTS

It was noted previously that the k'- and k''-values of dry soils did not vary much ($k' = 2$ to 4). However, a minor adjustment is made in some dielectric mixing models (4, 9) for the effects of bulk density of the soil on k'. The equation used by Dobson et al. (4) is

$$k' = (1 + 0.44\rho_b)^2 \qquad (2)$$

where ρ_b is the bulk density in grams per cubic centimeter. Because ρ_b typically varies between 1.0 and 1.7 g/cm³, the effect will be minor for most soils.

Early research on soil water–dielectric relationships, especially in remote sensing, was hindered by different opinions on exactly which soil water property should be used. Many studies used the gravimetric soil moisture and others related dielectric and emission parameters to moisture-tension characteristics. These approaches have been abandoned in favor of volumetric soil moisture. Bulk density is most important in converting gravimetric soil moisture to volumetric soil moisture.

In the Wang and Schmugge (3) model the bulk density is insignificant. The Dobson et al. (4) model uses the bulk density in its calculations of the conductance properties of the soil water that, in turn, affect the dielectric constant. Figure 3 shows the variation that might be observed. For a given soil, typical site variations on the order of ±0.1 g/cm² would have a minor effect. Major treatments such as tillage or compaction would have to be considered.

ORGANIC MATTER CONTENT

The effects of organic matter content have not been extensively studied. In the context of soil properties, an increase in the
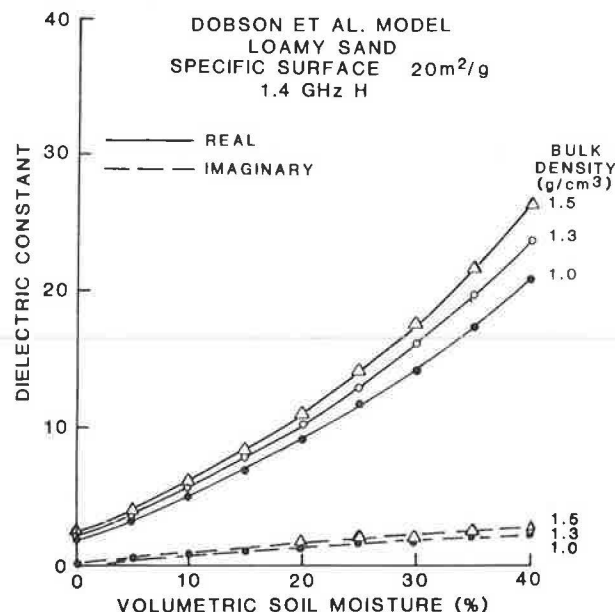

FIGURE 3 Effects of bulk density on the relationship between k' and k'' and volumetric soil moisture.

organic matter content reduces the specific surface of the soil and reduces the typical bulk density. The net effect is that the observed range of moisture is smaller at higher organic matter contents. Figure 4 is a series of emmissivity observations obtained over three plots with different organic matter contents. The conditions of the plots were such that emissivity was directly related to the dielectric constant (10).

SOIL WATER TEMPERATURE

Temperature effects on the dielectric properties of water have been extensively studied (1). These effects vary with frequency
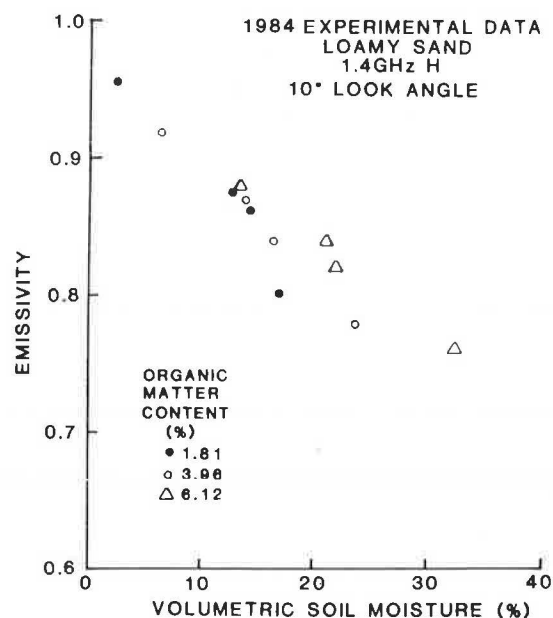

FIGURE 4 Observed values of emissivity and volumetric soil moisture on plots of varying organic matter content.

and in general are not as significant in the 5- to 21-cm wavelength range as at other wavelengths. At temperatures above freezing there is only minor variability and the same is true below freezing. However, at freezing there is a large transition in both k' and k'' as the dielectric properties of the water become those of ice. As a result, the effects can be important in the dielectric mixing models. Temperature effects can be ignored if the temperatures are above freezing.

The large difference in k' and k'' between frozen and unfrozen soils can be useful in determining such conditions using a dielectric device. If the moisture conditions are more or less uniform, the differences due to freezing would be quite apparent.

SALINITY EFFECTS

Carver *(11)* specifically considered the effects of salinity on the dielectric constant of a soil-water mixture. His approach was based on a straightforward adaptation of existing water-soil dielectric models using saline water values. The saline water values were based on well-known models of water at various levels of salinity. This approach is a good starting point because it considers the two variables of interest and can be adapted to any water-soil mixing model.

Some of the results found by Carver *(11)* on the effects of salinity include:

1. At a given microwave frequency, salinity decreases the real part of the dielectric constant and increases the imaginary part;

2. The sensitivity of the real part of the dielectric constant is relatively constant regardless of frequency (over the 1 to 10 GHz range); and

3. The sensitivity of the imaginary part of the dielectric constant to changes in salinity increases as the frequency decreases.
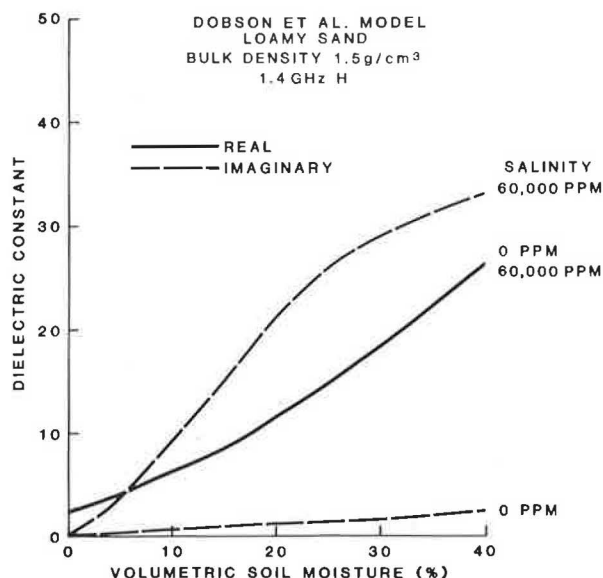

FIGURE 5   Effects of salinity of a saturated paste sample on the relationship between k' and k'' and volumetric soil moisture.

Any soil-water-mixing model can be adapted to consider salinity by including a component that adjusts the water k'- and k''-values using a model such as that of Stogryn *(12)*.

An alternative model for describing the effects of salinity has been proposed by Dobson et al. *(4)*. In their approach, the dielectric constant of the mixture depends on the conductivity of the solution. Salinity, of course, changes this conductivity. The conductivity of the water is also computed using a saline water dielectric model *(12)*. Figure 5 shows a summary of the mixture dielectric constants predicted using the Dobson et al. *(4)* model. At 1.4 GHz, 21-cm wavelength, salinity has no effect on k' but dramatically changes k''. Jackson and O'Neill *(13)* used this model to predict emissivity in a series of controlled plot experiments and found that it reproduced observations quite well. However, it should be noted that the net effect of typical field salinity variations on emissivity is small because emissivity is not particularly sensitive to the imaginary part of the dielectric constant.

SOIL STRUCTURE EFFECTS

Jackson and O'Neill *(5)* found that commonly used dielectric mixing models could not explain observations of emissivity made over tilled soils with smooth surface conditions (achieved by rolling). Using data from controlled plots they were able to conclude that the reason for the inadequacy of dielectric models, such as that of Dobson et al. *(4)*, is the structural differences between the laboratory samples these models are based on and the actual condition of tilled field soils. Laboratory soil samples are usually well mixed and consolidated or structureless. In contrast, after tillage field soil is made up of macro-aggregates and clods of varying sizes. A field soil will then retain this structure until it is broken down by wetting (irrigation or rainfall).

As mentioned previously, most theories used in developing dielectric mixing models recognize that the mixture value is the result of the component properties and their arrangement or structure. Considering the obvious physical differences between a consolidated soil and one consisting of aggregates, it appears to be logical that a mixture model that works for one condition would not work for the other.

Jackson and O'Neill *(5)* proposed a two-step approach to modeling the dielectric properties of a soil composed of aggregates and clods. First, the dielectric properties of the aggregates or clods are computed using a reliable model for consolidated soils such as that of Dobson et al. *(4)*. Second, the complex dielectric constant of a soil mixture made up of aggregates and voids is determined.

This approach was evaluated using a wide range of formulations in the aggregate-void step. Figure 6 shows a summary of the emissivity results obtained for several models tested by Wang and Schmugge *(3)*. The models are designated Type I (volumetric), Type II (refractive, dispersed spheres), and Type III (cubical array of spheres or geometric arrangement of disks). For a two-phase mixture, several of the models produce quite similar results. The category labeled Type III appears to explain the overall trend. Types I and II, which worked well in Figure 1, produced the worst results.

In addition to the formulations suggested by Wang and Schmugge *(3)*, two methods based on a capacitance analogy of
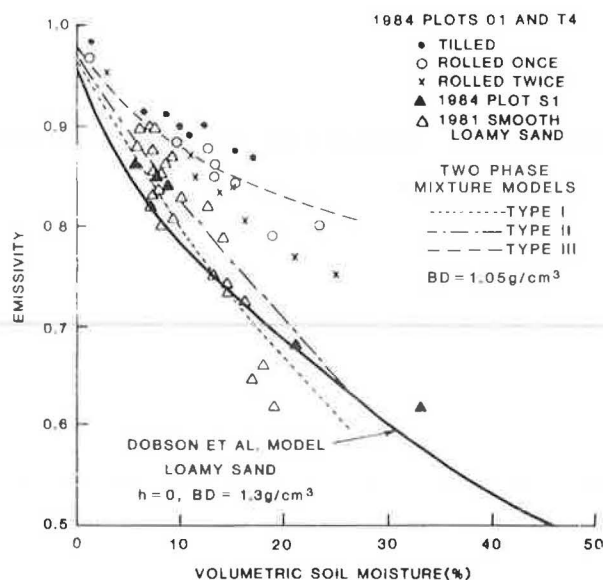
FIGURE 6 Predicted and observed relationships between volumetric soil moisture and emissivity using the Dobson et al. (4) model for the aggregate dielectric constant and the following models for the aggregate-void mixture: Type I volumetric; Type II refractive, dispersed spheres (Wagner and Bottcher); and Type III cubical array of spheres (Rayleigh) or geometric arrangement of disks (Polder and van Santen).
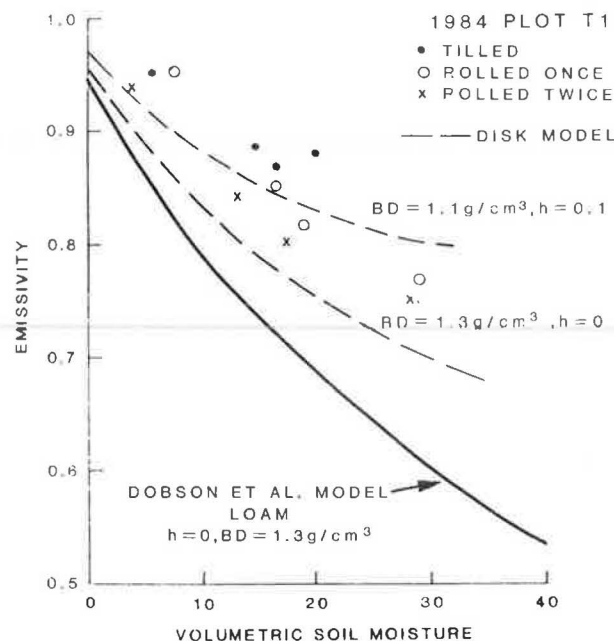
FIGURE 7 Predicted and observed relationships between volumetric soil moisture and emissivity using the disk inclusions aggregate-void dielectric mixing model for a loam.

the physical system were evaluated. In the first approach a general formulation presented by Sachs and Spiegler (14) was modified for an aggregate mixture. This model explained the data quite well; however, further analyses of the physical significance of some of the parameters is needed before this model can be widely used. The same is true of the second approach that was based on a model described by Ansoult et al. (15).

Jackson and O'Neill (5) also examined a model that was based on a theoretical representation proposed by Polder and van Santen (6) for disk-shaped inclusions in a host medium. Figure 7 shows the results obtained with this model. The authors concluded that because this model had a theoretical basis and required no parameter estimation it would be the one of choice.

SUMMARY

Microwave remote sensing has the potential for widespread use in soil moisture measurement because of the large contrast in the dielectric properties of dry soil and water. Recent research has examined the effects of a number of soil characteristics on the relationship between soil moisture and dielectric properties or emissivity. Soil texture, density, and structure have important effects that must be accounted for if soil moisture is to be estimated. Soil salinity, temperature, and organic matter content are not important at longer wavelengths.

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