Evaluation of Soil Porosity Using a Low MHz Range Dielectric Constant

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Abstract

Researchers have attempted to determine the dielectric constants of soil-water mixtures in order to establish relationships between dielectric constant and soil properties such as porosity. However, the suggested formulations were too complex to use for practical purposes. In order to effectively use the dielectric constant of soil-water mixtures, there is a need for a simple but well-defined formulation. In the first stage of this study, the dielectric constants of a natural sand and glass bead in two sizes at various porosities were determined at 13 MHz. Then the test results were compared with the independent data obtained on a wide range of soils, the second stage of the study. A linear relationship between the dielectric constant and porosity of soil-water mixtures was observed for both cases with coefficient of correlation values over 0.97. Based on the obtained results, it is suggested that the porosity of a soil-water mixture can be obtained using $n = 0.0136\varepsilon + 0.02$.

Key words: Dielectric constant, Soil, Porosity, MHz frequency, Liquefaction

Introduction

Several researchers have measured and evaluated the dielectric constant of soil-water mixtures to determine soil properties such as moisture content and porosity. Many empirical and semi-empirical relationships between porosity and measured dielectric constant have been developed. Excellent summaries of these studies are provided by Selig and Mansukhani (1975), Wobschall (1977), Arulanandan, (1991), and Teveyanagam, (1993). One of the purposes of the cited studies was to determine the porosity of granular soils from the measured dielectric constants; the porosity would then be used to evaluate possible liquefaction of granular soils. Knowledge of the porosity of granular soils is invaluable in order to evaluate the liquefaction potential during an earthquake. While methods are available to determine the in situ porosity of granular soils, they are usually difficult if not impossible to employ (Arulanandan, 1991; Tevenayagam, 1993; Arulanandan *et al.*, 2000). In addition, the developed relationships are either too complex for practical purposes or soil-type dependent. Thus, the purpose of this paper is (i) to determine the dielectric constant of two sizes of glass bead-water and natural sand-water mixtures to see if there is a unique relationship between porosity and dielectric constant, (ii) to compare the findings with the existing data in the literature, and (iii) to develop a simple relationship between the measured dielectric constant and the porosity of saturated soils for geotechnical applications.

Dielectric properties of soil and water

The dielectric constant is a measure of the relative ability of a material to store a charge for a given applied electric field, while dielectric loss is a measure of the proportion of the charge transferred in conduction and stored in polarization. The separation of the charge in simple materials can be explained

by: (i) a shift of the center of charge in electron motion relative to the nuclei (electron polarization); (ii) a shift of positively charged nuclei with respect to negatively charged ones (molecular polarization); (iii) rotation of dipolar molecules (orientation polarization); or (iv) ions drifting against barriers (interfacial polarization) (Kaya and Fang, 1997; Saarenketo, 1998).

The dielectric constant, ε, is a complex number and is a function of frequency. The relative dielectric constant, $\varepsilon^*(\omega)$, is the ratio of the complex dielectric constant, ε, to the dielectric constant of free space, ε_o. The real part of the dielectric constant of soil particles is between 3 and 6 depending on the orientation of the particles, whereas that of water is 80 at 20°C (Arulanandan, 1991; Thevanayagam, 1993). Thus, the dielectric constant of a soil-water mixture is between 4 and 80 depending on the proportion of each. This gives the opportunity to obtain the porosity of a soil-water mixture since the dielectric constant of the mixture can be readily measured. Considering the porosity of granular soils is the key to evaluate liquefaction potential during an earthquake; therefore, the importance of readily determined porosity is invaluable.

Experimental Study

Glass beads of two sizes, and a natural sand were used. The glass beads were 0.2 and 0.6 mm in diameter, manufactured by Potter Industry, INC, Brownwood, TX. The sand was clean and well graded.

The details of the experimental procedure for obtaining capacitance measurements used in determining the dielectric constants can be found in Kaya and Fang (1997). However, the test procedure is described briefly as follows. The measurements were obtained using a 4192A LF Impedance Analyzer (Hewlett Packard). This instrument is capable of obtaining capacitance measurements in the frequency range from 0.1 kHz to 40 MHz. The measurements for this study were obtained at 13 MHz. The soil-water mixture was confined in a U-shaped plexiglass cell, and the capacitance measurements were taken. To eliminate the impurities, the conductive areas (4.8 x 7.6-cm) were covered by silver plates. The separation distance between the conductive areas was 4.9 cm. The cell was sealed with a silicone sealant to avoid leakage during measurements.

Before conducting the capacitance measurement of soil water-mixtures, the accuracy of the system was checked by measuring the dielectric constant of air and the dielectric constant of water at various salt concentrations between 1MHz and 13 MHz (Fig. 1). As can be seen in Fig. 1, the variations in the dielectric constant values are negligible for the frequency and salt concentration at which measurements were carried out. The dielectric constant of air was found to be approximately equal to one.
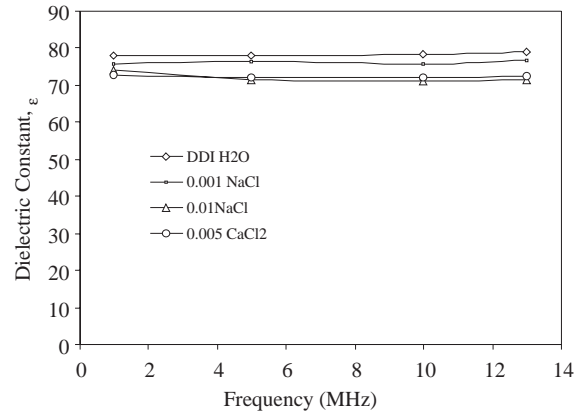

Figure 1. Dielectric constant of water at various salt concentrations as a function of frequency. As seen, for practical applications, the dielectric constant varies neither with frequency nor with salt concentrations.

After establishing the accuracy of the system, the sample cell was first filled with de-ionized water; then the soil was poured very slowly into the cell using the dry pulverization technique to avoid any air bubbles. Afterwards, the cell was connected to the impedance analyzer, and measured capacitance was converted to the dielectric constant using the following formulation.

Capacitance, C, of a material between two plates is given as

$$C = \frac{\varepsilon \varepsilon_o A}{d} \qquad (1)$$

where ε = dielectric permittivity of the medium, ε_o = permittivity of vacuum (8.854e-12 C N^{-1}), A = area of the plates, d = distance between the plates.

Knowing the geometric configuration (A and d), and measuring the capacitance, (C) the dielectric constant of the soil-water systems was computed by:

$$C = \frac{Cd}{\varepsilon_o A} \qquad (2)$$

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The measured dielectric constant and porosity ($n = V_v/V_T$; volume of void/total volume) of several soil-water mixtures are presented in Figure 2. There is a strong linear relationship between the dielectric constant and the porosity of the mixtures, which is independent of the type of solid particles. As can be seen from Fig. 2, the regression analysis of the measured data relates the porosity of the soil particles in terms of the measured dielectric constant $n = 0.014 - 0.025\varepsilon$ with $R^2 = 0.97$, where n is porosity and ε is the dielectric constant of the mixture. This result indicates that the measured dielectric constant can be used in determining the porosity of the granular soils with a high degree of confidence. However, regardless of the high correlation coefficient, it is better to be cautious at this point and compare the data with the data in the literature for further evidence of this statement.
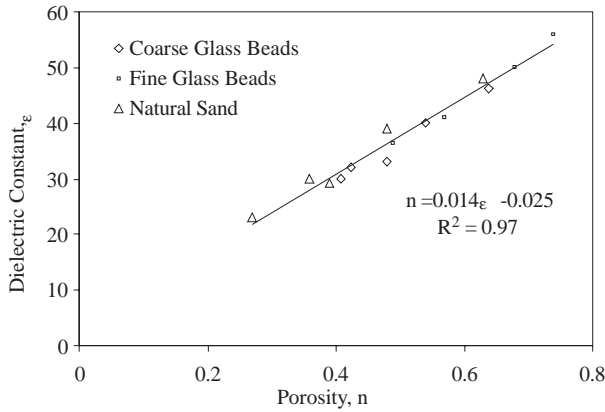

Figure 2. Dielectric constants of glass beads and a natural sand at various porosity values.

Comparison of data

We chose Arulanandan's (1991) data for comparison for the following reasons: (i) the frequency in Arulanandan's research (50 MHz) was within the same range considered in this study (13 MHz); (ii) in his study, he used a large range of soil types, and (iii) his data was considered high quality and was used in formulations by Thevanayagam (1993). Table 1 gives Arulanandan's (1991) data along with those obtained in this study.

Arulanandan (1991) measured the dielectric constant of soil-water mixtures in the horizontal and vertical directions; however, the dielectric constant measurements reflect the average dielectric constant in this study. Thus, to directly compare the results of this study, we averaged Arulanandan's (1991) data in the following manner:

Table 1. Dielectric constants of soils at various porosity values (Arulanandan, 1991; and this study).

Soil Type	n	ε_v	ε_h	ε_{avrg}
Arulanandan (1991)				
Snow cal (kaolinite+Illite)	0.56	34	43.2	40.1
	0.55	32.8	42.7	39.4
	0.52	31.4	40.1	37.2
	0.5	30.4	35.3	33.7
	0.47	29.5	38	35.2
	0.44	28.7	33.7	32.0
	0.42	27.5	33.1	31.2
	0.65	42.9	47.4	45.9
	0.61	41	45.2	43.8
Snow cal (kaolinite+ 5% Montmorillonite)	0.58	37.5	42.7	41.0
	0.54	35.6	39.9	38.5
	0.51	33.7	38.1	36.6
	0.47	31.2	36.5	34.7
	0.44	28.9	35	33.0
	0.42	25.4	33.9	31.1
	0.54	39.8	40.3	40.1
	0.52	36.7	39.8	38.8
Yolo loam	0.49	34.3	38.3	37.0
	0.47	33.5	37.4	36.1
	0.56	38.8	41.1	40.3
	0.55	34.7	41	38.9
Marysville red soil	0.52	33.9	40.1	38.0
	0.51	33	39.7	37.5
	0.86	60	70.6	67.1
	0.85	55	69	64.3
Snow cal (Kaolinite+ 30% Montmorillonite)	0.82	54	67.3	62.9
	0.74	49	57.5	54.7
	0.68	43.2	57.2	52.5
	0.45	28.3	33	31.4
	0.54	33	40.6	38.1
Illite kaolin MP	0.52	30.9	40.2	37.1
	0.51	30	37.3	34.9
	0.32	23.2	24.5	24.1
Sand	0.34	24	25.5	25.0
	0.36	25	29	27.7
	0.4	28	30	29.3
	0.4	27.5	29.6	28.9
	0.44	30.5	32.3	31.7
	0.51	30.4	37.1	34.9
Natural soils	0.52	34	38	36.7
	0.52	34	39.7	37.8
	0.56	33.4	42.7	39.6
	0.76	50	57.5	55.0
This Study				
Coarse glass beads	0.41			30.0
	0.48			33
	0.54			40
	0.64			46
Fine glass beads	0.43			32
	0.49			36.4
	0.57			41
	0.68			50
	0.74			56
Mixed sand	0.27			23
	0.36			30
	0.39			29
	0.48			39

$$\varepsilon_{avrg} = \left(\frac{\varepsilon_{ver} + 2\varepsilon_{horz}}{3} \right). \tag{3}$$

Figure 3 gives Arulanandan's data, whereas Figure 4 compares it with the results of this study. Both data sets are in good agreement. Regression analysis on Arulnandan's data gives $n = 0.0127\varepsilon + 0.038$ with $R^2 = 0.98$. Note that the data in Arulanandan (1991) ranges from those for montmorillonite to sand. The regression analysis on overall data gives $n = 0.013\varepsilon + 0.02$ with $R^2 = 0.97$. Analysis of two independent data sets, obtained from a wide range of soils, gives a linear relationship between the porosity and the dielectric constant of soil-water mixtures at low MHz frequency range.

The state of water in soil-water mixture

In soil-water mixtures, water may exist in either free or bound (adsorbed) forms. Both states of water have significantly different properties (Mitchell, 1993). Hence, when a soil-water mixture is formulated, the effects of these states should be taken into consideration. In 1955, Gasmann also stated that elastic wave velocities of rock-water could not simply take measurements from a dry rock, but a wetted rock (King and Nur, 1987). Taking Gasmann's (1955) statement as a basis, it may be said that the dielectric constant of a soil-water mixture cannot be predicted solely based on dielectric constants of dry soil and free water separately. Thus, the effect of the bound water should be taken into account in soil-water mixture formulations. Unfortunately, many researchers have ignored this fact; for example, to obtain a reasonable relationship between the observed and the predicted data, Thevanayagam (1995) had to use a dielectric constant value of 10 for kaolinite and 40 for montmorillonite, although both dry soil particles have an average dielectric constant of 4.5.

Based on electrical conductivity measurements, Knight and Dvorkin (1992) reported that the average thickness of bound water was about 3.5 °A, which is in agreement with the findings of Sposito (1989). However, Low (1987) stated that the thickness of bound water could be as high as 5 °A. Furthermore, Mitchell (1993) reported that the thickness of the bound water is between 5 and 10 °A depending on the type of soils. Figure 5 shows the dielectric permittivity of bound water vs. distance from the surface of soils (adapted from Conway *et al.*, 1952). From Fig. 5, it can be seen that the

corresponding dielectric constants are 24.8 and 56.4 for 5 and 10 °A, respectively, away from the surface. However, the dielectric constant of free water is 80. This result indicates that the effect of the bound water on dielectric formulation of soil-water mixture should never be neglected. As shown in the following sections, when the effects of bound water are taken into account, the modeling of soil-water mixture is straightforward.
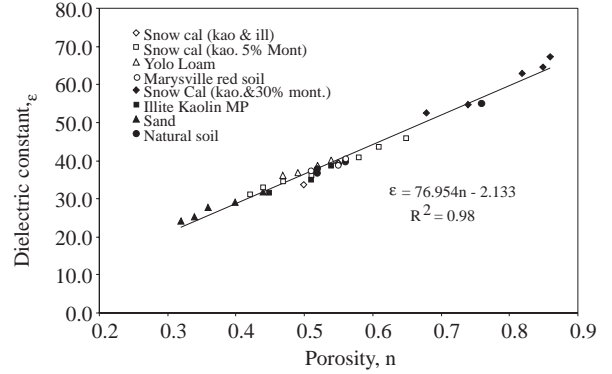

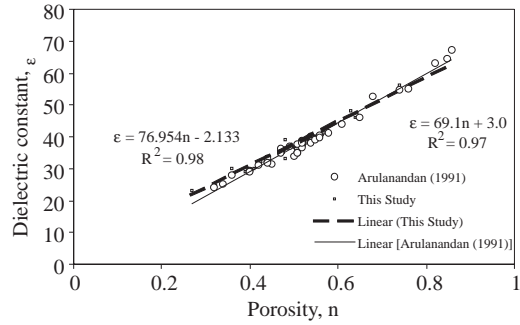**Figure 3.** Dielectric constant of tested soils at different porosities (Arulanandan, 1991).

Figure 4. Comparison of dielectric constants of soils of this study and those of Arulanandan (1991).

Formulation of Dielectric Constant of Soil-Water Mixtures

The simplest mixture rule for any given properties of a mixture is

$$P = p_1\phi_1 + p_2\phi_2 \tag{4}$$

where P stands for the given property, p_1 and p_2 are the corresponding property of the components 1 and 2 of the mixtures, and ϕ_1 and ϕ_2 are the concentrations of the components in the mixture.
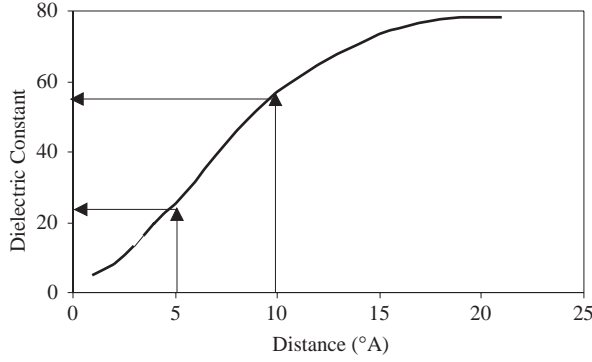
Figure 5. The dielectric constant of bound water with distance from the surface of the solid surface (data from Conway *et al.*, 1952). The dielectric constant of free water is affected from the surface until about 18 °A away.

Figure 6. The prediction of dielectric constants of soil water mixtures for different $d\varepsilon_1$ and $d\varepsilon_2$ values. The measured data fit best when $d\varepsilon_1$=10 and $d\varepsilon_2$=2, indicating that $\varepsilon_{water} = 70$ and $\varepsilon_{soil} = 6.5$.

If the simplest mixture rule is written for the dielectric constant of soil-water mixture

$$\varepsilon = \varepsilon_{water} n + \varepsilon_{soil}(1 - n) \qquad (5)$$

where n is the porosity of the mixture and ε_{soil} is the dielectric constant of soil and ε_{water} is the dielectric constant of pore water.

As mentioned before, some of the pore water is adsorbed by soil particles resulting in a decrease in the dielectric constant of the pore water but an increase in the dielectric constant of the soil. Considering this fact, the dielectric constant of soil-water for simple mixture rule can be written as

$$\varepsilon = (\varepsilon_{water} - d\varepsilon_1)(\varepsilon_{soil} + d\varepsilon_2)\,(1 - n) \qquad (6)$$

In Eq. 6, the values of $d\varepsilon_1$ and $d\varepsilon_2$ need to be determined and the equation is called the modified simplest mixture rule (MSMR).

The values of $d\varepsilon_1$ and $d\varepsilon_2$ in Eq. 6, were determined by trial and error. Figure 6 presents the predictions of the dielectric values of $d\varepsilon_1$ and $d\varepsilon_2$. The MSMR fits the data when $d\varepsilon_1 = 10$ and $d\varepsilon_2 = 2$, implying that in Eq. 3 $\varepsilon_{water} = 70$ and $\varepsilon_{soil} = 6.5$. The values of $d\varepsilon_1$ and $d\varepsilon_2$ give support to the idea of existing bound water, which increases the dielectric constant of soil particles but decreases that of water. However, the effect of the bound water remains almost constant at low MHz frequency range.
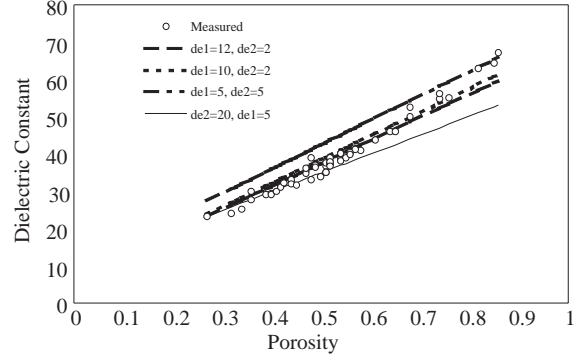
Warthon *et al.* (1980) proposed the Complex Refraction Index Model (CRIM) to compute the dielectric constant of soil-water mixtures. Researchers (Knoll and Knight, 1994; Robert, 1998) have shown the CRIM model to predict the dielectric constant of soil-water mixtures reasonably well; thus, it was decided to apply the CRIM model to the existing data.

For saturated soils the CRIM model is given as

$$\sqrt{\varepsilon} = (1 - n)\sqrt{\varepsilon_{soil}} + n\sqrt{\varepsilon_{water}} \qquad (7)$$

As seen in Eq. 7, the CRIM model also does not take the effect of bound water into account; thus, the model cannot directly be used. The values of ε_{water} and ε_{soil} need to be determined. For this reason, by trial and error, ε_{water} and ε_{soil} were determined in order to take into account the effect of bound water. After a few trials, it was determined that when $\varepsilon_{water} = 80$ and $\varepsilon_{soil} = 10$ in Eq. 7, the CRIM model predicts the measured data extremely well. The predictions are given in Figure 7.

It may seem a contradiction that in MSMR $\varepsilon_{water} = 70$ and $\varepsilon_{soil} = 6.5$ whereas these values are 80 and 10 for the CRIM model. However, it should be kept in mind that both models are quite different in nature; thus, the empirical models only give approximate values.
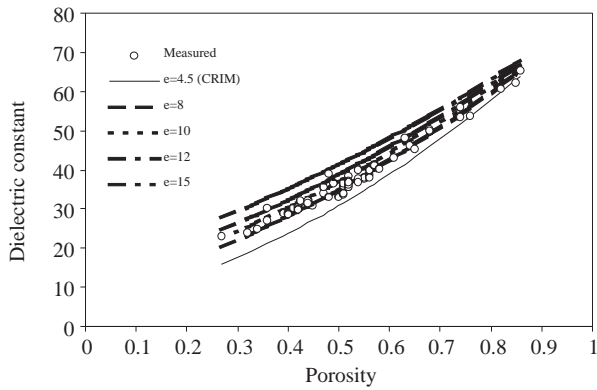
Figure 7. The CRIM prediction of the dielectric constant of soil-water mixtures. The original CRIM model underestimates the dielectric constant of the mixture; however, when $\varepsilon_{soil} = 10$, the model fits the measured data extremely well.

Practical Implications

Determination of the in situ porosity of granular soil is one of the key parameters for evaluating the liquefaction potential of granular soils (Figueroa *et al.*, 1994). However, with the existing technology it is difficult, if not impossible, to determine the in situ porosity of granular soils. It is quite apparent that the results of this study show a strong linear relationship between dielectric constant of a soil-water mixture and its porosity. This is important considering the fact that relationship between dielectric constant and porosity is independent from soil type at llow MHz frequency range. Therefore, the capacitance technique can be used to predict the in situ porosity of soils using a probe suggested by Arulanandan and Arulanandan (1985) or can be employed in CPT (Cone Penetration Test) similar to one suggested by Campanalle and Weemees (1990) to determine subsurface contamination.

Conclusions

Based on the discussion presented above the following conclusions may be drawn:

(1) At lower MHz frequency range (13-50), there is a unique relationship between the dielectric constant of a soil-water mixture and its porosity. The porosity of granular soils can be estimated using $n = 0.0136\varepsilon + 0.02$.

(2) The existence of bound water in soil-water mixtures significantly affects the dielectric constant of the mixtures. Thus, in formulations the effect of bound water should be taken into account.

Nomenclature

ε_o	dielectric constant of free space
ε	dielectric constant
$\varepsilon^*(\omega)$	ratio of complex dielectric constant
ε_{soil}	dielectric constant of soil
ε_{water}	dielectric constant of water
ε_{ver}	dielectric constant in vertical direction
ε_{hor}	dielectric constant in horizontal direction
ε_{aver}	average dielectric constant
$\phi_{1,2}$	concentrations of components in the mixtures
$p_{1,2}$	corresponding property of components 1 and 2
A	area of plates
C	capacitance
d	distance between plates
n	porosity

Acknowledgment

References

Arulanandan, K., "Dielectric Method for Prediction of Porosity of Saturated Soil." J. of Geotech. Engrg., ASCE, 117(2), 319-330, 1991.

Arulalanadan, K., and Arulanandan, S., "Dielectric Methods and Apparatus for *In Situ* Prediction of Porosity, Specific Surface Area i.e., Soil Type and for Detection of Hydrocarbon, Hazardous Waste Materials, and the Degree of Melting Ice to Predict *In Situ* Stress-Strain Behavior." Patent Application Serial No. 709,592, Regents of Univ. of California, 1985.

Arulanandan, K., Li, X.S., Sivathasan, K., "Numerical Simuation of Liquefaction-Induced Deformations." J. of Geotech. and Geoenvir. Engrg., ASCE, 126,657-666, 2000.

Campanella, R.G., and Weemees, I., "Development and Use of an Electrical Resistivity Cone for Groundwater Contamination Studies." J. Can. Geotech., 27, 557-567, 1997.

Conway, B.E., Bockris, J.O.M., and Ammar, I.A., "The Dielectric Constant of the Solution in the Diffuse and Helmholtz Double Layers at a Charged In-

terface in Aqueous Solution." Trans. Faraday Soc., 756-766, 1951.

Figueroa, J.D., Saada, A.S., Liang, L., and Dahisaria, M., "Evaluation of Liquefaction by Energy Principles." J. Geotech., ASCE, 120(9), 1554-1569, 1995.

Gassmann, F., "Uber die Elastizat Poroser Median: Vierteljahrsschr." Naturforsch Ges., Zurich, 96, 1-21, 1955.

Kaya, A., Fang, H.-Y., "Identification of Contaminated Soils by Dielectric Constant and Electrical Conductivity." J. Envir. Engrg., ASCE, 123(2), 169-177, 1997.

King, R.J., and Nur, A., "The Dielectric Constant of Sandstones, 60kHz to 40MHz." Geophysics, 52, 644-654, 1987.

Knight, R., and Dvorkian, J., "Seismic and Electrical Properties of Sandstones at Low Saturations." J. of Geophysical Research 97 (B12), 17425-17432, 1992.

Knoll, M.D., and Knight, R., "Relationship between Dielectric and Hydrogeologic Properties of Sand-Clay Mixtures." In Proc. of Int. Conf. on Ground Radar Penetrating Radar, 45-61, 1994.

Low, P.F., "Nature and Properties of Water in Montmorillonite-Water Systems". Soil Sci. Soc. Am. J., 40, 500-505, 1987.

Mitchell, J.K., Fundamentals of Soil Behavior 2nd Edition, John Wiley & Sons. Inc. 437, 1993.

Robert, A., "Dielectric Permittivity of Concrete between 50 Mhz and 1 Ghz and GPR Measurements for Building Materials Evaluation." J. Applied Geophysics, 40, 89-94, 1998.

Saarenketo, T., "Electrical Properties of Water in Clay and Silty Soils." J. Applied Geophysics, 40, 73-88, 1998.

Selig, E.T., and Manusukhani, S., "Relationship of Soil Moisture to the Dielectric Property." J. Geotech. Engrg., ASCE, 101(8), 755-770, 1975.

Thevanayagam, S., "Electrical Response of Two-Phase Soil: Theory and Applications." J. of Geotech. Engrg., ASCE, 119(8), 1250-1275, 1993.

Thevanayagam, S., "Frequency-Domain Analysis of Electrical Dispersion of Soils." J. of Geotech. Engrg., ASCE, 121(8), 618- 628, 1995.

Wharton, R.P., Hazen, G.A., Rau, R.N., and Best, D.L., "Electromagnetic Propagation Logging: Advances in Technique and Interpretation." Soc. Petr. Engrg., AIME. Paper No. 9267, 1980.

Wobschall, D., "A Theory of the Complex Dielectric Permittivity of Soil Containing Water: The Semi Disperse Model." IEEE Trans., 15, 49-58, 1977.