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A FEASIBILITY STUDY TO MONITOR SOIL MOISTURE CONTENT USING MICROWAVE SIGNALS

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Abstract

The recorded phase difference between the test signal from a buried leaky coaxial cable and a reference signal is used to continuously monitor the average moisture content of irrigated soil at a desired depth.

Introduction

The measurement of soil moisture content is of considerable interest to the agricultural community. Unfortunately, soil moisture content is not an easy variable to measure in field conditions. The commonly used methods have significant shortcomings. For example, gravimetric methods are slow, tedious, and necessitate the disturbance of the soil.[1] Soil conduction methods are inherently inaccurate and unreliable.[1] Radiation methods such as neutron thermalization and gamma ray attenuation are not simple to operate and are also limited by safety considerations.[1] Moreover, these measurements have a common disadvantage in that they are all based upon measurements at one specific location.

Improved soil moisture measurement techniques which are suited to field conditions are required. The radio wave method described in this paper has several important advantages. The soil moisture sensor covers a large portion of an irrigated field, thus an average measurement is determined. Once the sensing system is installed it is not necessary to disturb the soil in the measurement process. The system can be operated on a continuous basis, thus, an automated irrigation system could control the distribution of water to the field as prescribed by the user.

Review of Basic Concepts

Before introducing the radio wave method, it is useful to briefly review some basic concepts in soil engineering.[2-5] The soil is regarded as a matric which supports the plants and provides water and minerals. It consists of water, mineral particles, organic matter, and living organisms. A given volume of soil V, consists of a volume of water V_w, a volume of solids V_s, and a volume of air V_a, of mass M_w, M_s, and M_a respectively. Soil moisture content θ_m defined on the basis of weight is given by

$$\theta_m = M_w/M_s \tag{1}$$

The soil moisture content is not a very reliable measure of the availability of the water to the plants. A more useful concept has been defined and is referred to as the soil water potential ψ. The soil water potential is the amount of work required to move a given amount of water from one point to another, compared to the amount of work required to move the same amount of pure, unbound water the same distance. The soil water potential ψ is defined as a negative quantity, and is usually expressed in units of energy per unit mass. The soil water potential ψ is composed of three components, the matric potential ψ_m, the osmotic potential ψ_o, and the pressure potential ψ_p. The three components of soil water potential are additive, thus

$$\psi = \psi_o + \psi_m + \psi_p. \tag{2}$$

Normally, the water characteristics of a given soil are defined by the curve relating the matric potential ψ_m to the soil moisture content θ_m. A typical relationship is illustrated in Figure 1. There is a small amount of hysteresis between the wetting and drying curves. In Figure 2, ψ_m is plotted as a function of θ_m for different soil textures.[5]

The wilting point is defined by the soil moisture content at which the plants experience permanent wilting. This usually corresponds to a matric potential of -1500 J/Kg. Field capacity is defined by the moisture content of soil which is thoroughly saturated with water, allowing for all the water that can drain off by gravitational force to do so. This corresponds to a matric potential of -10 J/Kg. Available water is the water contained by the soil between the wilting point and field capacity. The available water provides an estimate of the moisture that is normally available to the plants.

Analysis

The measurement of soil moisture using radio waves is based on the strong dependence of the complex permittivity of soil $\varepsilon_1=\varepsilon_1'-j\varepsilon_1''$ on the moisture content. A small portion of the power transmitted through a leaky coaxial cable radiated into the soil surrounding it. For a monochromatic signal, the complex propagation coefficient $\gamma=\alpha+j\beta$, of the azimuthally symmetric mode is influenced by the environment surrounding the leaky cable. Thus, γ is influenced by changes in the soil permittivity which varies with its moisture content. Changes in γ can be measured by observing changes in the transmission coefficient for the buried cable.

Consider an infinitely long coaxial cable buried at a depth d below the surface of the earth and parallel to the z-axis, as illustrated in Figure 3.

In the application considered in this work, the leaky coaxial cable is buried at a depth of 0.5 meter below the earth surface and is excited by a 0.9 GHz signal. Thus, the cable is located many skin-depths δ_1 below the earth surface. Since $d \gg \delta_1$, the air-earth interface may be ignored and the coaxial cable is considered to be centered along the z-axis (see Figure 4) in an infinite medium (ε_1,μ_0). The structure has, in general, n+1 concentric regions (ε_1,μ_0), $i=1,2,\ldots,n+1$ which are separated by n interfaces $\rho=\rho_1$ $i=1,2,\ldots,n$. In this work n=5; i=6 - the inner conductor, i=5 - dielectric layer, i=4 - the slotted outer conductor, i=3 - flooding compound, i=2 - protective outer jacket and i=1 - the earth. The inner conductor of the cable, region n+1, is assumed to be a good conductor ($\sigma >> \omega\varepsilon$). Thus, it is represented by a surface impedance $Z_n^- = E_z/H_\phi$ at $\rho=\rho_n$. For good conductors, the surface impedance is given by

$$Z_n^- = (1+j)\left[\frac{\omega\mu_0}{2\sigma_m}\right]^{\frac{1}{2}} \tag{3}$$

where σ_m is the conductivity of the metal (in this work $\sigma_{n+1} = \sigma_m = 5.8 \times 10^7 (\Omega\text{-m})^{-1}$ is the conductivity of copper). The effective suface impedance Z_{n-1}^+ at an interface $\rho=\rho_{n-1}$ (defined by the ratio $-E_z/H_\phi$) is

$$Z_{n-1}^+ = R_{n-1} + jX_{n-1} = (1+j)R_{n-1} \tag{4}$$

where

$$R_{n-1} = \rho_{n-1}\left[\frac{\alpha - \mathrm{Re}(jk_n)}{\mathrm{Re}\left[\frac{(1+j)\omega\varepsilon_n}{2k_n \ln(\rho_{n-1}/\rho_n)}\right]} - \frac{R_n}{\rho_n}\right] \tag{5}$$

In (5) $\rho_{n-1} = \rho_4 = 0.623$ cm and $\rho_5 = \rho_n = 0.21717$ cm, d is the measured attenuation as a function of soil moisture content (see Figure 5) and

$$k_n = \omega(\mu_0\varepsilon_n)^{\frac{1}{2}},\ \mathrm{Re}(k_n) \geq 0,\ \varepsilon_n = \varepsilon_0(1.6 - j.0.0008) \tag{6}$$

The model equation in terms of the surface impedances Z_{n-1}^+ and Z_n^- at $\rho=\rho_{n-1}$ and $\rho=\rho_n$ respectively is[6]

$$[h_n J_0(\rho_n h_n) - j\omega\varepsilon_n Z_n^- J_1(\rho_n h_n)]\,[h_n N_0(\rho_{n-1}h_n) + j\omega\varepsilon_n Z_{n-1}^+ N_1(\rho_{n-1}h_n)]$$
$$= [h_n N_0(\rho_n h_n) - j\omega\varepsilon_n Z_n^- N_1(\rho_n h_n)]\,[h_n J_0(\rho_{n-1}h_n) + j\omega\varepsilon_n Z_{n-1}^+ J_1(\rho_{n-1}h_n)] \tag{7}$$

In (7) J_n and N_n are the Bessel function of the first and second kind and of order n. The characteristic value (mode number) h_n is related to complex propagation coefficient $\gamma = \alpha + j\beta$ as follows

$$\gamma = jk_n\left[1-(h_n/k_n)^2\right]^{\frac{1}{2}} \tag{8}$$

Illustrative Examples

The experimental work conducted in the field demonstrated that even sudden changes in the soil moisture content could be detected. When the soil moisture content increased (due to rainfall), a negative phase shift was recorded, and the amplitude of the test signal decreased. This corresponds to an increase in the phase factor β and the attenuation α. In addition, changes in the phase factor $\Delta\beta$ and the attenuation factor $\Delta\alpha$ were approximately equal, as predicted by the analysis. As the soil moisture content decreased, a positive phase shift $\Delta\phi_T$ was recorded and the amplitude of the test signal increased. A typical example of this is shown in Figure 6.

References

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Figures

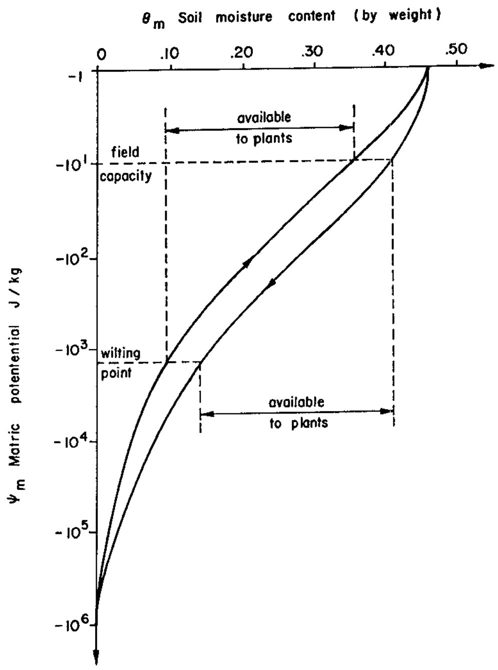

Fig. 1. Typical relationship between soil moisture content and matric potential (from Milthorpe [3]).

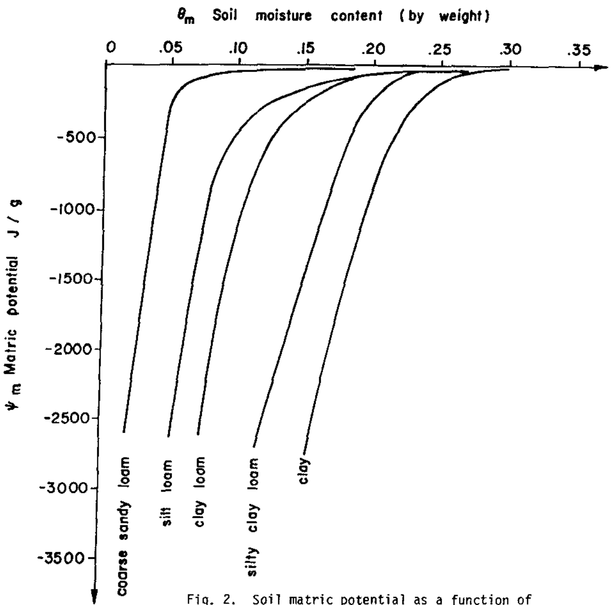

Fig. 2. Soil matric potential as a function of moisture content and texture (from Newton [5]).

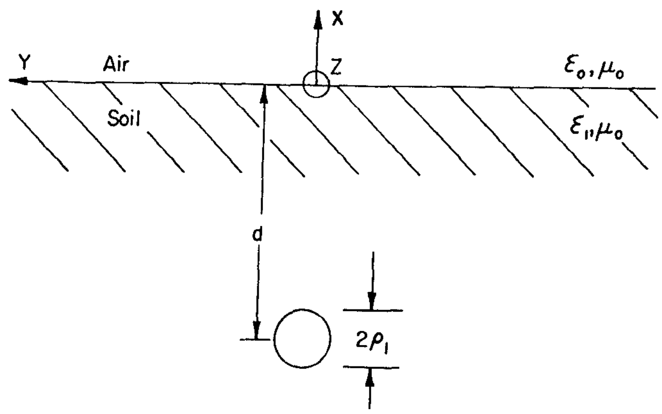

Fig. 3. Leaky coaxial cable buried at depth f below the air-earth interface.

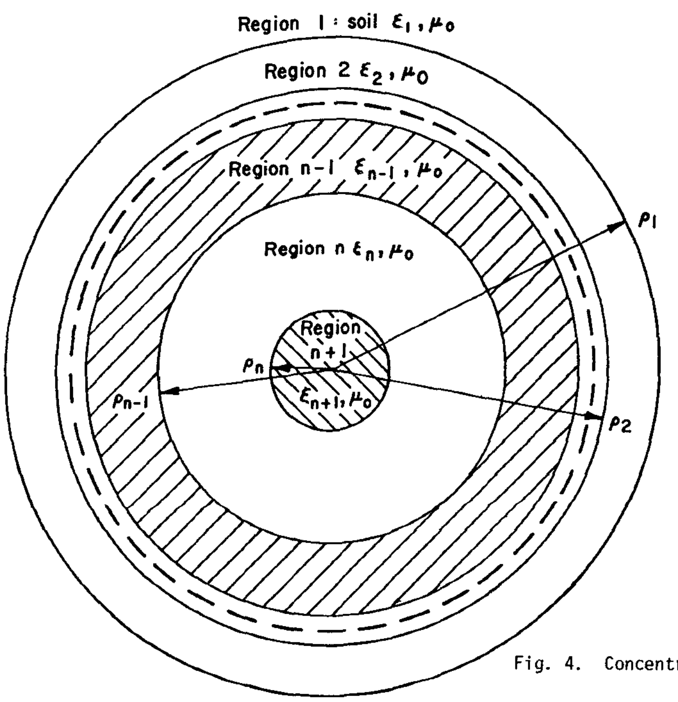

Fig. 4. Concentric geometry of the leaky cable.

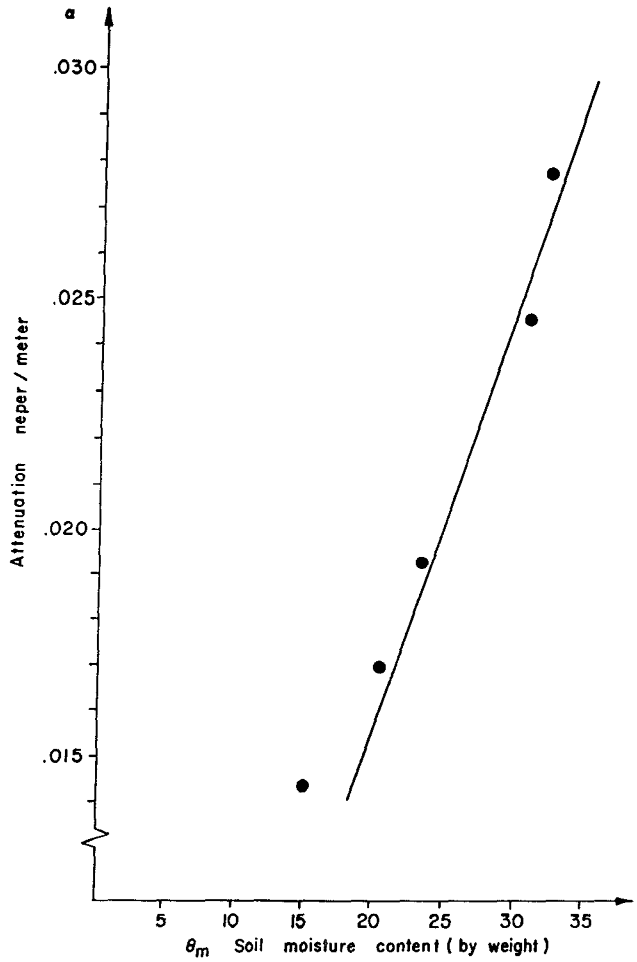

Fig. 5. Measured attenuation as a function of soil moisture content (f = 0.9 GHz).

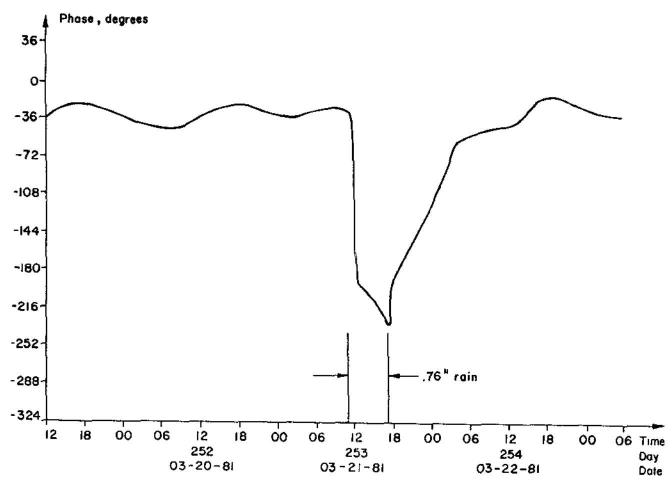

Fig. 6. Phase change $\Delta\phi_T = \Delta\beta\ell$ due to rainfall.