CAPACITANCE SENSOR
FOR SOIL MOISTURE MEASUREMENT

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Moisture content is an important parameter that controls the performance of earth materials. Because satisfactory techniques were not available, this study was undertaken to develop new instrumentation that could be permanently installed in highway substructures for long-term monitoring of moisture content. Moisture content determination requires that the amount of water and the dry weight in a given volume of soil be obtained. This study considered only the amount of water. A concept that involved the relationship between the amount of water in soil and the dielectric constant, an electrical property, was investigated. The electrical capacitance (C) of a pair of electrodes with moist material between them is related to the dielectric constant (K) by $C = (\alpha \epsilon_o)K$, where α is a constant based on the geometry of the electrodes and ϵ_o is the permittivity of the vacuum. So that instrumentation problems encountered in the measurement of capacitance and dielectric constant with laboratory methods used in the field could be overcome, the sensor electrodes and soil were incorporated in the resonance circuit whose frequency of oscillation is a function of the circuit components. The measured output is the difference between the frequency in soil and in an electronic reference substituted for the soil. The circuit design was first tested with the electrodes forming a container into which soil could be placed. Several configurations of the embedded sensor were designed and tested. The capacitance concept was useful for sensing change in the amount of moisture per unit volume of soil.

•MOISTURE CONTENT is one of the most important factors influencing the performance characteristics of earth materials. Insufficient or excessive moisture in the components of a highway system adversely affects the service behavior. Changes in moisture not only produce undesirable volume changes, but also increasing moisture reduces strength and traffic-supporting capability of materials used in the construction of bases, subgrades, and embankments.

Currently, engineers are hampered in their efforts to predict performance because of the lack of suitable instrumentation and techniques for adequate moisture measurement. One or more of the following limitations apply to monitoring moisture content: no remote readout capability, high cost, site disturbance, long-term instability, and inadequate response to moisture change. The development of an instrument that does not have these limitations is the objective of this paper.

A concept that appeared to be promising for fulfilling the objectives involves the relationship between soil moisture content and soil capacitance, which are sensed by a pair of embedded electrodes. An important part of this approach is that soil is used as the dielectric; i.e., it is part of the measurement circuit. This is believed to be a distinct improvement over previous approaches that depended on absorbing water from the soil into either a dielectric or resistive element and that used sensors that were highly influenced by placement conditions. It was also noted that the amount of water

absorbed depends on the soil type, unit weight, and the water content of the soil and that considerable hysteresis takes place during wetting and drying cycles.

At the outset of the study a literature review was conducted, which supplemented a previous review (1) so that information could be obtained on relevant past research related to capacitance methods for moisture determination. This information formed the basis for the sensor design and evaluation of the results.

After the literature reveiw, a preliminary, capacitance-measuring system was designed and constructed to evaluate the proposed electronic concepts and to obtain initial performance data for a range of soil types and moisture contents. Results from the initial tests led to an improved circuit design with a change in configuration of the sensor. A more extensive investigation was then made of the influence on sensor output of variables such as soil composition, soil density, soil moisture content, soil and sensor temperature, and electronic circuit characteristics. These tests resulted in further circuit modifications that improved the sensor performance.

The final task involved the selection of suitable configurations for the embedded sensor. The effects of geometry and size on sensitivity, accuracy, and placement techniques were examined. On the basis of the results, three final prototype sensor configurations containing printed electronic circuit boards were designed and fabricated. The evaluation of these sensors was conducted primarily in the laboratory by using a variety of prepared soil samples.

BASIC CONCEPTS

The two electrical properties of soil involved in the capacitance sensor concept are dielectric constant (K) and conductivity (σ). For most solid components of soil alone K lies in the range of 2 to 4, and the water component alone has the much higher value of 78 to 81. Therefore, K of a soil sample is expected to vary primarily with the amount of water present per unit volume of soil, which for our purposes is termed moisture density (m_v expressed in g/cm^3). This is in contrast to the conventional moisture content defined as the ratio of weight of water to the weight of dry soil (w) expressed as a percentage. These two definitions of the amount of moisture are, of course, related to each other by the dry density of the soil (γ_d) in g/cm^3 as follows

$$w = \frac{100 \, m_v}{\gamma_d} \tag{1}$$

It is not possible with any method to determine soil moisture without measuring the amount of water present and the weight of a given quantity of soil. This study concerns the means of determining the amount of water present per unit volume of soil. Other methods, a variety of which already exists, are needed for determining the soil density so that conventional moisture content can be computed.

The capacitance (C) of a sensor consisting of a pair of electrodes embedded in soil is related to dielectric constant by

$$C = \alpha \epsilon_o K \tag{2}$$

where

α = electrode geometry constant, and
ϵ_o = permittivity of the vacuum.

Similarly the electrical conductance (g) of the embedded electrodes is related to the soil conductivity (σ) by

$$g = \alpha \sigma \tag{3}$$

Conductance is the reciprocal of the resistance measured across the pair of electrodes, and the soil resistivity is the reciprocal of the conductivity.

In most previous studies, C and g have been measured by an impedance bridge that operates at various alternating current frequencies. K and σ may then be computed separately by using Eqs. 2 and 3. For soil, these values will depend on the oscillator frequency of the bridge at which C and g were measured and on the moisture content. We used an alternate measurement method that is based on the frequency shift of an oscillator circuit, which incorporates the soil electrodes as one component. For a given pair of electrodes, the frequency shift is a function of the nominal oscillator frequency and both K and σ.

The electrical measurement most commonly used in the past for moisture determination has been conductance (or its reciprocal, resistance). However, instead of incorporating the soil directly, one usually measured the conductance of a sensor that absorbs moisture from the soil. This approach has generally been too inaccurate for engineering use.

The capacitance or dielectric constant approach has been investigated with a wide variety of materials including coal; glass; paper; fiber-reinforced plastics; concrete; rock cores; soil types such as clay, silts, sands, and gravel; and agricultural products such as wheat, peas, and oats (2). Moisture contents from 0 to 450 percent have also been considered, depending on the type of material. The values over 100 percent are primarily montmorillonites. Many investigators have correlated C or K with w rather than with m_v. This has suggested much greater composition effects than actually exist. Reported experimental results clearly indicate that the electrical parameters should be correlated with m_v rather than w.

A variety of electrode configurations have been used in past studies (2). These basically may be classed as (a) containers in which the material being measured is placed in a device whose sides form the electrodes (Fig. 1), or (b) fringing probes in which the electrodes are placed against or inserted into the material (Fig. 2). The fringing probes are required for in situ measurements.

A range of measurement frequencies from 1000 Hz to 1.5 GHz has been used in the past. From instrumentation and composition considerations, the radio frequency range of 10 to 100 MHz seems to be best for soil applications.

Generally, K increases nonlinearly as m_v increases. For a given electrode configuration at a specific oscillator frequency, K, unlike σ, is primarily a function of m_v; secondary variations are caused by soil composition (Fig. 3). This trend is believed to be partly a result of the difference in electrical properties of free and absorbed water.

In addition K decreases with increasing frequency, and σ increases with increasing frequency (Fig. 4). This phenomenon is termed electrical dispersion. The frequency effect is present even though the values of K and σ for the individual solid and liquid components of soil (e.g., saturated illite Grundite) do not depend on frequency. These characteristics have been explained by the fact that the electrical equivalent circuit for soil consists of a network of parallel-series combinations of resistance and capacitance elements (4).

In summary, the capacitance method is promising and better than conductance methods for measuring m_v. Soil composition appears to be a secondary factor, which can be accounted for by calibration. The technique should work in most soils over any desired moisture content range if the sensor is properly designed; however, the measurement systems used in past studies are generally only suitable for laboratory use with short-term monitoring. Therefore, the main objective of this research was to develop an electrical circuit and sensor configuration for field use that can achieve the desired technical requirements.

SENSOR DESIGN AND RESULTS

A capacitance bridge used as a measurement device is not satisfactory as is a buried sensor, where remote readout is required. A better approach is to incorporate the electrodes containing the soil dielectric as part of a resonance circuit, which oscillates at a frequency based on the magnitude of the circuit components. A simple example of such a circuit is shown in Figure 5. In this example as the soil capacitance (C_s)

Figure 1. Device for studying soil electrical properties (3, 4).
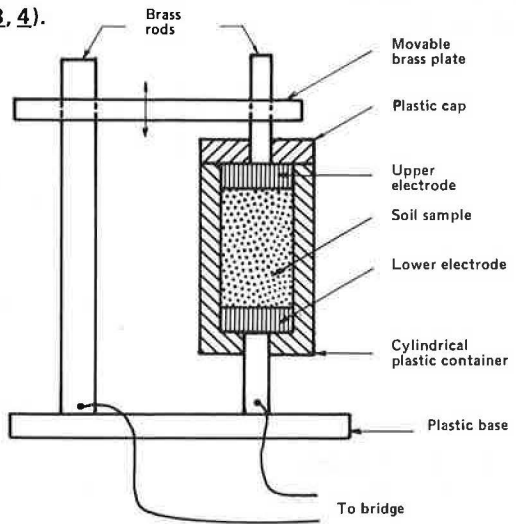

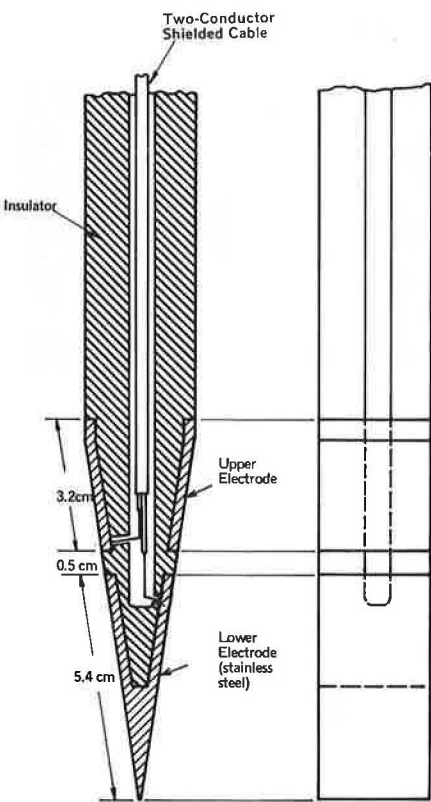Figure 2. Probe for soil moisture measurement (5).

Figure 3. Relationship between capacitance and moisture density for a variety of soils (5).
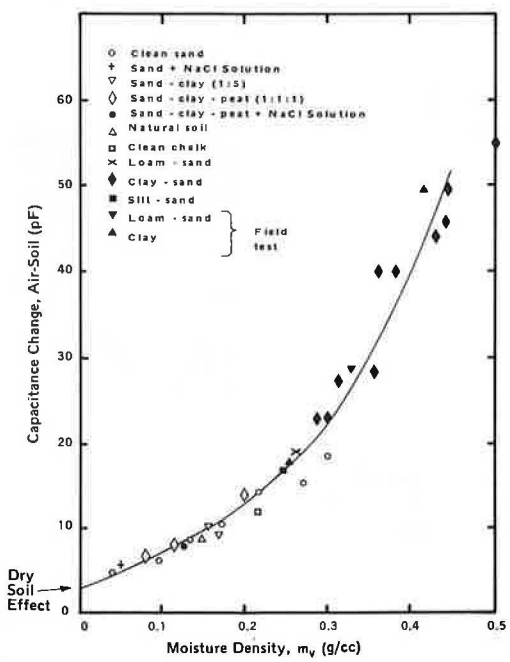
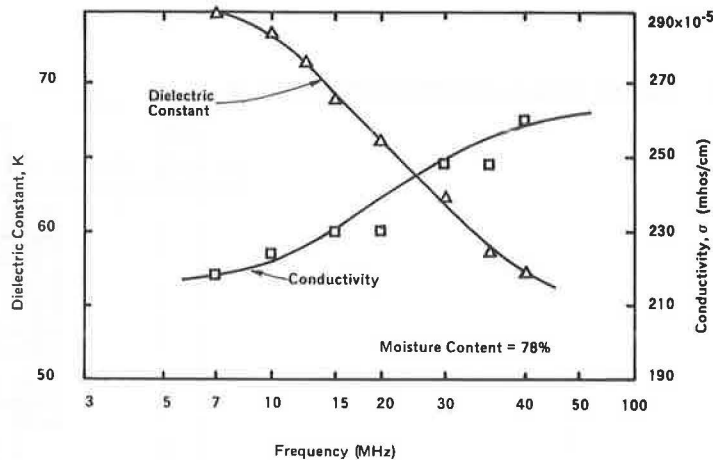Figure 4. Dielectric and conductivity dispersion characteristics of saturated illite Grundite (3).

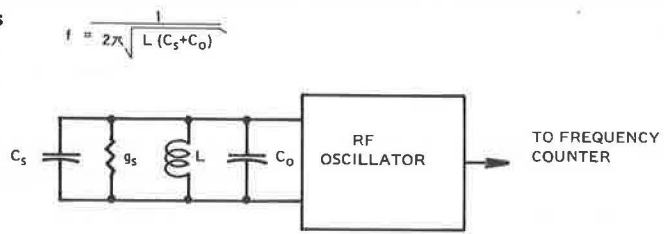Figure 5. Simplified apparatus for resonance frequency shift.

$$f = \frac{1}{2\pi \sqrt{L\,(C_s + C_o)}}$$

Figure 6. Rectangular container apparatus.

(a) assembled as in test   (b) disassembled

Figure 7. Cross section of rectangular container for laboratory tests.

Internal Vol. = 418 cc

Vol. = 32 cc

Brass Electrode

Plastic Insulator

Aluminum Case

1 cm

2.3 cm

4.4 cm

Plug-in Connections to Case (Ground Electrode)

3.2 cm

Plug-in Connection to Brass Electrode

b.) Small Container

changes, the measured frequency (f) changes. The frequency change with respect to dry soil (Δf_d) or an electronic reference (Δf_r) can be accurately measured from a remote station.

For a particular electrode, nominal frequency, and soil type, a calibration curve can be prepared relating Δf to m_v; however, the soil conductance (g_s) may be high enough to also affect Δf. The choice of nominal frequency and circuit component values can be selected to minimize this adverse effect of g_s for a particular soil. By use of the capacitance bridge approach, C_s and g_s can each be determined because they are independently measured; however, by use of the frequency shift method, in which only one parameter is measured, the effect on Δf of g_s changes cannot be distinguished from the effects of C_s changes. Preliminary experiments showed that circuit changes to minimize the effects of g_s also reduced the sensitivity of the system to m_v changes. Therefore, a compromise is needed between sensitivity and composition effects because the differences in g_s values among soils to be tested is expected to be the primary cause of calibration curve changes. It may not be possible to eliminate the effect of g_s sufficiently by the choice of circuit so that one calibration curve will be achieved for all soils.

The first sensors constructed were containers for evaluating various circuit designs and for studying the influence of soil conditions on system performance (Figs. 6 and 7). A conventional frequency counter was used as the readout device. At first, oscillator instability occurred in the bentonite clay at all moistures and at the higher frequencies and moistures tested for the other soils. This was believed to be a result of high conductivity; however, sensitivity in terms of $\Delta f / \Delta m_v$ also increased significantly as nominal frequency increased up to frequencies at which the circuit stopped functioning.

Improved performance was obtained through a long series of design changes and trials in which rectangular plug-in containers were used. The nominal operating frequencies obtained with this apparatus ranged from 15 to 40 MHz. The following conclusions were drawn from these tests:

1. Δf_r increased as m_v increased; however, the rate often decreased again at moisture densities above $m_v = 0.6$ to 0.8 g/cm^3 (Fig. 8). This latter trend is correctable by circuit component changes, but a reduction in sensitivity will also occur.

2. In the final set of tests with the rectangular container (at 21 MHz), most soils had approximately a common calibration curve (Fig. 9). Only bentonite departed significantly from this trend. All curves had a common intercept at $m_v = 0$.

3. Temperature change had little effect on the results as long as freezing was avoided.

4. The standard deviation of the Δf_r measurement variation was 0.1 to 0.2 kHz for the electronics over a 2-day period. Short-term variability with soil samples ranged from 0.2 to 1.4 kHz. The m_v values corresponding to these standard deviations are about 0.002 to 0.03 g/cm^3, which is equivalent to moisture content variation from 0.1 to 1.5 percent. However, most of this variation in soil was believed to be caused by specimen preparation rather than instrumentation.

5. If the container size was geometrically scaled up or down, then the calibration relationships remained essentially unchanged.

6. Void ratio or dry unit weight of a soil sample had little effect on the Δf_r-m_v calibration curve. Varying the amounts of specimen compaction for a constant w changed m_v, but Δf_r changed correspondingly.

7. The insensitivity to compaction made the container apparatus useful for rapid moisture determination of soil samples in the laboratory or field. So that w could be obtained the soil was uniformly tamped into the container, and the sample weight and Δf_r were measured.

After the system was evaluated with the rectangular container, the research effort was directed toward developing a fringing-probe type of sensor. Four sensors representing three configurations (cylindrical, parallel plate, and disk) were designed and tested (Figs. 10, 11, and 12). The electronic circuit used in these sensors (2) was

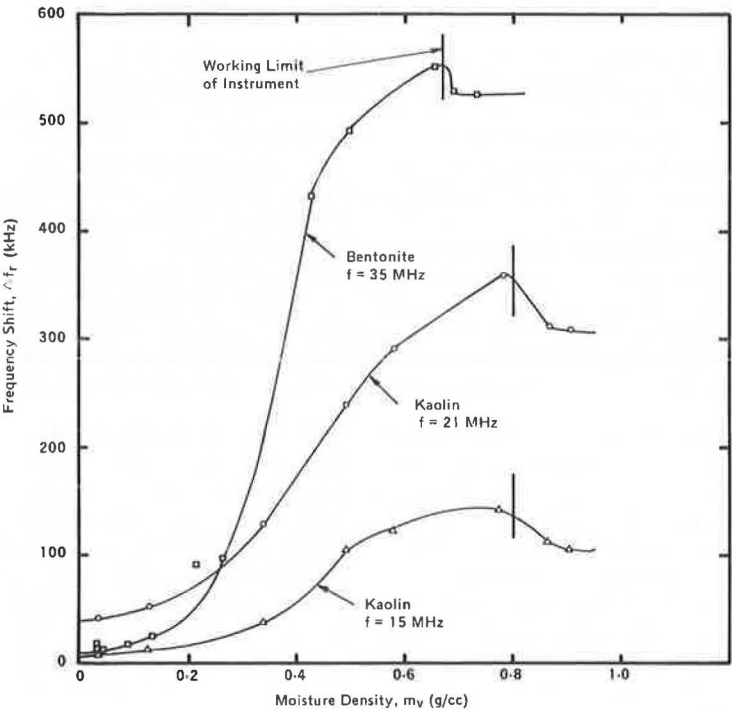Figure 8. Sensor response for tests on clays at three frequencies.

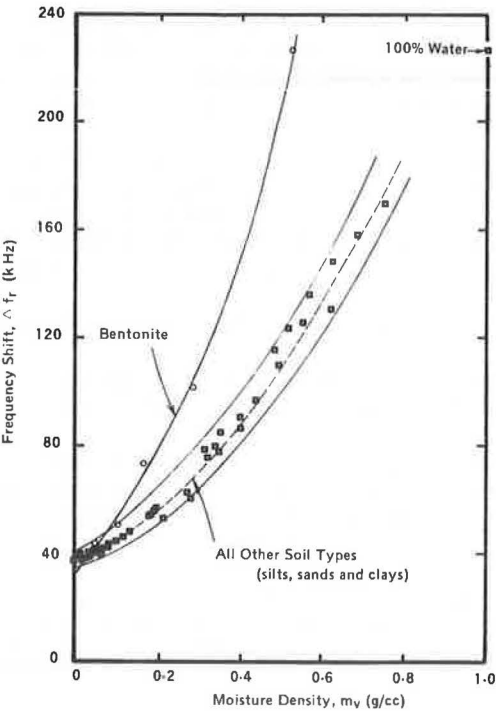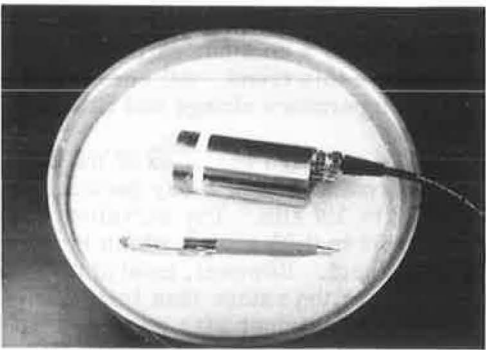Figure 9. Calibration curves for a range of soils tested with rectangular container at 21 MHz.
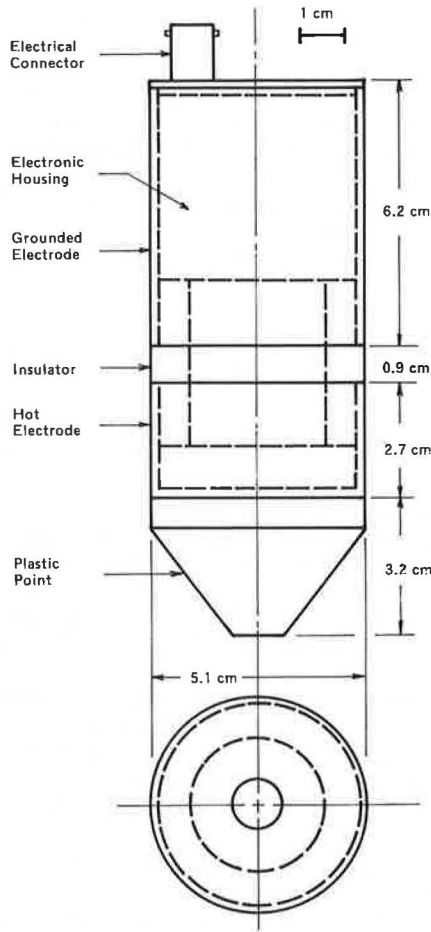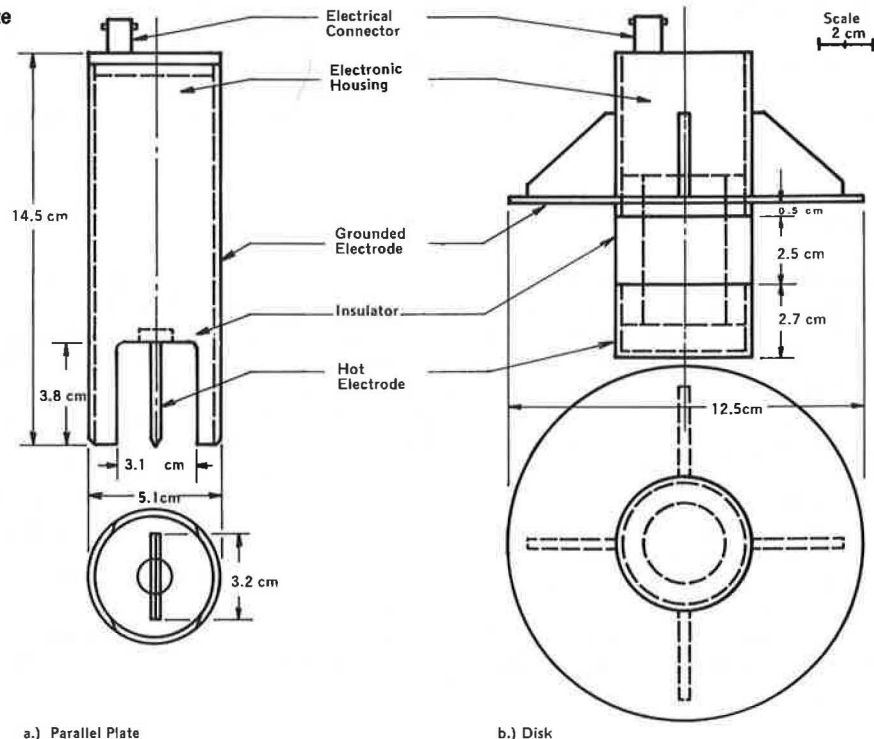

Figure 10. Prototype of cylindrical embedded sensor.

Figure 11. Cross section of prototype of cylindrical embedded sensor.

Electrical Connector

Electronic Housing

Grounded Electrode

Insulator

Hot Electrode

Plastic Point

1 cm

6.2 cm

0.9 cm

2.7 cm

3.2 cm

5.1 cm

Figure 12. Alternate configurations for embedded sensor.

Electrical Connector

Electronic Housing

Grounded Electrode

Insulator

Hot Electrode

Scale 2 cm

14.5 cm

3.8 cm

3.1 cm

5.1cm

3.2 cm

0.5 cm

2.5 cm

2.7 cm

12.5cm

a.) Parallel Plate

b.) Disk

essentially the same as the final version for the rectangular container. Printed circuit boards holding most of the electronic components were placed inside the sensors. A coaxial cable connected the sensor to the remote readout station, which consisted of a power supply, control switch, and frequency counter. The nominal operating frequency was 25 MHz. The approximate fringing fields indicating the zone of soil influencing the reading in each case are shown in Figure 13.

The following conclusions were drawn from the evaluation tests done with an embedded sensor:

1. The frequency shift increase was approximately proportional to the moisture density increase (measured with cylindrical, disk, and parallel-plate sensors) for the coarse-grained soils (Figs. 14, 15, and 16). The frequency shift with the kaolin was higher than that for any of the other soils tested, and it increased as moisture density increased. The extension of the curves for the coarse-grained soils corresponded with the Δf_r values in water alone.

2. The three configurations had about the same sensitivity to moisture change and the same intercept at zero moisture. The choice of sensor used, therefore, was primarily dictated by the type of application and method of installation.

3. The soil types involved in the sensor evaluation included clay up to 100 percent moisture content, silt, sand, and gravel up to 1 in. (2.54 cm). Although no single sensor was satisfactory over this entire range of conditions, the results suggested that sensors can be designed to handle all of these conditions.

4. For coarse-grained materials, the minimum sensor size is limited by the particle size of the material. Sensor electrode spacing should probably be at least as great at the D_{90} particle size (size below which 90 percent of the sample falls). The maximum associated sensor dimensions will depend on the sensor geometry.

5. The output appeared to be sensitive to changes in salt concentration and soil composition.

6. The short-term variability of the electronic system expressed as standard deviation of Δf_r was about 0.15 kHz for the small cylindrical sensor and 0.75 kHz for the large cylindrical sensor. These values correspond to standard deviation errors in m_v of about 0.002 g/cm^3 and 0.005 g/cm^3 and in w of about 0.1 and 0.3 percent for the small and large cylinders respectively. A few repeated tests in soil with the small cylindrical sensor gave Δf_r standard deviations of 0.5 to 1.7 kHz, which correspond to 0.002 to 0.01 g/cm^3 variation in m_v and 0.1 to 1.5 percent variation in w. Sample preparation variability probably was the main reason for the larger errors with soil.

7. Field installation techniques can be expected to have a big effect on the results. This may be the major source of error in determining m_v with the frequency shift sensor concept.

SUMMARY OF SENSOR CAPABILITIES

The frequency-shift sensor can be designed to operate in almost any soil type including highly plastic clays and gravelly materials. The sensor can be monitored from a remote station and can be permanently sealed to operate when it is submerged. It can easily be made rugged enough to withstand shock and, by proper case design, it can withstand the loading intensity involved in highway applications: The case must be rigid enough to avoid geometry change under loading. Of the configurations tested, the cylindrical sensor is best. There should be no inherent hysteresis in the calibration curve during moisture fluctuations because the sensor monitors the soil moisture directly. Although moisture measurements in frozen soil are quite different from those in unfrozen soils, the sensor electronics can be selected to remain operative at any anticipated temperature.

Difficulty with sensor stability over many weeks, encountered in the early stages of this study, has been overcome. Although long-term performance tests have not yet been conducted, it is expected that, if reliable electronic components and printed circuit boards are used and the sensor is permanently sealed, 1- to 5-year operation periods are feasible.
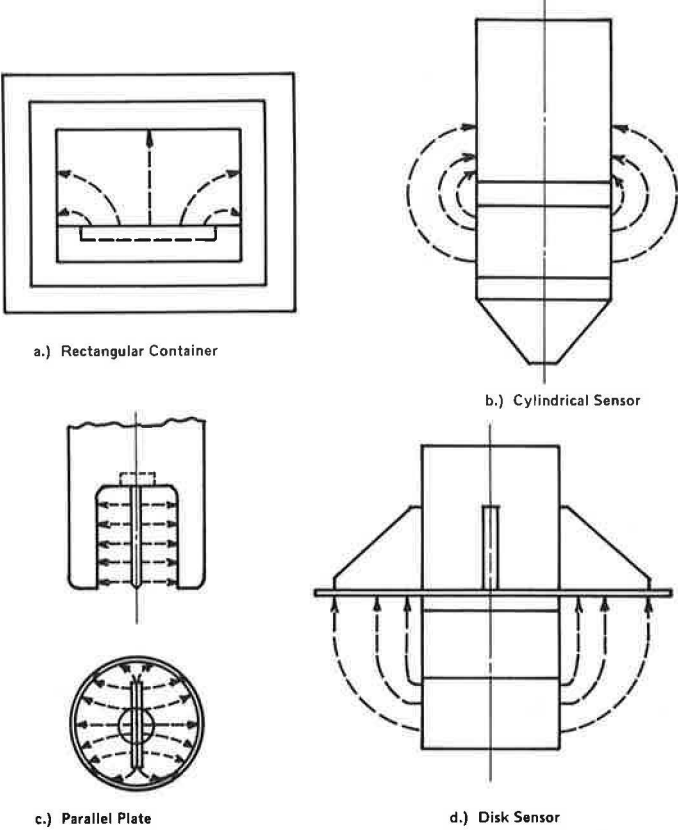
The image covers essentially the full page - two figures with diagrams.

Figure 13. Fringing fields for sensors.

a.) Rectangular Container

b.) Cylindrical Sensor

c.) Parallel Plate

d.) Disk Sensor

Figure 14. Calibration curve for cylindrical sensor.

f = 25 MHz

- ·o Medium Sand
- △ Fine Gravel
- ▫ Kaolin
- + Gravelly Sand
- × Silt and Clay

Water

Air

Δf_r (kHz)

m_v (g/cc)

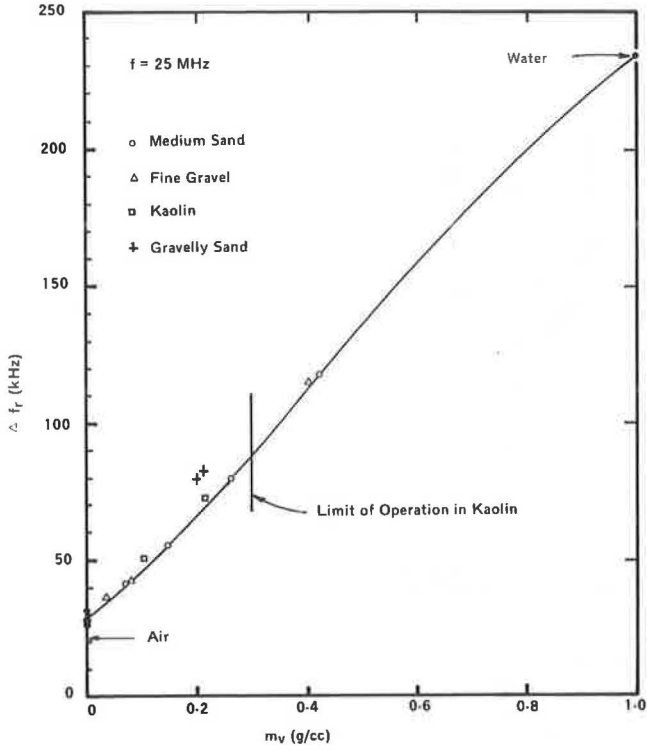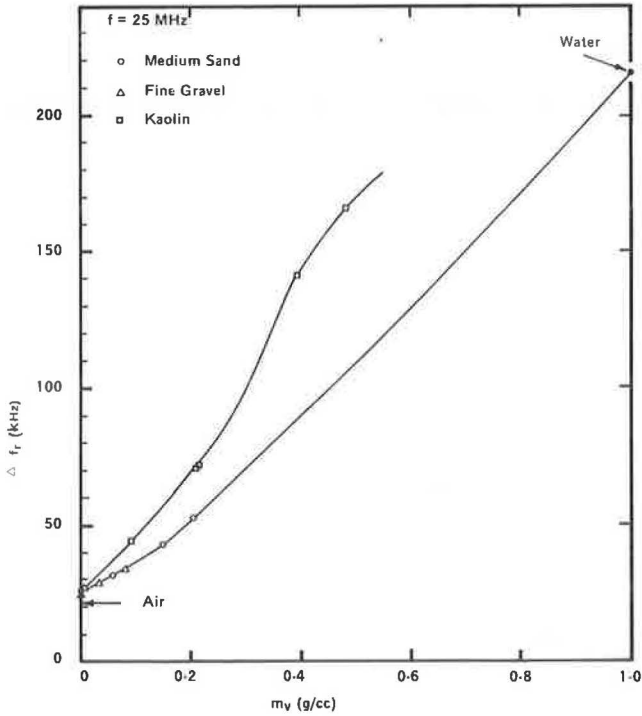Figure 15. Calibration curve for disk sensor.

Figure 16. Calibration curve for parallel-plate sensor.

Sensor readout at a single oscillator frequency can be accomplished with a readily available battery-operated frequency counter. However, proper interfacing components, which are inexpensive and simple to construct, are needed. Special purpose readouts will simplify the process and permit multiple frequency readout. This latter arrangement may make it possible to eliminate the soil composition effect on the sensor calibration.

The sensor concept is scalable so that almost any size is possible. The smallest size, governed by the degree of circuit miniaturization for the electronic components within the sensor, is about $1\frac{1}{2}$ in. (3.8 cm) long. The desired size will primarily be dictated by the soil conditions. The smallest size will be for silts and clays with uniform moisture content, and the largest size will be for gravelly materials and soils with heterogeneous moisture conditions. In these cases, the electrode spacing probably will need to be at least equal to the D_{90} size or the dimensions of the heterogeneity. However, disturbance of soil conditions by sensor installation is also determined by the sensor configuration and installation procedures. The sensor concept can easily provide the variety of configurations needed for optimum results over the range of desired highway applications.

The sensor can be designed to operate over almost any range of moisture content in any soil. However, there are several qualifying factors for meeting this objective: (a) A single circuit design will not be optimum for all possible conditions, (b) more than one calibration curve may be needed for each sensor geometry and circuit design to account for composition effects, and (c) the best sensor size and configuration will vary with the soil and application conditions. In addition, it must be recognized that the sensor only measures moisture content in terms of weight of water per unit volume of soil. Density measurements are also needed to compute moisture content in terms of ratio of weight of water to weight of dry soil. This is a limitation of all methods, however.

If a nominal dry unit weight of soil of 1.6 g/cm^3 (100 lb/ft^3) is assumed, then a 1 percent moisture change is equivalent to 0.016 g/cm^3 change in water per unit volume. The frequency-shift concept has the sensitivity to detect such moisture changes; however, accuracy depends not only on this sensitivity (precision) but also on such factors as long-term instrument stability, calibration curve accuracy, and placement conditions. Thus, overall accuracy is hard to assess. The sensor circuit design incorporates an internal reference to minimize errors caused by changes in the electronic system. (More experience is needed to determine the effectiveness of this technique.) Other sources of error must be controlled by the user.

In addition to the system capabilities described, one other useful application of the capacitance system for moisture determination has developed from this research. This application concerns disturbed soil samples such as those obtained in laboratory soil classification and compaction tests or in moisture control for field compaction. In these situations, a rapid method for moisture determination is desirable. The capacitance method can provide this capability by constructing a sensor in the form of a container in which to put the sample. This approach involves, first, uniformly tamping the soil into the container by hand. The electrical reading is then taken to get moisture per unit volume, and the sample weighed to get the wet weight per unit volume. These two immediate measurements will permit calculation of moisture content. This method can be used in the field as well as in the laboratory because the instrumentation system is portable. The electronic circuit is the same as that used in the embedded sensor system. By use of the proper calibration curves and size of container, essentially any soil type and moisture range can be tested.

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