DEVELOPMENT OF AN ELECTRONIC SENSOR FOR SOIL STRENGTH MEASUREMENTS

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Received on: 13/6/2006 ***Accepted on: 21/8/2006***

ABSTRACT

A voltage-based sensor was developed to electronically determine soil physical properties and soil penetration resistance. The sensor was designed to generate a voltage output when a change in one, or more, of the soil properties took a place, disrupting the balance state of the sensor resistance. The performance of the sensor was tested on two soil types, sand soil acquired from a field in Saudi Arabia and clay soil obtained from the delta valley of Egypt. Due to its low water holding capacity, only three levels of soil moisture content (MC) namely 4, 6 and 10% were used when testing the sensor with the sand soil, however, six MC levels (8, 12, 15, 20, 24 and 26%) were used when testing the sensor with the clay soil. For both soil types and for all MC levels considered, the soil bulk density was determined to range from 1.15 to 2.65g/cm^3.

Results of the study revealed that the value of the voltage generated from the sensor was proportional to the soil MC. On the average, the sensor voltage increased from 1.98 to 2.42V when the sand soil moisture content increased from 4 to 6% at an average soil bulk density of 1.72gm/cm^3 with a linear relationship determination factor (R^2) value of above 0.99. For the clay soil, the average voltage increased from 0.38 to 2.12V when the MC increased from 8 to 26% at an average bulk density of 1.32 gm/cm^3 with a value of R^2 above 0.98. In addition, the sensor voltage was found to be proportional to the soil bulk density (ρ), where for all MC levels, the values of the R^2 of the linear relationship between soil ρ and sensor voltage were above 0.90 for the sand and the clay soil, except for soils at MC of 4 and 15% where the R^2 value was above 0.80. However, the rate of increase in senor voltage due to increase in soil ρ was observed, for both soil types, to decrease at higher MC levels. Results also showed that the sensor voltage output was proportional, at all MC levels, to the clay soil penetration resistance, where the R^2 values were above 0.85. The rate of voltage change as a response to change in soil penetration resistance was higher at lower soil MC levels. The sand soil, on the other hand, did not show any resistance to penetration at all MC levels; therefore, no voltage output was observed from the sensor.

***Key words:** Sensor, voltage, circuit, soil, moisture content, bulk density, penetration resistance.*

INTRODUCTION

Soil moisture content is a determinant factor that is widely used to evaluate the amount of water in the soil available for plants and to arrange irrigation schedules (Bosch, 2002). In addition, soil bulk density and soil penetration resistance are two interrelated important soil characteristics that are usually used to ascertain degree of soil compaction in agricultural tillage practices (Raper et al., 2005, Mckyes and Raghavan, 1977, Chesness et al., 1972). Soil bulk density, being a measure of soil compaction, was found to affect draft forces, where these forces were observed to be proportional to soil bulk density (Raper et al., 2005).

Field soil moisture content is usually determined using laboratory techniques. These techniques are often laborious, time consuming and costly. Recent advances in soil water studies have led to the development of soil water sensors that are capable of rapidly determining, in site, soil moisture and bulk density. However, high procurement and maintenance cost that is usually associated with these sensors limits their availability to low income farmers. Therefore, Ismail (1998) developed, using a transistor 2N743, a low cost electronic soil moisture sensor that was intended to replicate the functions of modern sensors and be readily available to low income farmers. However, the amplification ratio of the developed sensor was too low limiting its applicability.

Soil penetration resistance was found to be a function of soil moisture content and soil bulk density (Ayers and Perumpral, 1982). On the other hand, the voltage output of the sensor developed by Ismail (1998) was also found to be a function of soil moisture content and soil bulk density. However, the relation between the sensor voltage output and soil penetration resistance has not been determined. Therefore, the specific objectives of this study are:

1) To develop an electronic circuit for sensing soil moisture content, soil bulk density and penetration resistance,
2) To test the response of the developed sensor as a measure for the change in the physical soil properties and soil penetration resistance.

LITERATURE REVIEW

Soil moisture content, soil bulk density and soil penetration resistance are all interrelated soil characteristics that have been a subject for several studies. Ayers and Perumpral (1982) investigated the relationship between soil cone index, soil moisture content and soil bulk density. The results of their study revealed that the cone index was a measure of soil penetration resistance and was a function of a number of factors including soil moisture content, soil density and soil type. They also developed, based on experimental data, an equation for soil cone index for

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different soil types. For a specific soil type, the cone index equation was shown to be a function of soil density and soil moisture content. A similar cone index equation was developed by Chesness et al. (1972); however, the application of their equation was reported to be limited to a narrower soil moisture range compared to that used with Ayers and Perumpral (1982) equation.

Korayem et al. (1996) investigated soil shear strength and penetration resistance using soil properties. Soil penetration resistance was found to be related to soil shear strength parameters, such as soil cohesion (C) and angle of soil internal friction (Φ), and a linear regression model that related penetration resistance indices to soil cohesion was developed. Results of the study showed that the soil shear parameters were extremely important to determine traction forces. In addition, soil shear strength and soil penetration resistance were observed to be affected by various variables such as soil type, soil moisture content and soil bulk density. Furthermore, the study revealed that the value of soil penetration index increased significantly with increasing initial soil bulk density and increasing soil moisture content up to 13%, which was equal to soil field capacity, and dropped beyond this limit. Lammers and Yurui (2004) developed a combined capacitance-penetrometer sensor for simultaneous determination of cone index and soil water content. A sensor calibration test revealed that the developed sensor was adequately sensitive to determine soil moisture content; however, a soil-specific calibration was required. Laboratory and field tests proved that the developed sensor was capable of providing valuable data for analyzing the relationships between bulk density, penetration resistance and soil water content.

Ismail (1998) utilized an electronic circuit to develop a sensor to measure soil moisture content. The developed circuit was a modification of the colpitts oscillator which incorporated the transistor 2N743 (Texas Instruments Inc, 1968). The sensor accuracy in measuring soil moisture content (MC%) was tested by connecting the sensor to a soil chamber containing two terminals (sensor input side) and to a voltmeter (sensor output side) that recorded sensor voltage output. The recorded voltage was used as an indicator of soil MC%. Soil MC% values produced by the sensor for different soil types were compared to the soil MC% values determined using the conventional method and used as a reference. Results of the comparison showed that the coefficient of correlation between the two data sets, sensor-produced MC% values and reference MC% values, was as high as 0.98. This high degree of correlation between the two data sets indicated that the sensor developed was very accurate in determining soil MC% for different soil types. However, the amplification factor associated with the developed sensor was found to be too low, introducing the need for developing a sensor with a higher amplification factor.

Campbell, Decagon devices Inc. (2005) developed a voltage-based dielectric sensor (ECHO) that used a specialized circuitry to measure dielectric constant media surrounding its probe. They carried out a calibration on several dielectric probes with respect to soil water content and studied the effects of soil salinity and texture on the stability of the calibration. It was noted that at low or moderate soil electrical conductivity (EC) of less than 12.9 mmhos/cm, there was no appreciable effect on calibration, thus probe performance. However, at soil EC values of above 12.9 mmhos/cm, deviation from the standard calibration was observed. A calibration shift was clearly observed in the measurements on sand loam and loam soils. However, after regressing the data for all probes used, a maximum deviation of less than 4% from unity was noted, which implied that the calibration was not probe specific or dependant. For soils with low to moderate sand contents, a good correlation was shown between the sensor voltage output and the soil volumetric water content. Data from sand loam and loam soil types both showed a regular bias in probe output. High clay soils also exhibited errors in form of defective sensor measurements, thus warranted further study. The ECHO sensor did not show any dependence on soil texture with moderate clay content. In general and for all soils sampled, dielectric probes output was found to have a near linear relationship with the volumetric water content.

SENSOR DEVELOPMENT

A Wheatstone bridge was incorporated in the development of the soil moisture content sensor, illustrated in the diagram shown in figure 1, which used an operational amplifier in a differential input mode.

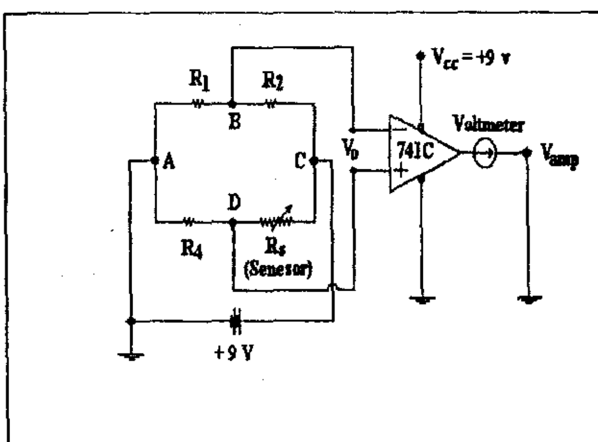

Figure 1: Diagram of the electronic circuit developed to measure soil moisture content

The bridge was utilized to generate a voltage signal (V_o) greater than zero when the balance of the bridge arm, where $V_o = 0$, was disturbed. Disturbance occurred as a result of a change in sensor resistance (R_S) due to a change in the sensed moisture of the medium (soil) under study. The voltage signal (V_o) was found to be linearly proportional to the changes in R_S (ΔR_S). The sensor sensitivity can be drawn from the following sequence of formulas:

Assume, in figure 1, that $R_1=R_2=R_4=R_s=R$ (1)

$$i_{AB} = \frac{V}{R_1+R_2} \quad \text{then} \quad V_{BC} = V\frac{R_2}{R_1+R_2} \qquad (2)$$

$$i_{AD} = \frac{V}{R_s+R_4} \quad \text{then} \quad V_{CD} = V\frac{R_s}{R_s+R_4} \qquad (3)$$

where:

i_{AB} and i_{AD} are the currents in the arms AB and AD, respectively,
V is the input voltage to the Wheatstone bridge circuit,
V_{BC} is the voltage between points B and C,
V_{CD} is the voltage between points C and D,
R_1, R_2 and R_4 are the resistances of the bridge arms,
R_s is the resistance of the soil.

When in balance state,

$$V_{BC} = V_{CD} = \frac{V}{2} \qquad (4)$$

$$V_O = V_{CD} - V_{BC} = 0 \qquad (5)$$

where:
V_o is the signal voltage.

If R_s changes by ΔR_s, then,

$$V_{CD} = V\frac{(R_S + \Delta R_S)}{(R_S + \Delta R_S + R_4)} \quad \text{or}$$

$$V_{CD} = V\frac{(R_S + \Delta R_S)}{(2R + \Delta R_S)} \qquad (6)$$

$$\because\ V_o = V_{CD} - V_{BC} \qquad (7)$$

$$\therefore\ V_O = V\frac{(\Delta R_S)}{(4R + 2\Delta R_S)} \qquad (8)$$

when $\Delta R_S \ll R$ then ΔR_s can be neglected in the denominator of equation 8, so it can be written as:

$$V_O = V\frac{(\Delta R_S)}{4R} \qquad (9)$$

Therefore, sensor sensitivity (K) can be determined as:

$$K = \frac{V_O}{\Delta R_S} = \frac{V}{4R} \qquad (10)$$

Parameters in equation 10 were designed to obtain the maximum sensitivity of the developed sensor. The value of input voltage to the Wheatstone bridge circuit (V), appearing in equation 10, was set to 9 volts. To increase the accuracy of the developed sensor measurements, power in the circuit was kept low to eliminate or greatly minimize soil moisture evaporation as a result of a heat caused by passing current. In addition, adequate penetration of current through the soil under test was provided.

MATERIALS AND METHOD

The experimental work designed to test the accuracy of the developed sensor involved the utilization of the materials shown in figure 2, which included the following:

Soil:

Two soil types were implemented in this study; sand soil acquired from a field in the Kingdom of Saudi Arabia and clay soil acquired from a field in the Delta valley of Egypt.

Soil Test Chamber:

An aluminum cylinder with a diameter of 6.3 cm and a height of 5 cm was designed to be utilized as the soil test chamber. The chamber was equipped with a covering cap, which was used to apply a pressure on the soil inside the chamber to reach a desired soil compaction. A sensing electrode was fixed at the center of the test chamber and served as the positive terminal; the chamber wall was used as the negative terminal.

Circuit:

The electronic circuit developed in this study (figure 1) was designed for the purpose of electronically measuring the electrical resistance, being a function of soil moisture content and bulk density, of soil placed in the test chamber. The positive and negative terminals mentioned above were connected to the points D and B, respectively (figure 1). The resistance of the soil placed in the test chamber (R_s) caused a voltage change across the points D and B, which was amplified by the use of a 741C amplifier (Nelson, 1983). The resulting amplified voltage (V_{amp}) was recorded by a digital multimeter and used as an indicator of soil water content. The voltage changed as a response to a change in soil moisture content, providing the ability to measure a wide range of soil moisture contents utilizing the developed circuit.

Multimeter:

A Maxcom, MX-280, digital multimeter was utilized to measure the change in voltage between soil chamber electrodes (V_{amp}). The meter was reported to maintain an accuracy of 0.01 volts.

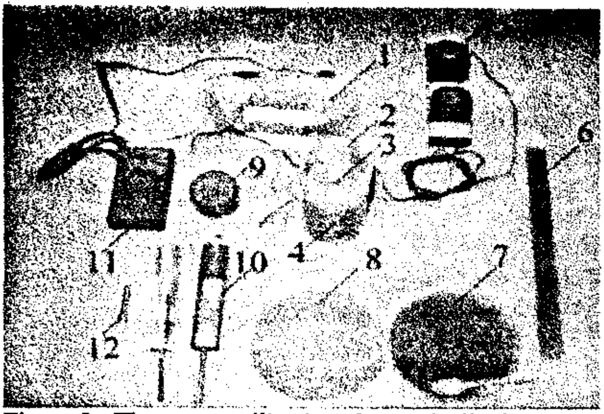

Figure 2: The set up utilized to electronically detect soil moisture content.

1. Sensor	7. Clay soil
2. In-chamber ruler	8. Sandy soil
3. Positive electrode	9. Soil compaction cap
4. Soil test chamber	10. Flat penetration
5. DC electricity source	11. Multimeter
6. Ruler	12. Cone head

Scale:

A GS-200 acculab weighing digital scale was utilized to determine the weight of soil samples used for the calculation of the different soil bulk densities and moisture contents. The utilized scale was reported to have a capacity of 200g and a weighing accuracy of 1g.

PROCEDURE

Soil Preparation:

For each of the two soil types involved in this study, an amount of 150g of air dried soil sample was placed in a Petri dish and a pre-determined amount of water was sprayed on the sample to reach a desired moisture content. The soil sample was then ground using a pestle and mixed up to reach a state of homogeneous soil sample. The homogeneous sample was placed in a plastic bag and kept in the refrigerator for a period of 24 hr to obtain uniform moisture content. For this study, the soil moisture content levels were selected to provide a reasonable number of observations in the range of 4 to 10% for sand soil samples and 8 to 26% for clay soil samples, based on the water holding capacity of each soil type.

Determination of Soil Bulk Density:

The soil sample prepared at the desired moisture content was carefully placed in the soil test chamber and was compacted to a desired height (h) using the test chamber cap. The bulk density of the soil placed in the test chamber (ρ) was determined using the following formula:

$$\rho = \frac{W_s}{\frac{\pi}{4} D^2 h} \qquad (11)$$

where:

W_s is the weight of soil sample placed in the test chamber (g),
ρ is the desired soil bulk density (g/cm^3),
D is the diameter of the soil test chamber (cm),
h is the height of soil level inside the test chamber (cm).

Determination of Soil Moisture Content :

The arrangement shown in figure 2 illustrates the experimental setup that was implemented to measure soil moisture content. The prepared weighted soil at a desired level of moisture content (known moisture) was placed in the soil test chamber and compacted to a certain height inside the soil chamber using the soil compaction cap. Compaction was exerted on the soil sample, reducing h in equation 11, until the required bulk density level was reached (as determined from equation 11). At that point, the measurement of the sensor output voltage, recorded by the voltmeter connected to the circuit board, was an indication of the soil moisture content at a specific level of soil bulk density.

Determination of Soil Penetration Resistance:

Soil penetration tests were carried out on the soil samples using a hand-held flat penetrometer manufactured according to the ASAE standards, S 313.1 FEB04 (ASAE Yearbook, 2003). The tests were conducted immediately after the desired soil bulk density was reached. Thus, soil penetration resistance was a measure of soil shear strength at a specific level of soil compaction and moisture content. A calibration procedure was performed in order to convert the penetrometer readings and obtain the values of soil resistance in kg.

Statistical Analysis:

The data obtained from the experiments were analyzed using the statistical procedures available on the microcomputer (SAS, 1982). Mainly, stepwise procedure was used for that purpose where it is mostly helpful for providing an insight into the relationship between the independent variables and dependent variable. The selecting criterion of a model was based on the value of 'Cp' static which is a measure of the total squared error. It has gained a great popularity in recent years and was developed by Mallows (1973). It could be defined as follows:

$$Cp = \frac{SSEp}{S^2} - (n - 2p) \qquad (12)$$

where:

S^2=the MSE for the full model that contains all possible variables and is presumed to be reliable unbiased estimate of error variance
SSEp=the sum of squares error for model containing p variables plus the intercept
n=number of observations
P=number of variables in the model

If the Cp is graphed with p, it is recommended that the best model is at where Cp first approaches p. This means that the parameter estimates of the model are unbiased. Thus, the final best model can be build up based on the best subset regression using R^2 and Cp resulted from the stepwise regression technique (Draper and Smith, 1981 and Hocking, 1976).

RESULTS AND DISCUSSION

The relationship between sensor voltage output and soil moisture content (MC) was investigated for the two soil types incorporated in this study. Due to its low water holding capacity, three low MC levels (4, 6 and 10%) were associated with the sand soil; however, six different MC levels (8, 12, 15, 20, 24 and 26%) were associated with the clay soil. For both soil types, the sensor voltage output was noted to be proportional to the soil MC (figure 3). For the sand soil at an average bulk density (ρ) of 1.72gm/cm^3, the linear relationship between sensor output voltage and sand soil MC maintained an R^2 value of above 0.99 and is written as follows:

$$\text{Volt} = 0.075\ \text{MC} + 1.65 \quad (13)$$

where:

Volt is the sensor output voltage (V,

MC is the sand soil moisture content (%).

The sensor responded to the increase in soil MC from 4 to 10% by increasing its output voltage from 1.98 to 2.42V. Increasing the MC of the clay soil from 8 to 26% at an average ρ of 1.32 gm/cm^3 generated a response from the senor represented by increasing the voltage output from 0.38 to 2.12V. The polynomial relationship between the clay soil MC and the voltage output with an R^2 value of above 0.98 can be illustrated in the following equation:

$$\text{Volt} = -0.008\ (\text{MC})^2 + 0.366\ \text{MC} - 1.987 \quad (14)$$

where:

Volt is the sensor output voltage (V)

MC is the clay soil moisture content (%).

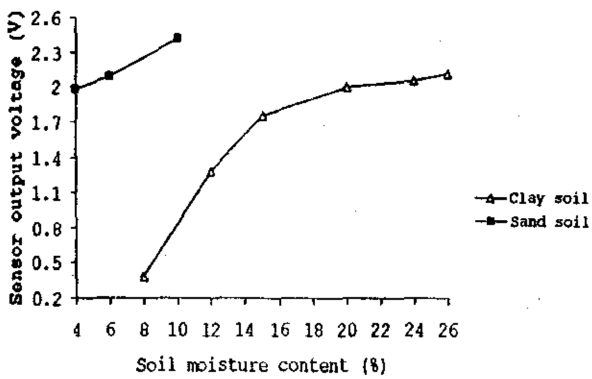

Figure 3: Sensor response due to different soil moisture contents.

Results of the study have also demonstrated that for both soil types and different MC levels, the sensor voltage output was found to be proportional to the soil bulk density (figure 4 and 5). The values of the R^2 of the linear relationship between the two variables at all MC levels were above 0.90 for both soil types, except for soils at MC of 4 and 15% where the R^2 value was above 0.80. Increasing the sand soil bulk density from 1.16 to 1.72 gm/cm^3 at an MC level of 4% caused the sensor voltage output to increase from 1.84 to 2.05 V (11.4%). For the clay soil, increasing its bulk density from 1.16 to 1.41 gm/cm^3 at an MC level of 8% resulted in an increase in the voltage output from 1.16 to 1.41 V (21.6%). In addition and for both soil types, increasing the soil MC level at a specific soil bulk density produced higher senor output voltage values. For example, the sensor voltage output was found to increase from 1.56 to 1.94 V at a clay soil bulk density of 1.44 gm/cm^3 when the soil MC was raised from 12 to 15%. At a sand soil bulk density of 2.04 gm/cm^3, the voltage output increased from 2.14 to 2.42 V when the MC level increased from 6 to 10%. However, the rate of increase in the sensor voltage output as a response to the increase in soil bulk density was found to decrease with increasing soil MC, where the line representing the relationship between the two variables was observed to flatten out at higher soil MC levels (figure 4 and 5). For instance, increasing the clay soil bulk density by 21.6% at an MC of 8% caused an increase of 454.5% in the sensor voltage output; however, an increase of 60.4% in bulk density at the MC level of 26% caused an increase of voltage output of only 4.9%. For the sand soil, increasing the soil bulk density by 48.3% caused an increase of 11.4% in the sensor output voltage at an MC of 4%; however, at an MC of 10%, 130.4% increase in soil bulk density caused an increase of only 1.3% in the sensor output voltage. This result leads to the conclusion that, for both soil types, the sensor response to changes in soil bulk density was inversely proportional to the increase in soil MC level. This was attributed to the fact that as the soil MC increased approaching soil field capacity and saturation state, the sensor produced its maximum output voltage when the electrical resistance between the two soil chamber electrodes approached its lowest level due to increasing soil MC values.

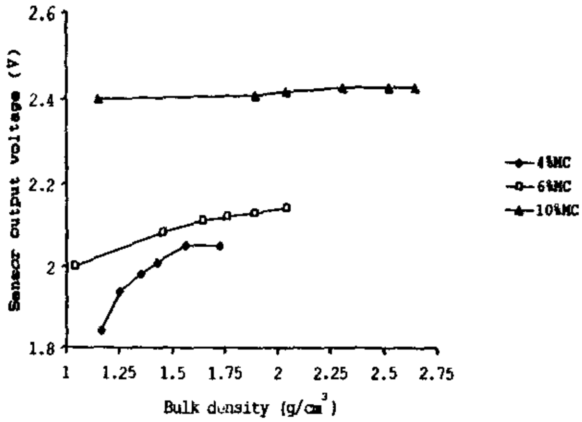

Figure 4: Effect of sand soil bulk density on sensor output voltage at different MC levels.

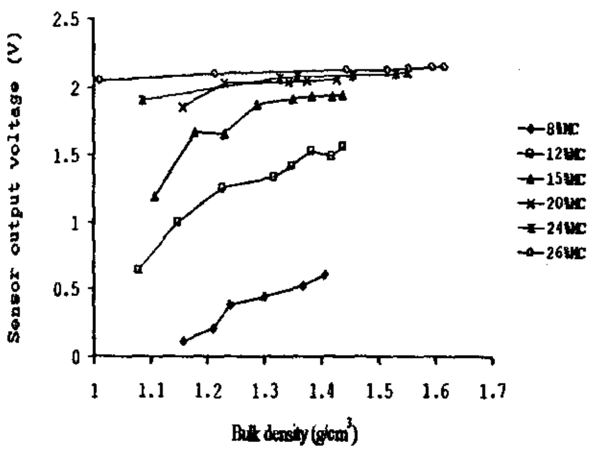

Figure 5: Effect of clay soil bulk density on sensor output voltage at different MC levels

The statistical analysis performed on the data obtained for sand soil revealed that the value of determination factor (R^2) of the relationship between the output voltage of the developed sensor and both soil bulk density and soil moisture content was higher than 0.99. Values of other parameters of the relationship were also estimated (table 1) using SAS statistical software (SAS, 1982). These parameters included the Cp, which is a measure of the total squared error, and was developed by Mallows (1973). The relationship between the Cp and the R^2 was revealed by Kennard (1971). The parameters; Cp and R^2, were used to produce the best statistical model that predicted the output voltage as a function of soil bulk density and moisture content as follows:

$$Volt = 1.3899 + 0.03789\ MC + 0.00609\ MC^2 + 0.03665\ \rho - 0.03465\ \rho * MC \quad (15)$$

where:

Volt is the sensor output voltage (V),
MC is the soil moisture content (%),
ρ is the desired soil bulk density (g/cm^3).

For the clay soil, statistical analysis revealed that the R^2 value of the relationship between the output voltage of the sensor and both soil bulk density and moisture content was higher than 0.94 (table 2). The values of the other parameter shown in table 2 were utilized to build up the statistical model that could be used to predict the sensor output voltage as a function of clay soil bulk density and moisture content as follows:

$$Volt = -4.019 + 0.34215\ MC - 0.004712\ MC^2 + 2.4349\ \rho - 0.08207\ \rho * MC \quad (16)$$

where:

Volt is the sensor output voltage (V),
MC is the soil moisture content (%),
ρ is the desired soil bulk density (g/cm^3).

The statistical models shown in equations 15 and 16 were selected by the stepwise regression based on the values of Cp and R^2 shown in tables 1 and 2, where the number of variables entered in the models approached the value of Cp. The value of the significance level required for any variable to take a place in the model was set to 0.05. The models showed that the effect of soil bulk density on the output voltage was linear, while the effect of soil moisture content on the output voltage was quadratic (second degree).

Table 1: Results of statistical analysis for sandy soil data where MC denotes soil moisture content and ρ denotes soil bulk density. All variables left in the model are significant at the 0.050 level.. R^2=0.99614 and Cp=5.29

Var	DF	Sum of Squares	Mean Square	F
Reg.	4	0.67065	0.16766	840 **
Error	13	0.00259	0.00019	
Total	17	0.67325		
Var.	Parameter Estimate	Stand. Error	F	
INT	1.3899	0.0529	689.54**	
MC	0.037	0.0130	8.48**	
MC^2	0.006	0.00095	40.99**	
ρ	0.3665	0.02853	165.02**	
$MC*\rho$	-0.0346	0.00346	100.16**	

Table 2: Results of statistical analysis for clay soil data where MC denotes soil moisture content and ρ denotes soil bulk density. All variables left in the model are significant at the 0.050 level. R^2=0.9427 and Cp=5.08.

Var.	DF	Sum of Squares	Mean Square	F
Reg.	4	23.017	5.7543	160**
Error	39	1.3992	0.0359	
Total	43	24.416		
Var.	Parameter Estimate	Stand. Error	F	
INT	-4.01895	0.80935	24.66**	
MC	0.34215	0.03686	86.18**	
MC^2	-0.00471	0.00072	42.92**	
ρ	2.43491	0.68255	12.73**	
MC*ρ	-0.0820	0.03220	6.49**	

For both soil types, a flat head penetrometer was utilized to measure the soil penetration resistance at the predetermined soil moisture contents. Soil penetration resistance was mainly a function of soil moisture content and bulk density. For the clay soil, it was observed that, at a specific soil MC, the soil penetration resistance was proportional to soil bulk density; however, it was inversely proportional to the MC at a specific soil bulk density (figure 6). The sand soil, on the other hand, did not exhibit any resistance to penetration at any of the predetermined soil moisture content values and a relationship could not be established. As shown in figure 6, increasing soil bulk density increased soil penetration resistance due to increasing soil compaction level, however, the increasing rate decreased with increasing soil moisture content, which agreed with the results reached by Korayem, et al (1996) and John (1988).

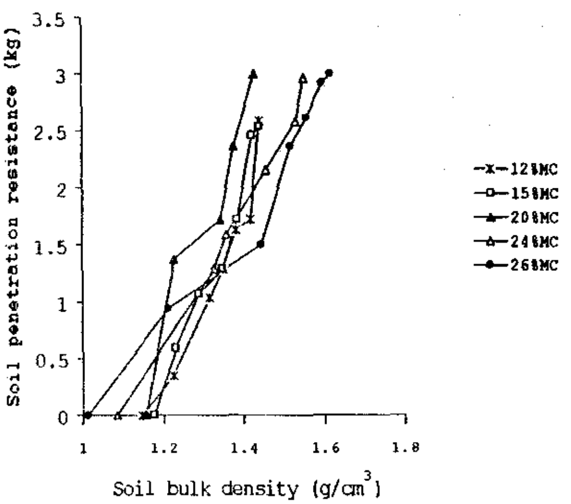

Figure 6: Effect of clay soil bulk density and moisture content on soil penetration resistance.

The response of the developed sensor to the change in soil penetration resistance was studied for the clay soil only, as the sand soil did not show resistance to penetration at all MC levels incorporated in the study. The voltage output was found to be proportional to the soil penetration resistance at all MC levels (figure 7); however, the rate of increase in the voltage as a response to the increase in soil bulk density was noted to decrease with higher MC values. At soil MC of 12%, the voltage output increased by 56% when the soil penetration resistance increased from 0 (at ρ of 1.15g/cm^3) to 2.58kg (at ρ of 1.44g/cm^3). However, at a higher MC value of 26%, the increase in voltage output was limited to 4.4% as the soil penetration resistance increased from 0 (at ρ of 1.01g/cm^3) to 2.62kg (at ρ of 1.56g/cm^3). The relationship as shown in figure 7 tended to be nonlinear at low soil MC values with R^2 values of above 0.85; however, a linear relationship was formed as the MC values increased, where an R^2 value of above 0.90 was obtained at an MC value of 26%, causing the soil to approach its soil field capacity at soil bulk density ranging from 1.10 to 1.62 g/cm^3.

CONCLUSIONS

A voltage-based sensor was developed into an electronic means to measure soil moisture content (MC) and soil bulk density (ρ). In addition, the sensor was also utilized to determine soil penetration resistance as a function of soil moisture content and bulk density. Two soil types, clay and sand, were involved in testing the performance of the developed sensor and its response to the changes in the three physical soil characteristics. Conclusions of the study can be listed as follows:

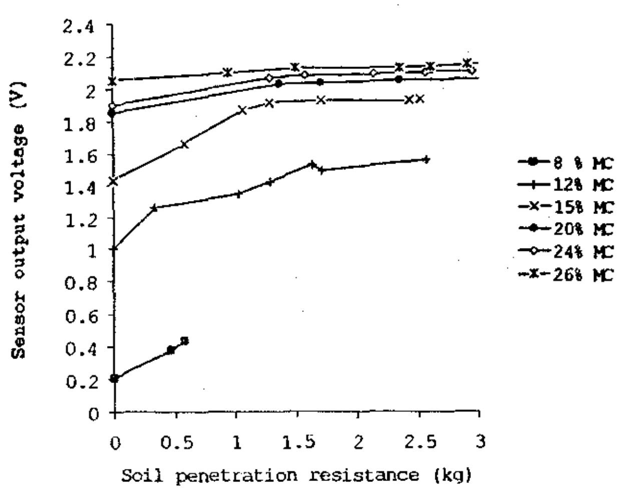

Figure 7: Effect of clay soil penetration resistance on sensor output voltage.

1-For the two soil types, the sensor was found to be responsive to changes in soil MC, where the average sensor output voltage was observed to be proportional to the soil MC levels incorporated in the study. Increasing the sand soil MC from 4 to 6% caused the sensor voltage to increase by 22.2% (from 1.98 to 2.42V), where the linear relationship between the two variables maintained a value of R^2 to be above 0.99. For the clay soil, an increase of 457.9% (from 0.38 to 2.12V) in sensor voltage output was recorded as a response to an increase of the soil MC from 8 to 26%, where the value of R^2 value of above 0.98 was obtained.

2-The sensor was observed, for both soil types, to be responsive to changes in soil ρ at all studied soil MC levels, where the sensor output voltage was proportional to the soil ρ values. However, the rate of change in output voltage as a response to a change in soil ρ for both soil types was found to be lower at higher MC values, where the soil was approaching its field capacity. At an MC value of 8%, increasing the clay soil ρ by 21.6% caused the sensor voltage to increase by 454.5%; however, at an MC value of 26%, increasing the soil ρ by 60.4% produced an increase in the sensor voltage output of only 4.9%. For both soil types, the sensor voltage output value was observed, at a specific ρ, to be higher with higher MC levels. The values of the R^2 of the linear relationship between soil ρ and sensor voltage were, at all MC levels, above 0.90 for both soil types, except for soils at MC of 4 and 15% where the R^2 value was above 0.80.

3-The sand soil did not exhibit any resistance to penetration at all study MC levels. However, the clay soil penetration resistance was found to be proportional to soil ρ at all MC levels. The rate of change in soil penetration resistance as a response to the changes in soil ρ was observed to decrease with higher MC values.

4-The sensor output voltage was proportional to the clay soil penetration resistance at all soil MC levels. This increase in the sensor output voltage at specific moisture content is caused by the increase in soil bulk density that caused an increase in the soil penetration resistance. The relationship was observed to be smoother and more linear at higher moisture content values, where the R^2 value of above 0.90 was obtained at MC level of 26%, while the R^2 value of above 0.85 was obtained at lower MC levels.

RECOMMENDATIONS

The developed electronic circuit produced satisfactory results as shown above. However, it is recommended to test the performance of the developed circuit with more soil types and with soils containing polymers. Moreover, calibrating the circuit against commercially available moisture sensors would provide a means to better evaluate the performance of the developed sensor.

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الملخص العربي

تطوير حساس إليكتروني لقياس صلابة التربة

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تم تطوير حساس إلكترونى لقياس رطوبة وكثافة التربة بالإضافة إلى مقاومة التربة للاختراق وقد تم تصميم هذا الحساس حيث يتم توليد فولت كدالة في المحتوى الرطوبي وكثافة التربة الظاهرية. وقد أعتمد التصميم على استخدام دائره إليكترونية باستخدام Wheatstone Bridge التى صممت من أربع اذرع مقاومات تم اختبارها للحصول على أكبر نسبة تكبير باستخدام مكبر إشارة رقم 741C.

ولقد تم استخدام نوعين من التربة أحدهما تربة رملية أحضرت من المملكة العربية السعودية (مزرعة مركز البحوث الزراعية) والأخرى طينية من دلتا الوجه البحرى بمصر.

أختبرت الدائرة الإليكترونية بالمعمل عند مستويات كثافة ظاهرية تراوحت من ١,١٥ إلى ٢,٦٥ جرام/سم^{٣} بينما كانت مستويات المحتوى الرطوبي فى التربة الطينية ٨، ١٢، ١٥، ٢٠، ٢٤، ٢٦% بينما مستويات الرطوبة في التربة الرملية ٤، ٦، ١٠% . شكلت هذه المستويات معاملات مختلفة لإختبار آداء الحساس المقترح.

أمكن إيجاد علاقات إرتدادية بين خرج الحساس وبين كل من المحتوى الرطوبي والكثافة الظاهرية للتربة وكذلك مقاومة التربة للاختراق. ولقد وجد أن العلاقة بين خرج الحساس كفولت وبين رطوبة التربة داله طردية من الدرجة الثانية وذلك فى التربة الطينية بينما كانت داله طردية فى الدرجة الأولى فى التربة الرملية ربما بسبب قلة عدد المستويات. كان تأثير كثافة التربة الظاهرية على خرج الحساس (كفولت) خطى كما لوحظ أن معدل الزيادة فى خرج الحساس قد نقص مع زيادة الرطوبة بسبب الوصول إلى حد السعة الحقلية للتربة والذى يتعاظم عنده خرج الحساس. وجد كذلك أنه كلما زادت مقاومة الاختراق زاد خرج الحساس كفولت لكل من نوعي التربة تحت الاختبار.

توصلنا في هذا البحث الى تصميم حساس سريع الاستجابة ورخيص التكاليف وسهل الاستعمال كما أدى البحث إلى إكتشاف علاقة جديدة بين مقاومة التربة للاختراق وخرج الحساس وبالتالى يفتح المجال إلى المزيد من الأبحاث بهذا الشأن.