A150-431-5M-L180

TEXAS AGRICULTURAL EXPERIMENT STATION

A. B. CONNER, DIRECTOR
COLLEGE STATION, BRAZOS COUNTY, TEXAS

BULLETIN NO. 426 APRIL, 1931

DIVISION OF AGRICULTURAL ENGINEERING

Determination of Soil Moisture by the Method of Multiple Electrodes

AGRICULTURAL AND MECHANICAL COLLEGE OF TEXAS
T. O. WALTON, President

STATION STAFF†

ADMINISTRATION:
A. B. Conner, M. S., *Director*
R. E. Karper, M. S., *Vice-Director*
Clarice Mixson, B. A., *Secretary*
M. P. Holleman, Jr., *Chief Clerk*
J. K. Francklow, *Assistant Chief Clerk*
Chester Higgs, *Executive Assistant*
C. B. Neblette, *Technical Assistant*

CHEMISTRY:
G. S. Fraps, Ph. D., *Chief; State Chemist*
S. E. Asbury, M. S., *Chemist*
J. F. Fudge, Ph. D., *Chemist*
E. C. Carlyle, B. S., *Assistant Chemist*
Waldo H. Walker, *Assistant Chemist*
Velma Graham, *Assistant Chemist*
T. L. Ogier, B. S., *Assistant Chemist*
Athan J. Sterges, B. S., *Assistant Chemist*
Jeanne M. Fuegas, *Assistant Chemist*
Ray Treichler, M. S., *Assistant Chemist*
Ralph L. Schwartz, B. S., *Assistant Chemis*
C. M. Pounders, B. S., *Assistant Chemist*

HORTICULTURE:
S. H. Yarnell, Sc. D., *Chief*
L. R. Hawthorn, M. S., *Horticulturist*

RANGE ANIMAL HUSBANDRY:
J. M. Jones, A. M., *Chief*
B. L. Warwick, Ph. D., *Breeding Investigations*
Stanley P. Davis, *Wool Grader*

ENTOMOLOGY:
F. L. Thomas, Ph. D., *Chief; State Entomologist*
H. J. Reinhard, B. S., *Entomologist*
R. K. Fletcher, Ph. D., *Entomologist*
W. L. Owen, Jr., M. S., *Entomologist*
J. N. Roney, M. S., *Entomologist*
J. C. Gaines, Jr., M. S., *Entomologist*
S. E. Jones, M. S., *Entomologist*
F. F. Bibby, B. S., *Entomologist*
Cecil E. Heard, B. S., *Chief Inspector*
Otto Mackensen, B. S., *Foulbrood Inspector*
W. B. Whitney, *Foulbrood Inspector*

AGRONOMY:
E. B. Reynolds, Ph. D., *Chief*
R. E. Karper, M. S., *Agronomist*
P. C. Mangelsdorf, Sc. D., *Agronomist*
D. T. Killough, M. S., *Agronomist*
H. E. Rea, B. S., *Agronomist*
————————, *Agronomist*
B. C. Langley, B. S., *Assistant in Soils*

PUBLICATIONS:
A. D. Jackson, *Chief*

VETERINARY SCIENCE:
*M. Francis, D. V. M., *Chief*
H. Schmidt, D. V. M., *Veterinarian*
F. P. Mathews, D. V. M., M. S., *Veterinarian*
W. T. Hardy, D. V. M., *Veterinarian*
F. E. Carroll, D. V. M., *Veterinarian*

PLANT PATHOLOGY AND PHYSIOLOGY:
J. J. Taubenhaus, Ph. D., *Chief*
W. N. Ezekiel, Ph. D., *Plant Pathologist*
W. J. Bach, M. S., *Plant Pathologist*
————————, *Plant Pathologist*

FARM AND RANCH ECONOMICS:
L. P. Gabbard, M. S., *Chief*
W. E. Paulson, Ph. D., *Marketing*
C. A. Bonnen, M. S., *Farm Manaegment*
**W. R. Nisbet, B. S., *Ranch Management*
**A. C. Magee, M. S., *Farm Management*

RURAL HOME RESEARCH:
Jessie Whitacre, Ph. D., *Chief*
Mary Anna Grimes, M. S., *Textiles*
Elizabeth D. Terrill, M. A., *Nutrition*

SOIL SURVEY:
**W. T. Carter, B. S., *Chief*
E. H. Templin, B. S., *Soil Surveyor*
A. H. Bean, B. S., *Soil Surveyor*
R. M. Marshall, B. S., *Soil Surveyor*

BOTANY:
V. L. Cory, M. S., *Act. Chief*
Simon E. Wolff, M. S., *Botanist*

SWINE HUSBANDRY:
Fred Hale, M. S., *Chief*

DAIRY HUSBANDRY:
O. C. Copeland, M. S., *Dairy Husbandman*

POULTRY HUSBANDRY:
R. M. Sherwood, M. S., *Chief*

AGRICULTURAL ENGINEERING:
H. P. Smith, M. S., *Chief*

MAIN STATION FARM:
G. T. McNess, *Superintendent*

APICULTURE (San Antonio):
H. B. Parks, B. S., *Chief*
A. H. Alex, B. S., *Queen Breeder*

FEED CONTROL SERVICE:
F. D. Fuller, M. S., *Chief*
S. D. Pearce, *Secretary*
J. H. Rogers, *Feed Inspector*
K. L. Kirkland, B. S., *Feed Inspector*
Sidney D. Reynolds, Jr., *Feed Inspector*
P. A. Moore, *Feed Inspector*
E. J. Wilson, B. S., *Feed Inspector*
H. G. Wickes, B. S., *Feed Inspector*

SUBSTATIONS

No. 1, Beeville, Bee County:
R. A. Hall, B. S., *Superintendent*

No. 2, Troup, Smith County:
P. R. Johnson, M. S., *Superintendent*

No. 3, Angleton, Brazoria County:
R. H. Stansel, M. S., *Superintendent*

No. 4, Beaumont, Jefferson County:
R. H. Wyche, B. S., *Superintendent*

No. 5, Temple, Bell County:
Henry Dunlavy, M. S., *Superintendent*
————————, *Plant Pathologist*
H. E. Rea, B. S., *Agronomist; Cotton Root Rot Investigations*
Simon E. Wolff, M. S., *Botanist; Cotton Root Rot Investigations*

No. 6, Denton, Denton County:
P. B. Dunkle, B. S., *Superintendent*

No. 7, Spur, Dickens County:
R. E. Dickson, B. S., *Superintendent*
————————, *Agronomist*

No. 8, Lubbock, Lubbock County:
D. L. Jones, *Superintendent*
Frank Gaines, *Irrigationist and Forest Nurseryman*

No. 9, Balmorhea, Reeves County:
J. J. Bayles, B. S., *Superintendent*

No. 10, College Station, Brazos County:
R. M. Sherwood, M. S., *In charge*
L. J. McCall, *Farm Superintendent*

No. 11, Nacogdoches, Nacogdoches County:
H. F. Morris, M. S., *Superintendent*

****No. 12, Chillicothe, Hardeman County:**
J. R. Quinby, B. S., *Superintendent*
**J. C. Stephens, M. A., *Assistant Agronomist*

No. 14, Sonora, Sutton-Edwards Counties:
W. H. Dameron, B. S., *Superintendent*
————————, *Veterinarian*
W. T. Hardy, D. V. M., *Veterinarian*
**O. G. Babcock, B. S., *Entomologist*
O. L. Carpenter, *Shepherd*

No. 15, Weslaco, Hidalgo County
W. H. Friend, B. S., *Superintendent*
Sherman W. Clark, B. S., *Entomologist*
W. J. Bach, M. S., *Plant Pathologist*

No. 16, Iowa Park, Wichita County:
C. H. McDowell, B. S., *Superintendent*

No. 17, ————————
————————, *Superintendent*

No. 18, ————————
————————, *Superintendent*

No. 19, Winterhaven, Dimmit County:
E. Mortensen, B. S., *Superintendent*
L. R. Hawthorn, M. S., *Horticulturist*

No. 20, ————————
————————, *Superintendent*

Teachers in the School of Agriculture Carrying Cooperative Projects on the Station:

G. W. Adriance, Ph. D., *Horticulture*
S. W. Bilsing, Ph. D., *Entomology*
V. P. Lee, Ph. D., *Marketing and Finance*
D. Scoates, A. E., *Agricultural Engineering*
A. K. Mackey, M. S., *Animal Husbandry*
J. S. Mogford, M. S., *Agronomy*
F. R. Brison, B. S., *Horticulture*
W. R. Horlacher, Ph. D., *Genetics*
J. H. Knox, M. S., *Animal Husbandry*

---

*Dean School of Veterinary Medicine.

†As of April 1, 1931.

**In cooperation with U. S. Department of Agriculture.

This Bulletin reports the theoretical principles used in adapting electrical measurements of soil resistivity to the determination of soil moisture, and the results obtained during the summer of 1930 at Substation No. 7, located near Spur, Dickens County. Comparison of soil-moisture measurements by the auger method with the moisture measurements given by the calibration obtained during this investigation has not been sufficient to determine the accuracy of the method. However, readings made on the control plats of Substation No. 7, indicate that the method should prove useful in obtaining relative measurements of soil moisture and may possibly be used to determine the percentage of moisture in soils at various locations. There is also included a brief statement of the steps to follow in making moisture determinations by resistance measurements of soil at other locations. The apparatus is such that it can be readily obtained from companies dealing in scientific and laboratory supplies, and is reasonably portable.

CONTENTS

BULLETIN NO. 426 APRIL, 1931

DETERMINATION OF SOIL MOISTURE BY THE METHOD OF MULTIPLE ELECTRODES

W. H. McCORKLE*

In connection with a study (2) of factors influencing runoff and soil erosion in which the field work was done at the Spur Experiment Station located in the rolling plains region, it seemed desirable to devise some better method than soil sampling for use in determining the relative moisture contents of different plots being studied, since the many samplings required by the auger method would enter as an erosion factor. To this end the project leaders—Mr. A. B. Conner, Mr. R. E. Dickson, and Mr. D. Scoats—initiated a plan to use the electrical conductivity method for measuring the relative soil moisture in the series of plots.

In this preliminary paper it is the purpose of the author to set forth an adaptation of the electrical method for determining soil-moisture content by electrical resistance measurements in which a sufficient number of electrodes are used to make it possible to eliminate the changes of contact between the soil and the electrodes by solving simultaneous equations which involve the changing contacts as unknowns. It is also desired to give the results obtained so far in determining the possibilities of the method in making relative measurements of soil moisture, and its usefulness in determining the percentage of moisture in the soil.

PREVIOUS AND RELATED WORKS

In one of the earliest attempts to connect the electrical conductivity of soils with their moisture contents, Whitney, Gardner, and Briggs (7) obtained some promising results but the apparatus used required too frequent calibration for practical purposes. Results of investigations (mostly unpublished) have usually not been very encouraging and have caused a somewhat general feeling of doubt concerning the reliability of the electrical method of determining moisture content when applied to soils.

A theoretical consideration of a four terminal conductor method of measuring earth resistivity has been given by Wenner (6). This method, using an alternating current potentiometer to balance potentials, when applied to earth resistance measurements by McCollum and Logan (5), gave results which seemed sufficiently accurate for the study of the electrolysis of underground structures. The investigators found the instruments and method too unwieldy for most measurements, and no entirely satisfactory method of correcting for changing contact between the soil and the electrodes was developed. The method of Wen-

---

*Assistant Professor of Physics, A. and M. College of Texas.

ner (6) has been developed further by numerous investigators and used in Geophysical researches and prospecting.

APPARATUS

The apparatus used in this investigation consisted of an Alternating Current Bridge (which will be referred to as an A. C. Bridge through the remainder of this paper) with sensitive telephone receivers and microphone hummer, with a battery of five dry cells connected in series, soil augers, drying oven, balances weighing to 1/100 gram, and thermometers for determining the temperature of the soil. The above instruments were all of standard make and can be procured from companies dealing in scientific and laboratory apparatus.

In addition to the apparatus mentioned, soil electrodes were constructed of $\frac{3}{8}$-inch carbon rods about 6 inches long secured to No. 14 rubber-insulated copper wire as follows: at one end of the wire for a distance of approximately 2 inches the insulation was removed, after which the bare wire was heavily tinned by application of solder and non-corrosive flux, and a loop formed on the end of the wire, which was inserted in a hole drilled in one end of the carbon rod. The hole, enlarged at the bottom, was filled with molten type-metal, which adhered closely to the tinned wire and expanded on cooling to form a firm connection between the carbon rod and the copper wire. The copper wire was cut sufficiently long to leave 2 to 3 inches exposed to connect with the A. C. Bridge wires by a Fahnestock connector when the electrode was inserted in the soil to the desired depth. The insulation was removed from about three inches of the top end of the wire and this part of the wire also was well tinned. The carbon rod and attached wire were then secured in a glass tube of suitable bore and length and the joints sealed against moisture by sealing wax, leaving the carbon rod extending 4 inches out of the glass tube. (This length was chosen as a convenient length for use in the experiment.) The electrodes thus had the appearance of two coaxial cylinders of different radii joined end to end with a slight enlargement at the juncture as shown in Fig. 1. A rod of nearly similar shape was obtained from a local blacksmith shop and used to form the holes in the soil to the desired depths, after which the electrodes were put in place by filling the holes with a thick mud slush and carefully working the electrodes up and down to remove air bubbles and allow

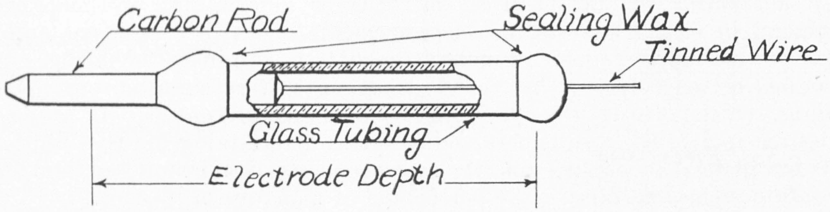

Fig. 1. Broken-away sectional view of an electrode.

the slush to settle around the carbon rods. Sufficient slush was used to fill the holes to overflowing, thus preventing the formation of depressions in the soil immediately surrounding the electrodes, which otherwise would permit water to collect around the electrodes and give a much lower value for the resistance of the soil between the electrodes than should be found. The electrodes, once installed, were left undisturbed and after sufficient time had elapsed for the moisture of the slush to distribute itself evenly through the surrounding soil, measurements of soil resistivity were begun.

The general arrangement of the apparatus for determining soil resistivity is shown in Fig. 2 (a).

For measurement of resistivity at any one location and depth, four similar electrodes were used, arranged as indicated in Fig. 2 (b).

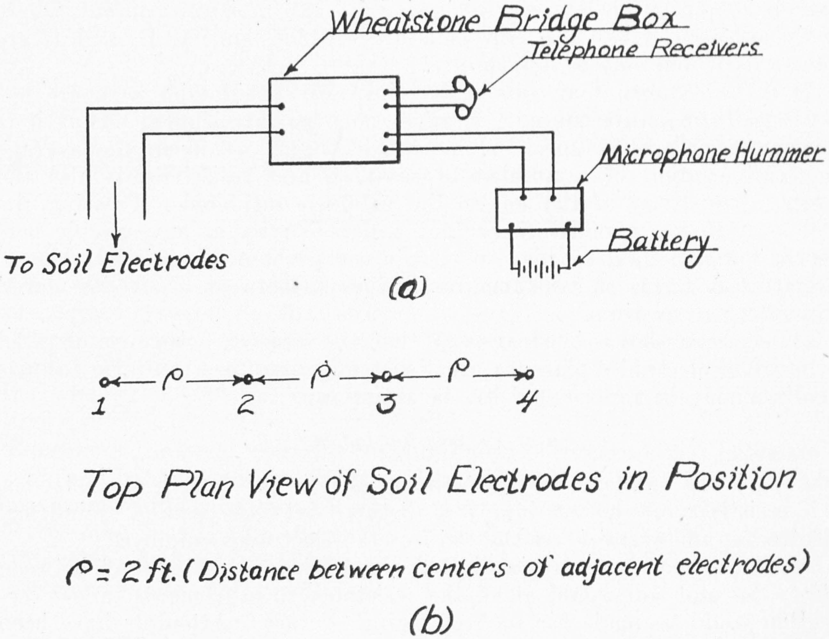

Fig. 2. Resistance-measuring apparatus, (a) schematic diagram of The A. C. Bridge and other essential apparatus, (b) top plan view of electrodes placed in the soil.

THEORY

In measurements of soil resistivity, or specific resistance, the soil, with its salts, organic matter, water, etc., is considered as an electrolyte. The conductivity (conductivity being the reciprocal of resistivity) of electrolytes is shown by Kraus (4) to be a function of the temperature, the viscosity of the solution, the dissociation of the salts, the kind of salts, etc. Usually the conductivity of the soil electrolyte is considered chiefly a function of the dissociation and temperature, but the effect of the fluid state, or viscosity, should evidently be considered. As shown by Anderson and Mattson (1), colloidal material in the soil must influence viscosity; therefore, we should expect soil conductivity to increase generally with dissociation of the salts, with increase of temperature, and with decrease of viscosity. Viscosity should depend on the soil colloids and moisture content. Thus the conductivity function must have a complicated form which could hardly be stated from theoretical considerations alone. By the application of divided difference theorems (9) to observed soil resistance measurements and corresponding moisture contents (obtained during this investigation) the equation relating soil resistivity and moisture content was found to be a cubic equation. The type of equation

$$Y = A/X^3 + B/X^2 + C \qquad 1$$

satisfied the relation between soil resistivity and moisture content, where Y is soil resistivity, X is soil moisture content, and A, B, and C are constants which may be determined.

It is well known that soils underlying any considerable area are not uniform in moisture content, as auger borings have shown. Thus it is understood when we speak of moisture content we mean the average moisture content of a number of samples, and resistivity is also the average resistivity of the soil in the volume considered. Treating the soil as uniform in moisture content and resistivity at any specific percentage of moisture, we may then state our problem of resistivity determination in terms of resistance measurements between electrodes placed in a uniform medium.

It has been shown by Jeans (3) that the resistance between parallel cylindrical electrodes placed a great distance apart in a uniform infinite medium may be represented by the equation

$$\mu = (\tau/2\pi) \log (\rho^2/a.b) \qquad 2$$

where μ is the resistance of the medium between unit length of electrodes, τ is resistivity of the medium, ρ is distance between parallel cylindrical electrodes, and a and b are the radii of the electrodes employed.

It can be readily appreciated that change in area of contact between electrodes and soil would affect the resistance measurements unless correction could be made for such changing contact. Attempts have been made to overcome this error by frequent recalibration of electrodes. The method, of course, is inconvenient and not satisfactory. From Equation 2, when applied to electrodes of length l, may be obtained

$$\mu' = (\tau/2\,\pi\,l) \log (\rho^2/a.b) \qquad 3$$

where μ' is the resistance between parallel cylindrical electrodes of length l and radii a and b, placed a great distance ρ apart in a uniform infinite medium.

Jeans (3) states that if two electrodes of any shape are placed in an infinite medium at a distance ρ apart which is great compared with their linear distance, we may express to a first approximation the resistance between the electrodes by the equation

$$R = \tau/4\pi \, (p_{11} + p_{22}) \qquad 4$$

where τ is the resistivity of the medium, and p_{11} and p_{22} are the coefficients of potential.

"It accordingly appears that the resistance of the infinite medium may be regarded as the sum of two resistances—a resistance $\tau \, p_{11}/4\pi$ at the crossing of the current from the first electrode to the medium, and a resistance $\tau \, p_{22}/4 \, \pi$ at the return of the current from the medium to the second electrode. Thus we may legitimately speak of the resistance of a single junction between an electrode and the conducting medium surrounding it."

From Equation 3, it is clear that a decrease in l (the length) causes an increase in resistance between the electrodes. Change in contact area must, consequently, change the effective length of the electrodes and could be considered as causing an added resistance at the electrodes because of poor contact. Letting R represent the resistance measurements between two electrodes, as determined by an A. C. Bridge or some other suitable device, we may write,

$$R = \mu' + r_1 + r_2 \qquad 5$$

where μ' is the resistance of the soil when electrodes make contact with the soil over their entire surfaces, r_1 the increase of resistance caused by poor contact between the first electrode and the soil, and r_2 the increase of resistance caused by poor contact between the second electrode and the soil. The values r_1 and r_2 may change from day to day, or following rains; thus it is essential that corrections be made that may eliminate r_1 and r_2.

Equation 5, however, contains three unknowns; therefore it is necessary to obtain further equations relating the unknows to make possible the elimination of the contact resistance between the several equations.

By placing four similar electrodes at known distances apart, as shown in Fig. 2 (b), and taking resistance measurements between two electrodes at a time, we may obtain equations as follows:

$$R_1 = \mu'_1 + r_1 + r_2 \qquad (a)$$
$$R_2 = \mu'_2 + r_1 + r_3 \qquad (b)$$
$$R_3 = \mu'_3 + r_1 + r_4 \qquad (c)$$
$$R_4 = \mu'_4 + r_2 + r_3 \qquad (d)$$
$$R_5 = \mu'_5 + r_2 + r_4 \qquad (e)$$
$$R_6 = \mu'_6 + r_3 + r_4 \qquad (f)$$

where R_1 is resistance reading between electrodes 1 and 2, R_2 between 1 and 3, R_3 between 1 and 4, R_4 between 2 and 3, R_5 between 2 and 4, and R_6 between 3 and 4; μ'_1 is actual soil resistance between electrodes 1 and 2, μ'_2 between 1 and 3, μ'_3 between 1 and 4, μ'_4 between 2 and 3, μ'_5 between 2 and 4, and μ'_6 between 3 and 4; r_1, r_2, r_3, and r_4 are the added resistances caused by poor contact with the soil at the respective electrodes.

From Equations (b) and (c) we may obtain

$$R_3 = \mu'_3 + R_2 - \mu'_2 - r_3 + r_4 \qquad 6$$

By adding Equations 6 and (f) we have

$$R_6 + R_3 - R_2 = \mu'_6 + \mu'_3 - \mu'_2 + 2r_4 \qquad 7$$

Also, from Equations (a) and (c) we obtain

$$R_3 = \mu'_3 + R_1 - \mu'_1 - r_2 + r_4 \qquad 8$$

By adding Equations 8 and (e) we have

$$R_5 + R_3 - R_1 = \mu'_5 + \mu'_3 - \mu'_1 + 2r_4 \qquad 9$$

Subtracting 7 from 9 gives

$$(R_5 + R_2) - (R_6 + R_1) = (\mu'_5 + \mu'_2) - (\mu'_6 + \mu'_1) \qquad 10$$

which is free of added resistances caused by poor contact at the electrodes.

With the electrodes placed at known distances apart in a uniform medium, we may obtain from Equation 3 the relations of μ'_6, μ'_5, and μ'_2 to μ'_1 and may then express Equation 10 as follows:

$$\mu'_1 = \frac{(R_5 + R_2) - (R_6 + R_1)}{K} \qquad 11$$

where μ'_1 is the soil resistance between two electrodes at a known distance apart; R_5, R_2, R_6, and R_1 are resistance measurements obtained by A. C. Bridge or other suitable instrument; and K is a constant depending on distances separating the four electrodes used and their depth in the soil.

EXPERIMENTAL PROCEDURE

In determining the moisture content of the soil, cores of the soil were taken with soil augers having diameters of about 1¾ inches. The parts of the cores obtained from the soil at the same depth as the electrodes, and also approximately equal in length to the contact portions of the electrodes, were placed in aluminum sample boxes and weighed. Later the samples were dried for 12 hours in an oven at a temperature of 110° C. to 120° C. The moisture was then expressed in per cent of dry soil.

To observe the effect of change of contact area between the electrodes and the soil, on the soil resistance between the electrodes, two pairs of electrodes of different contact lengths were placed in a small plat of ground (called The Office Plat) near the Experiment Station Office. One pair of the electrodes had a contact length of 10 inches and the other pair of electrodes had a contact length of 3 inches. Both pairs of electrodes were placed the same depth in the soil and the members of each pair were separated the same distance.

An electrode set-up for the purpose of calibration was made outside of the control plats in an area covered with Buffalo grass. Electrodes were placed also in each of the eight control plats of the Experiment Station at depths of 12 inches, 18 inches, and 30 inches. The electrodes in the calibration plat were placed at the same depths and distances apart as those in the control plats. A space 11½ feet by 15¼ feet on the grass area containing the calibration electrodes was dammed up and flooded with cistern water. At a depth of 12 inches the moisture content was in excess of 24 per cent, as determined by the soil auger. After drying out for a period of several days the plat was again flooded and a moisture content of nearly 29 per cent was found at the 12-inch depth. During the first few days following flooding of the plat, auger samples were taken daily at various depths and records made of moisture content, temperature of the soil, and resistance measurements. This was continued until the change of resistance with changing moisture content became considerably more than at first. The readings were then taken at two-day intervals. Measurements of moisture content by auger, soil temperature by mercury in glass thermometers, and resistance between electrodes by the A. C. Bridge were also made on the control plats.

Since it was desirable to measure the moisture content of the control plats under various conditions of weather, an instrument house was erected at one end of the control plats and wires run from each control plat to the instrument house, where readings were made in the same manner employed on the calibration electrodes. The use of long connecting wires and their necessarily crowded arrangement required the use of a small variable condenser of about .001 m.f. maximum capacitance in parallel with the resistance coils of the bridge to produce a sharp minimum in the telephone receivers. The inductance of the connecting wires seemed to cause no serious difficulty.

The electrical resistance of the soil between electrodes was obtained from the equation:

$$\mu'_1 = \frac{(R_5 + R_2) - (R_6 + R_1)}{K} \qquad 11$$

where μ'_1 is the soil resistance between specified electrodes; R_5, R_2, R_6, and R_1 are resistance readings obtained from the A. C. Bridge; and K is a constant depending on the distance between electrodes and depth in the soil.

Temperature of the soil was determined at the depths of the electrodes by placing a thermometer, registering up to 50° C. by tenths, in a hole as deep as the middle of the contact portion of the electrodes.

Temperature correction of soil resistance was made by employing the average temperature coefficient for soils as determined by Whitney, Gardner, and Briggs (7).

A calibration curve for the electrodes placed at specified distances and depths was then obtained by plotting soil resistance between electrodes against soil moisture, thus enabling soil moisture to be obtained from the curve reading corresponding to a soil resistance measured between specified electrodes.

EXPERIMENTAL RESULTS

Table No. 1.—Resistance between 10-inch electrodes in office plat and corresponding moisture content.

Resistance in ohms	Temperature in degrees C.	Moisture in per cent
60.15	20.7	20.92
63.45	20.0	20.52
64.20	20.2	20.33
66.60	20.2	19.16
70.15	20.2	17.79
72.80	21.7	17.97
78.35	22.8	17.49
83.75	23.6	16.68
88.50	24.6	16.56

Table No. 2.—Resistance between 3-inch electrodes in office plat and corresponding moisture content.

Resistance in ohms	Temperature in degrees C.	Moisture in per cent
153.2	20.2	17.79
159.5	21.7	17.97
172.9	22.8	17.49
181.0	23.6	16.68
185.7	24.6	16.56

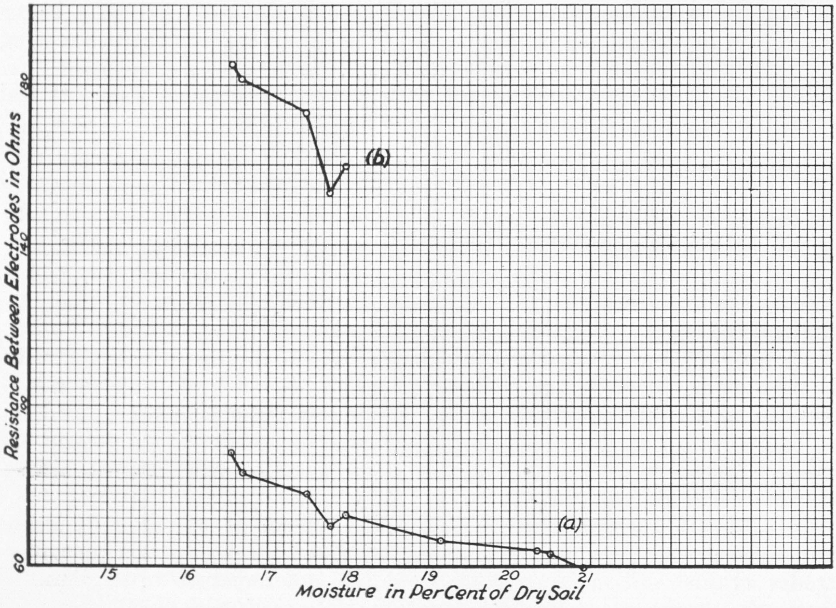

Fig. 3. Influence of electrode length on resistance measured between electrodes, (a) 10-inch electrodes 1 ft. deep, (b) 3-inch electrodes 1 ft. deep.

Table No. 3.—Resistance (corrected to 60° F.) between electrodes and corresponding soil-moisture content for calibration plat.

Electrodes 1 Ft. Deep		Electrodes 1½ Ft. Deep		Electrodes 2½ Ft. Deep	
Resistance in Ohms/Const.	Soil moisture in per cent	Resistance in Ohms/Const.	Soil moisture in per cent	Resistance in Ohms/Const.	Soil moisture in per cent
2.30	21.51	3.17	21.15	....	....
2.59	20.18	2.99	19.81	....	....
2.52	19.40	3.20	19.56	....	....
1.29	28.80	2.00	25.40	....	....
1.67	27.06	2.28	23.10	2.48	....
1.86	26.23	2.24	23.20	2.88	20.0
1.86	24.00	2.24	22.30	2.98	....
1.86	24.30	2.31	23.30	2.57	19.2
1.72	23.60	1.85	21.40	3.41	....
2.80	23.20	1.96	21.80	3.16	17.0
2.38	20.35	2.49	19.50	2.66	....
2.52	20.88	3.05	21.12	3.47	18.15
2.56	20.58	2.78	20.30	3.61	17.97
2.65	19.63	3.02	19.25	3.99	17.56
2.70	19.23	3.02	19.02	3.92	16.45
3.22	17.88	3.44	18.25	4.57	16.80
3.51	17.24	3.99	17.06	5.20	15.48
4.26	16.04	4.12	15.75	5.79	14.45
4.49	16.32	5.05	16.40	6.55	15.02
5.55	14.73	6.20	14.43	8.32	12.21
6.58	15.16	6.67	14.51	9.73	13.15

Table No. 4.—Resistance (corrected to 60° F.) between adjacent electrodes in control plats and corresponding soil-moisture content.

Plat No.	μ'_c in Ohms/Const.	Moisture (in per cent)	Depth (feet)
1	8.73	13.5	1½
	9.74	12.84	1
	8.68	12.45	2½
2	....	13.5	1½
	....	11.48	1
	8.48	10.48	2½
3	13.20	13.76	1½
	13.90	11.58	1
	9.25	11.68	2½
4	....	15.09	1½
	....	16.32	1
	4.70	12.56	2½
5	4.35	16.72	1½
	5.48	17.12	1
	5.57	14.4	2½
6	25.40	10.22	1½
	29.90	8.96	1
	19.90	7.35	2½
7	14.82	12.26	1½
	13.72	11.82	1
	8.55	10.68	2½
8	....	13.9	1½
	....	13.7	1
	7.64	9.06	2½

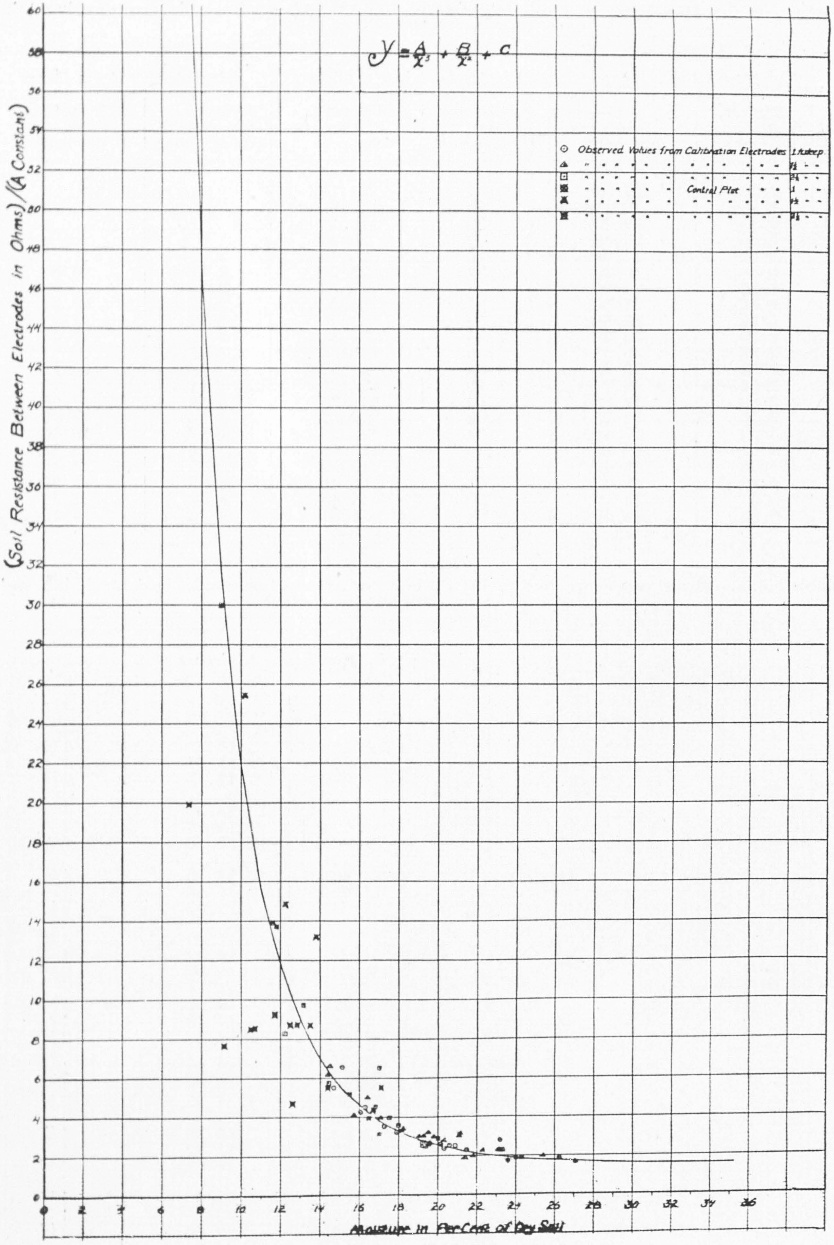

Fig. 4. Calibration Curve for the Apparatus Used to Determine the Moisture Content by Soil Resistance.

Table No. 5—Readings on control plat electrodes (1-foot deep) following rainfall of 1.67 inches.

Resistance in Ohms				Soil Resistance in Ohms/Const.		Date	Plat No.
R_1	R_2	R_5	R_6	μ'_1	μ'_c		
				4:00	P. M.	8/7/30	
313.3	348.3	342.3	364.4	7.72	12.19	8/7/30	1
305.3	227.6	289.4	198.7	7.78	12.28	8/7/30	2
162.5	176.8	183.7	165.0	8.97	14.14	8/7/30	3
82.6	89.0	80.9	80.5	4.07	6.41	8/7/30	4
88.8	97.0	90.5	93.1	3.35	5.28	8/7/30	5
387.4	471.6	539.0	597.5	15.4	21.3	8/7/30	6
227.1	263.7	273.8	296.0	8.62	13.6	8/7/30	7
165.3	181.0	231.6	237.8	5.68	8.95	8/7/30	8
				9:50	A. M.	8/8/30	
304.0	348.2	314.8	347.7	6.76	10.22	8/8/30	1
306.7	226.6	289.2	197.7	6.82	10.45	8/8/30	2
163.3	177.5	163.8	166.1	7.12	10.75	8/8/30	3
84.3	90.5	82.4	82.5	3.65	5.52	8/8/30	4
90.8	98.6	92.2	94.6	3.23	4.88	8/8/30	5
397.5	473.8	546.5	601.0	13.05	17.7	8/8/30	6
228.5	265.0	271.0	295.3	7.3	11.03	8/8/30	7
163.9	183.0	232.7	242.7	5.14	7.77	8/8/30	8

Table No. 6.—Change of moisture as determined from change of soil resistance for electrodes 1-foot deep in control plat and corresponding rainfall (penetrating).

Moisture (in per cent)		Change of moisture (in per cent)	Rainfall (penetrating) (in inches)	Plat No.
4:00 P. M. 8/7/30	9:50 A. M. 8/8/30			
11.9	12.5	.6	1.60	1
11.86	12.42	.56	1.43	2
11.4	12.35	.95	1.31	3
14.4	15.05	.65	1.17	4
15.3	15.7	.4	.96	5
9.7	10.7	1.0	1.42	6
11.5	12.3	.8	1.53	7
13.0	13.6	.6	1.36	8

DISCUSSION OF RESULTS

From Tables 1 and 2, which show, respectively, resistance readings between pairs of electrodes 10 inches long and pairs of electrodes 3 inches long, with their centers 12 inches below the surface of the soil, and the corresponding soil-moisture content, as determined by soil auger, there can be seen a correspondence of decreasing moisture content to increasing resistance between electrodes. This correspondence between resistance and moisture content is shown graphically. Figure 3 (a), which is a graphical representation of Table 1, shows, on comparison with figure 3 (b), which is a graphical representation of Table 2, a much smaller value for the resistance between the 10-inch electrodes for the same moisture content than is found between the 3-inch electrodes. This is to be expected and is in accord with Equation 3. Since irregularities caused by changing contact between soil and electrodes were evident, the relation of resistance between electrode pairs to soil-moisture content was not found for many percentages of moisture content. However, the results obtained encouraged further testing of electrodes arranged to eliminate contact error.

Table 3 shows soil resistance (corrected to 60° F.) between adjacent electrodes of the calibration plat and corresponding soil-moisture content, as determined by the multiple electrode method and soil auger samples, respectively. The values from Table 3 and those from Table 4 (which shows similar determinations made in the same manner on the eight control plat areas) are represented on Fig. 4 along with a graph of Equation 1,

$$Y = A/X^3 + B/X^2 + C$$

The soil-moisture content of the control plats was, in general, very ununiform, even with samples taken a short distance apart. The agreement between the observed values from the control plats and those from Equation 1 above (which satisfies the relation of soil resistance between electrodes to moisture content as determined for calibration electrodes), is close.

Tables 5 and 6, which are readings made on the control plats following a rainfall of 1.67 inches, indicate agreement between changes in moisture content by percolation of rain water and the amount of water penetrating the soil. Table 5 also shows variations in R_1, R_2, R_5 and R_6 between the two successive readings, which are evidently caused by changing contact between electrodes and soil as a result of rainfall, since the value of the soil resistance between electrodes, $\mu'_1 = [(R_5 + R_2) - (R_6 + R_1)]/K$, decreased for all of the control plats consistent with the amount of rainfall penetrating the plats.

MOISTURE DETERMINATION BY SOIL RESISTANCE

To find the soil moisture with the resistance-measuring apparatus used in this investigation, the operator should place the four electrodes in a line, the individual electrodes 2 feet apart. Then measure the resistances R_1, R_2, R_5, and R_6, which are indicated by Fig. 5;

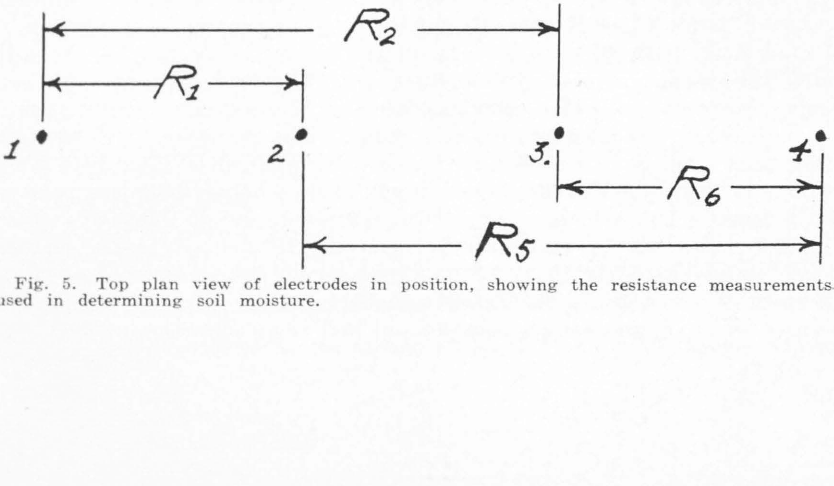

Fig. 5. Top plan view of electrodes in position, showing the resistance measurements used in determining soil moisture.

where R_1 is the resistance between electrodes 1 and 2, R_2 is the resistance between electrodes 1 and 3, R_5 is the resistance between electrodes 2 and 4, and R_6 is the resistance between electrodes 3 and 4.

Determine the temperature of the soil by placing a thermometer in a hole of such depth that the thermometer bulb will be the same distance below the surface as the middle of the contact portion of the electrodes.

From the following equation

$$\mu'_1 = \frac{(R_5 + R_2) - (R_6 + R_1)}{K} \qquad 11$$

is obtained μ'_1, the average resistance of the soil between electrodes 2 feet apart. When the electrodes are 1 ft. deep $K = 1.67$, when the electrodes are $1\frac{1}{2}$ ft. deep $K = 1.45$, and when the electrodes are $2\frac{1}{2}$ ft. deep $K = 1.01$.

The resistance μ'_1 is corrected to the value μ'_c which it would have at 60° F. or 15.5° C. by the use of the equation,

$$\mu'_c = \frac{\mu'_1}{[1 + H\,(t - 15.5)]} \qquad 12$$

where $H = -.0273$, and t is the temperature of the soil in degrees Centigrade. Then by the use of Fig. 4 the soil moisture is read from the curve for the value of μ'_c obtained above.

As an illustration of the use of soil-resistance and temperature measurements in determining soil moisture consider the following example. The values measured for electrodes 1 ft. deep are $R_1 = 60.0$ ohms, $R_2 = 63.0$ ohms, $R_5 = 62.0$ ohms, $R_6 = 59.2$ ohms, and the soil temperature $t = 25.5°$ C.

$$\text{Then } \mu'_1 = \frac{(R_2 + R_5) - (R_1 + R_6)}{K} = \frac{125.0 - 119.2}{1.67}$$

$$\mu'_1 = 3.47.$$

$$\text{But } \mu'_c = \frac{\mu'_1}{[1 + H\,(t - 15.5)]},$$

$$\text{Therefore } \mu'_c = \frac{\mu'_1}{[1 - .0273\,(25.5 - 15.5)]}$$

$$\mu'_c = \frac{3.47}{.727}$$

$$\mu'_c = 4.77.$$

From the curve of Fig. 4. the soil moisture corresponding to the value of $\mu'_c = 4.77$ is found to be 15.8%.

The calibration of the electrodes given by Fig. 4. will probably not be the right one to use with soils that differ much from that of the control plats of the Spur Experiment Station. In such cases a new calibration can be obtained by making three determinations of the temperature-corrected resistance μ'_c for three soil-moisture values which differ by two per cent or more. Each of the moisture values should be obtained from the average of five or more auger samples taken at the same time that the value of μ'_c is determined. From these three determinations of soil resistance between electrodes placed 2 ft. apart, and the soil-moisture content, a new calibration curve can be constructed using the equation,

$$Y = \frac{A}{X^3} + \frac{B}{X^2} + C \qquad 1$$

where Y is the determined soil resistance corrected to 15.5° C. and designated by μ'_c in Equation 12, X is the corresponding soil moisture as determined from the auger samples, and A, B, and C are constants

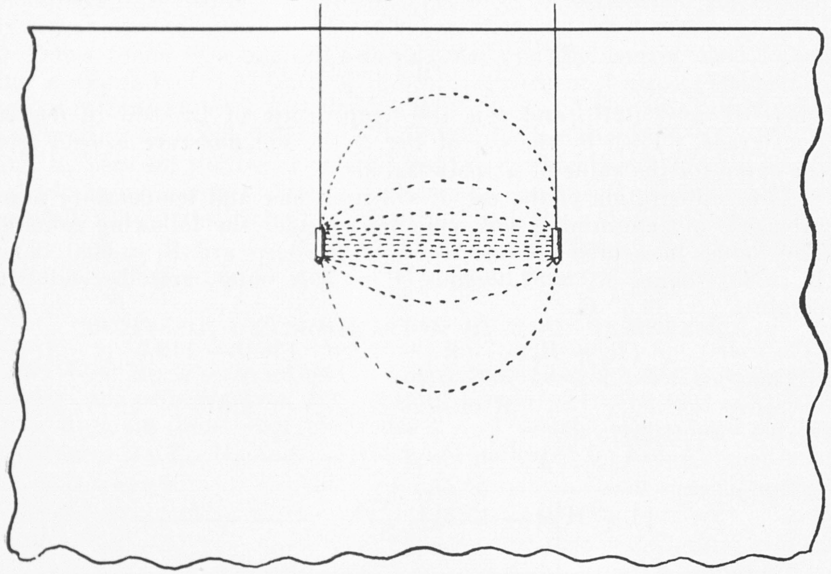

Fig. 6. Representation of electrodes in uniform soil, showing region where most of the current is conducted between electrodes.

which can be found by methods of algebra when the three values of resistance and soil moisture are placed in the equation.

If the calibration provided by the curve of Fig. 4. gives soil-moisture values that do not differ much from those obtained by auger samples, a complete recalibration should not be necessary. In this case the only change necessary would be in the value of the constant K from the equation

$$\mu'_1 = \frac{(R_5 + R_2) - (R_6 + R_1)}{K} \qquad 11$$

The new value of K may be found by multiplying the present value of K by the ratio of the observed value of μ'_c to the value of μ'_c which corresponds to the moisture-content on the curve of Fig. 4. as determined by the average of a number of auger samples.

When resistance measurements are used to determine the soil moisture, the results obtained are modified if there is a very wet or very dry layer of soil close above or close below the contact portion of the electrodes. As shown in Fig. 6, above, most of the conduction of the current occurs as represented by the dotted lines between the electrodes when the soil is uniform in moisture content. If there is a wetter layer of soil close above or below the layer which is to be investigated more of the current will pass through the wet layer than is normally the case, and a lowered resistance value will be obtained. The amount of this effect and its influence on the accuracy of the results obtained has not yet been determined.

SUMMARY AND CONCLUSIONS

The multiple electrode method of eliminating contact errors from the measurement of soil resistivity removes also the necessity of considering the resistance of lead wires and increases the accuracy of the resistance measurements.

Use of the equation relating soil moisture and resistivity enables easy calibration of the apparatus for different locations.

The change of salt content of soils throughout a period of time has not been determined and it is not known if the change would require frequent calibration of the apparatus. Data from the apparatus used on the control plats show that the change of salt content of the soil at the Spur Substation is not rapid enough to require more than one or two calibrations during a year. This would probably not be the case with irrigated or fertilized soils.

The small amount of data obtained after completing the installation of the apparatus does not permit definite conclusions to be reached, but indicates that the method can be used successfully to measure relative moisture contents and with further development may be used to measure the percentage of moisture in soils at various locations.

BIBLIOGRAPHY

(1) Anderson, M. S., and Matson, S. E. 1926. Properties of the colloidal soil material. U. S. Dept. Agric., Bureau of Soils, Bul. 1452, 18-20.

(2) Conner, A. B., Dickson, R. E., and Scoats, D. 1930. Factors Influencing Runoff and Soil Erosion, Texas Agricultural Experiment Station, Bul. 411, 24-25, 33, 34, Illus.

(3) Jeans, J. H. 1925. The mathematical theory of electricity and magnetism. Ed. 5, 350-352. London.

(4) Kraus, C. A. 1922. The properties of electrically conducting systems, 19-45, 67-175. Illus. New York.

(5) McCollum, B., and Logan, K. H. 1915. Earth resistance and its relation to electrolysis of underground structures. Technologic Papers of the U. S. Bureau of Standards, No. 26, 7-8.

(6) Wenner, F. 1915. A method of measuring earth resistivity. Scientific Papers of the U. S. Bureau of Standards, No. 258. Illus.

(7) Whitney, M., Briggs, L. J., and Gardner, F. D. 1897. An electrical method of determining the moisture content of arable soils. U. S. Dept. of Agriculture, Division of Soils, Bul. 6, 5-26. Illus.

(8) ————, Briggs, L. J., and Gardner, F. D. 1897. An electrical method of determining the temperature of soils. U. S. Dept. of Agriculture, Division of Soils, Bul. 7, 9-10.

(9) Whittaker, E. T., and Robinson, G. 1923. The calculus of observations. Ed. 2, 22-25. London.

ACKNOWLEDGMENT

The author wishes to make acknowledgment to Mr. A. B. Conner, Director, Texas Agricultural Experiment Station, and Mr. R. E. Dickson, Superintendent, Substation No. 7, Spur, Texas, who were primarily responsible for initiating this study and securing the funds necessary for the investigation; to Mr. D. Robinett of the Spur Substation for assistance in obtaining soil samples and resistance measurements; and to Dr. O. W. Silvey, Professor of Physics, Agricultural and Mechanical College of Texas, for suggestions and comments in connection with the preparation of this manuscript.