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Measurement of Inverted Electrical Conductivity Profiles Using Electromagnetic Induction[1]

D. L. CORWIN AND J. D. RHOADES[2]

ABSTRACT

Due to sharp discrepancies in the relative response of the horizontal and vertical coil configurations of the Geonics Limited EM-38 electromagnetic induction soil conductivity meter for the top 15 cm of soil, the accuracy of measurement of bulk electrical conductivity for soil having a high surface electrical conductivity relative to deeper depths (i.e., an inverted electrical conductivity profile) has been unreliable. Two new approaches have been developed to compensate for these discrepancies, either through compensations in the vertical coil configuration response curve or the reestablishment of EM$_{0,H}$ adjustment curves utilizing data solely from inverted conductivity profiles. Both approaches yield more consistently reliable calculated bulk soil electrical conductivities when compared to measured electrical conductivities using the four-electrode probe. The latter approach, however, appears to be more accurate.

Additional Index Words: **soil salinity, soil resistivity, electro-magnetic conductivity.**

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THE POTENTIAL for the use of electromagnetic induction (EM) techniques as a means of performing reconnaissance surveys of soil salinity is self-evident. Williams and Baker (1982) measured apparent soil electrical conductivities (σ_a) to depths ranging from 7.5 to 60 m for an area of 10 000 km^2 using EM techniques. From these measurements areas of apparent high salinity were inferred. Others have demonstrated that soil bodies of widely differing salinity can be delineated by EM techniques (DeJong et al., 1979).

Since plant root activity occurs primarily within the top 0.9 m of soil, the electrical conductivity of this portion is extremely important in assessing soil salinity from the standpoint of agricultural productivity. Therefore, once areas of potential soil salinity hazard are delineated, it is necessary to be able to survey these areas more intensively within relatively shallow soil depths (i.e., 0–0.9 m). In situ methods of measuring soil electrical conductivity within such depths are available (Rhoades, 1978; Rhoades, 1979), but remote measurements would offer advantages of reduced labor, time, and cost. We have previously shown that bulk soil electrical conductivities by depth increments through the soil profile can be determined with reasonable confidence from remote EM measurments using the Geonics Limited[3] EM-38 instrument (Rhoades and Corwin, 1981; Corwin and Rhoades, 1982). Initially this required the solution to a complex system of simultaneous equations obtained for each general site from multiple regression analysis relating electromagnetic conductivity measurements to σ_a (Rhoades and Corwin, 1981). Subsequently, we developed a simplified and more general method (Corwin and Rhoades, 1982) in which incremental depth response curves for the Geonic EM-38 instrument and "adjustments" to the readings to compensate for inequalities in profile volumes of measurement between vertical and horizontal coil configurations were used to calculate the distribution of σ_a through the soil.

The use of this new method on a wider variety of electrical conductivity profiles revealed, however, that the predicted bulk soil conductivities for inverted conductivity profiles (i.e., profiles where the electrical conductivity decreases rapidly with increased depth) consistently deviated from the corresponding "ground truth" conductivities as measured with the four-electrode probe (Rhoades and van Schilfgaarde, 1976). This fact pointed out an obvious insufficiency in the newly developed method. It is the purpose of this paper to present an alternative approach for the measurement of inverted conductivity profiles using electromagnetic induction.

METHODS AND MATERIALS

Theory

When an electromagnetic induction conductivity reading is taken with the EM-38 meter placed on the surface of a medium, the resultant value of σ_a reflects the cumulative relative contributions of the conductivities above a selected depth in the profile (see Fig. 1). As an example, with the verticle dipole orientation, 0.022 of the EM 38 conductivity reading is contributed by the top 0.1 m of soil and 0.978 is contributed by the soil below 0.1 m. Furthermore, relative contributions of conductivity are dependent on the orientation of the receiver/transmitter coils with respect to the soil surface (see Fig. 1 and Corwin and Rhoades, 1982 for more detail). An analysis of the ratio of response of the vertical and horizontal coil configurations for various composite depths as determined from Fig. 1 (i.e., for 0–0.15 m $R_H(Z)/R_v(Z) = (1.0–0.818)/(1.0–0.978) = 8.3$, for 0–0.3 m $R_H(Z)/R_V(Z) = (1.0–0.670)/(1.0–0.925) = 4.4$, etc.) is given in Fig. 2. The figure reveals a potential reason for the discrepancy between the bulk soil electrical conductivities predicted from EM readings and the "ground truth" measured σ_a's of inverted conductivity profiles. As seen, the greatest relative response discrepancy between measurements taken with the coils oriented vertically and those oriented horizontally to the soil surface is for the top 0.3 m. As a result, the influence of a substantial portion (i.e., approximately 0.15 m) of the top 0.3 m of soil upon the vertical measurement is quite negligible compared to its influence on the horizontal measurement. Consequently, if there is a sizeable change in conductivity within the top 0 to 0.3 m of soil, especially between the 0 to 0.15 m and 0.15 m to 0.30 m increments, such as may occur in an inverted soil salinity profile, then the predicted conductivities from the EM reading using the simplified, general method of Corwin and Rhoades (1982) will be in error since the vertical coil configuration scarcely detects the top 0.15 m of soil. In order to deal adequately with such inverted profiles, therefore, some other method must be developed which compensates for this inherent weakness of the electromagnetic inductive measurement of inverted conductivity profiles. The equations derived by Corwin and Rhoades (1982) must be either modified to reflect the lack

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[1] Contribution from the U.S. Salinity Laboratory, USDA-ARS, 4500 Glenwood Drive, Riverside, CA 92501. Received 21 Mar. 1983. Approved 14 Nov. 1983.

[2] Soil Scientist and Supervisory Soil Scientist, respectively.

[3] The citation of particular products or companies is for the convenience of the reader and does not imply any particular endorsement, guarantee, or preferential treatment by the USDA or its agents.

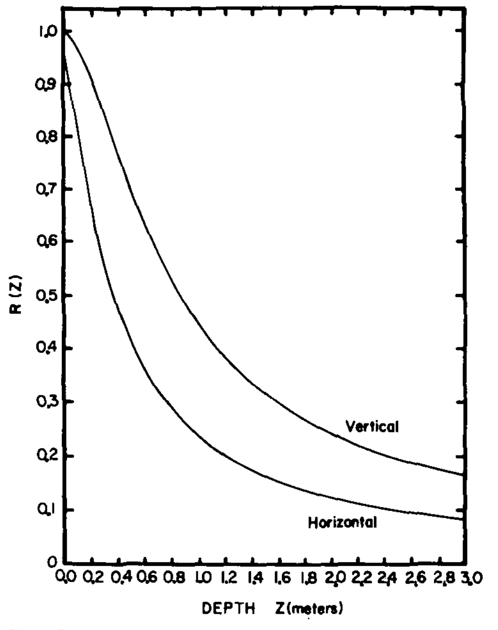

Fig. 1— Cumulative contribution of all soil electrical conductivity *R(Z)* below various depths to the EM-38 reading when the device is held in a horizontal (parallel) and vertical (perpendicular) dipole position.

of response of the vertical EM measurement to the top 0.3 m and/or new adjustment curves based solely on inverted profile data must be developed to shift the emphasis on adjustment to the surface.

We evaluated two approaches for using the EM-38 instrument for measuring σ_a-depth relations of inverted profiles. The first approach (referred to subsequently as Modified-Approach no. 1) compensates for the discrepancy in relative response between horizontal and vertical measurements over the 0- to 0.3-m depth by the establishment of $EM_{0,H}$ adjustment curves as described in Corwin and Rhoades (1982) but, in this case, using data only from inverted conductivity profiles and the analogous equations presented there. The second approach (referred to as Modified-Approach no. 2) eliminates the influence of the top 0 to 0.3-m depth increment from the vertical measurement by the removal of the weighted response of that layer and its addition to the adjacent 0.3- to 0.6-layer in the equations used by Corwin and Rhoades (1982) to relate the surface vertical electromagnetic measurement, $EM_{0,V}$ to bulk electrical conductivity, σ_a. This resulted in the set of composite and successive increment bulk electrical conductivity equations shown in Table 1, which are analogous to and obtained following the procedure previously outlined by Corwin and Rhoades (1982) for more typical (i.e., non-inverted) soil salinity profiles.

Experimental Procedure

Eleven sites with inverted bulk soil electrical conductivity profiles were sampled from locations scattered throughout California. The sites were selected in order to provide a variety of soil types. Since the horizontal EM conductivity reading for an inverted conductivity profile is characteristically greater than the vertical reading, the identification and location of an inverted conductivity profile is simplified. Measurements were made with a Geonics Limited EM-38 meter at the soil surface of each site, with the coils in both the vertical and horizontal configurations. Corresponding "ground truth" electrical conductivity readings were taken at 15-cm increments through the soil profile to a depth of 0.90 m with a four-electrode probe (Rhoades and van Schilfgaarde, 1976) at the exact same location. Since the measurement of the top 0.3 m was extremely critical for this particular study, from 6 to 10 four-electrode probe σ_a measurements were taken and averaged to obtain an accurate value for this depth increment. Up to three four-electrode probe readings were taken at each remaining depth increment and an average was then determined from the accumulated data for each 0.3-m composite increment down to 0.9 m: 0 to 0.3 m, 0 to 0.6 m, and 0 to 0.9 m.

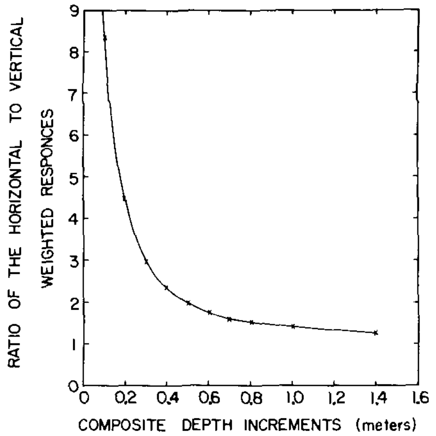

Fig. 2—Ratio of vertical and horizontal weighted responses at various composite depth increments (i.e., 0–0.15, 0–0.3, 0–0.45, 0–0.6 m, etc.).

Linear regression techniques were used as a means of evaluating the correspondence of the predicted and measured bulk soil electrical conductivities.

RESULTS AND DISCUSSION

Table 2 summarizes the measured and calculated bulk soil electrical conductivities for the 11 selected inverted conductivity profiles. From a cursory analysis, all three methods appear to provide adequate results when compared to the measured "ground truth"

Table 1—Modified-Approach no. 2 equations used to calculate electrical conductivities for soil increments from electromagnetic conductivity measurements.

Depth, m	Equations for electrical conductivity
	Composite Depths
0–0.3	$\sigma_{0-0.3} = 2.299\ EM_{0,H(\text{adjusted, 0-0.3m})} - 1.299\ EM_{0,V}$
0–0.6	$\sigma_{0-0.6} = 1.717\ EM_{0,H(\text{adjusted, 0-0.6m})} - 0.717\ EM_{0,V}$
0–0.9	$\sigma_{0-0.9} = 1.671\ EM_{0,H(\text{adjusted, 0-0.9m})} - 0.671\ EM_{0,v}$
0–1.2	$\sigma_{0-1.2} = 1.684\ EM_{0,H(\text{adjusted, 0-1.2m})} - 0.684\ EM_{0,V}$
	Successive Depths
0–0.3	$\sigma_{0-0.3} = 2.299\ EM_{0,H(\text{adjusted, 0-0.3m})} - 1.299\ EM_{o,V}$
0.3–0.6	$\sigma_{0.3-0.6} = 3.434\ EM_{0,H(\text{adjusted, 0-0.6m})} - 2.229\ EM_{0,H(\text{adjusted, 0-0.3 m})} - 0.135\ EM_{o,V}$
0.6–0.9	$\sigma_{0.6-0.9} = 5.013\ EM_{0,H(\text{adjusted, 0-0.9m})} - 3.434\ EM_{0,H(\text{adjusted, 0-0.6m})} - 0.579\ EM_{0,V}$
0.9–1.2	$\sigma_{0.9-1.2} = 6.736\ EM_{0,H(\text{adjusted, 0-1.2m})} - 5.013\ EM_{0,H(\text{adjusted, 0-0.9m})} - 0.723\ EM_{0,V}$

conductivities of the four-electrode probe, at least for the top 0 to 0.3 m and for conductivities of low magnitude. The unmodified approach, however, shows sharp discrepancies between measured and calculated σ_a's with increased composite increment depth in the soil. This deviation becomes even more pronounced as the magnitude of the conductivities increases as for sites 10 and 11. A comparison of the significant linear regression statistics (see Table 3) for the three methods confirms that the unmodified approach is not as consistently accurate as the two modified approaches in the calculation of σ_a from EM readings; consequently, the need for an alternative means of handling inverted conductivity profiles aside from that proposed by Corwin and Rhoades (1982) is substantiated.

Table 3 shows that both modified approaches provided an excellent one-to-one correspondence between measured and calculated σ_a's. Approach no. 1, however, yields a slightly better correspondence with less scatter.

A look at Table 4 provides some insight as to the reason for the insufficiency of the unmodified approach. Since the adjustment curves correct the $EM_{0,H}$ readings for inequalities in volume of measurement between vertical and horizontal coil configurations (Corwin and Rhoades, 1982), the adjustments for inverted profiles would be expected to be the opposite of those for electrical conductivity profiles which are found to increase with depth. The difference in the two electrical conductivity profiles manifests itself in different slopes of the adjustment curves; consequently, the slope should decrease sharply with depth up to some point. The modified approaches show this to be the case in Table 4.

Table 2—Measured and calculated bulk soil electrical conductivities for composite 0.3 m depth increments.

	EM readings				Calculated σ_a		
Site	$EM_{0,H}$	$EM_{0,V}$	Depth	Measured σ_a	Unmodified (Corwin & Rhoades, 1982)	Modified-approach no. 1	Modified-approach no. 2
			cm	dS/m			
1	2.25	1.40	0–0.3	3.45	4.06	3.92	3.86
			0–0.6	2.55	3.67	2.97	2.86
			0–0.9	2.21	4.60	2.78	2.72
2	1.25	1.10	0–0.3	1.70	1.82	1.70	1.73
			0–0.6	1.41	1.62	1.47	1.52
			0–0.9	1.35	1.88	1.33	1.37
3	1.20	0.72	0–0.3	2.32	2.43	2.31	2.10
			0–0.6	1.54	1.99	1.86	1.72
			0–0.9	1.31	2.16	1.66	1.54
4	1.45	1.10	0–0.3	2.47	2.38	2.26	2.24
			0–0.6	2.42	2.11	1.84	1.83
			0–0.9	2.36	2.49	1.69	1.68
5	0.63	0.62	0–0.3	1.08	0.96	0.85	0.76
			0–0.6	0.77	0.70	0.88	0.88
			0–0.9	0.71	0.48	0.72	0.71
6	1.02	0.94	0–0.3	1.93	1.48	1.37	1.36
			0–0.6	1.47	1.27	1.24	1.28
			0–0.9	1.33	1.36	1.09	1.12
7	1.55	1.47	0–0.3	2.24	1.93	1.82	2.01
			0–0.6	2.19	1.88	1.56	1.72
			0–0.9	1.83	2.38	1.45	1.59
8	1.98	1.38	0–0.3	2.33	3.33	3.20	3.21
			0–0.6	2.07	3.04	2.48	2.46
			0–0.9	2.02	3.80	2.32	2.32
9	0.92	0.77	0–0.3	1.36	1.53	1.42	1.33
			0–0.6	1.19	1.25	1.27	1.24
			0–0.9	1.18	1.24	1.11	1.08
10	7.33	6.27	0–0.3	9.21	8.80	8.63	10.36
			0–0.6	5.55	9.77	6.30	7.28
			0–0.9	5.54	14.64	6.44	7.38
11	9.35	8.30	0–0.3	10.02	10.50	10.32	8.86
			0–0.6	8.10	12.08	7.50	6.57
			0–0.9	8.53	18.52	7.78	6.86

SUMMARY AND DISCUSSION

Using previous calculation methods, the measurement of inverted electrical conductivity profiles using electromagnetic induction techniques produced unreliable results. Two approaches were suggested to improve the accuracy of calculating σ_a's by depth intervals in inverted soil salinity profiles from soil surface electromagnetic induction conductivity measurements made with the coils positioned in the vertical and horizontal configurations, $EM_{0,V}$ and $EM_{0,H}$, respectively. Approach no. 1, which uses the same equations relating EM conductivity and σ_a as derived by Corwin and Rhoades (1982) but reestablishes the $EM_{0,H}$ adjustment curves using only inverted conductivity profile data, appears to be the more accurate method.

Since it is possible to determine whether or not an inverted conductivity profile has been encountered by the fact that the $EM_{0,H}$ reading is greater than the $EM_{0,V}$ reading, it is an easy matter to program a hand-held programmable calculator of sufficient memory capacity to convert horizontal and vertical EM readings to an electrical conductivity profile. The increased capability of handling inverted conductivity profiles with greater accuracy and reliability further enhances the

Table 3—Linear regression analysis statistics for various methods used to calculate bulk electrical conductivities of inverted conductivity profiles from EM induction conductivity measurements.

Method	Slope	Y-intercept	R^2	Std. error of est.
Unmodified-Corwin & Rhoades (1982)	1.51	−0.37	0.78	2.65
Modified-approach no. 1	0.98	0.06	0.97	0.46
Modified-approach no. 2	0.96	0.12	0.92	0.73

Table 4—$EM_{0,H(adjusted)}$ equations for various methods used in the calculation of bulk electrical conductivities from EM induction conductivity measurements.

Method	Depth, m	$EM_{0,H(adjusted)}$ Equations	R^2
Unmodified-Corwin & Rhoades (1982)	0–0.3	$EM_{0,H(adjusted)} = 0.950\ EM_{0,H} + 0.152$	0.995
	0–0.6	$EM_{0,H(adjusted)} = 1.065\ EM_{0,H} - 0.002$	0.977
	0–0.9	$EM_{0,H(adjusted)} = 1.436\ EM_{0,H} - 0.330$	0.961
Modified-approach no. 1	0–0.3	$EM_{0,H(adjusted)} = 0.948\ EM_{0,H} + 0.118$	0.997
	0–0.6	$EM_{0,H(adjusted)} = 0.826\ EM_{0,H} + 0.229$	0.992
	0–0.9	$EM_{0,H(adjusted)} = 0.846\ EM_{0,H} + 0.150$	0.991
Modified-approach no. 2	0–0.3	$EM_{0,H(adjusted)} = 1.100\ EM_{0,H} + 0.003$	0.990
	0–0.6	$EM_{0,H(adjusted)} = 0.907\ EM_{0,H} + 0.211$	0.964
	0–0.9	$EM_{0,H(adjusted)} = 0.934\ EM_{0,H} + 0.096$	0.959

usefulness of the EM-38 instrument as a tool for surveying large areas for soil electrical conductivity and salinity.

At the present time, all of our work using the EM-38 for measuring bulk soil electrical conductivity has been done on soils of relatively low magnetic susceptibility. In order to demonstrate its general reliability in the measurement of bulk soil electrical conductivity, it is necessary to examine the effects that magnetic materials in soils have upon the measurement. This is an area of research presently receiving attention.

In summary, it is now possible to describe bulk soil electrical conductivity–depth relations for both increasing and inverted conductivity profiles. The approach developed in this paper and by Corwin and Rhoades (1982) does not presume to be able to describe all σ_a-depth relations, but rather calculates σ_a with depth on an integrated basis so that they fall into either an increasing or an inverted conductivity profile type. The accuracy at each depth depends to a degree on how closely the actual conductivity profile conforms to the general shape of an increasing or inverted electrical conductivity profile. For example, σ_a-depth relations that fluctuate abruptly are not as closely predicted as profiles that show a steady increase or decrease in electrical conductivity. This places strict limitations on the accuracy and application of this measurement technique, since any rapid fluctuations of conductivity with depth are smoothed out.

The electromagnetic induction technique of bulk soil electrical conductivity has its greatest utility as a survey tool. Once areas of high salinity are delineated, alternate methods of salinity measurement can be utilized to provide more detailed descriptions of σ_a-depth relations (Rhoades and Corwin, 1983).

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