An Improved Technique for Determining Soil Electrical Conductivity–Depth Relations from Above-ground Electromagnetic Measurements

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ABSTRACT

An improved method has been developed for determining the depth distribution of bulk soil electrical conductivity, $EC_a$, through the soil from electromagnetic measurements taken at the soil surface with the Geonics Limited EM-38 device. Induced electromagnetic conductivity readings taken with the EM-38 device's coil configuration oriented parallel and then perpendicular to the soil surface provided sufficient information, when used with equations derived from geophysical instrumentation data, to produce a soil electrical conductivity–depth profile. The simplicity of this method further enhances the practicability of the newly developed electromagnetic technique for field measurements of salinity and for saline seep diagnosis.

Additional Index Words: soil salinity, soil resistivity, electromagnetic conductivity.


Recently, Rhoades and Corwin (1981) have shown that bulk soil electrical conductivity, $EC_a$, of incremental depth intervals within the soil profile can be obtained from above-ground electromagnetic measurements of apparent soil electrical conductivity, EM, using multiple regression coefficients which relate electromagnetic conductivity to $EC_a$. This initial method required the solution of a complex system of simultaneous equations. The coefficients of these equations were determined by multiple regression analyses of EM readings taken at five incremental heights (0, 0.3, 0.6, 0.9, and 1.2 m) above the soil and of $EC_a$ values measured (using a four-electrode probe) at corresponding depths (0 to 0.3, 0.3 to 0.6, 0.6 to 0.9, and 0.9 to 1.2 m) in the soil. It is the purpose of this paper to describe a less complicated method for obtaining $EC_a$–depth relations of any soil from only two EM measurements taken at the soil surface. In this approach the EM readings are related to $EC_a$ by a series of simple equations derived from instrumentation data provided by the manufacturer of the EM device (EM-38).3

THEORY

The design of the EM-38 soil electromagnetic conductivity meter is such that when a conductivity reading is taken at the surface of a homogeneous medium the result reflects a cumulative relative contribution of soil conductivities from the various strata above some depth (Fig. 1). Furthermore, the relative contribution of conductivity from the various depths depends upon the orientation of the transmitter coil (Fig. 2) with respect to the soil surface. Assuming that the EM-38 response curve holds for measurements taken over nonhomogeneous media, it is possible to derive a series of equations which relate $EC_a$ within a soil depth interval to the horizontal and vertical electromagnetic conductivity measurements, i.e., apparent conductivity.

For the 0- to 0.3-m increment of soil, the equations derived from Fig. 1 are:

\[
EM_{0V} = 0.15 \text{EC}_{0.03V} + 0.85 \text{EC}_{0.3V}, \text{ and } [1] \\
EM_{0H} = 0.435 \text{EC}_{0.03H} + 0.565 \text{EC}_{0.3H}, \text{ [2]}
\]

where $EM_{0V}$ and $EM_{0H}$ are the electromagnetic apparent conductivities measured at the soil surface in the vertical and horizontal positions, respectively; and $EC_{0.03V}$, $EC_{0.3V}$, $EC_{0.03H}$, and $EC_{0.3H}$ are the actual bulk soil electrical conductivities for the 0- to 0.3-m and >0.3-m soil depth intervals, respectively.

Discussions with the manufacturer of the EM-38 revealed that the volume of soil measured within the 0- to 0.3-m increment is very similar for the vertical and horizontal orientations; therefore, it is reasonable to assume that $EC_{0.03V} = EC_{0.03H}$. However, in the case of the >0.3-m increment, the volumes of measurement are quite different (as reflected in Fig. 1); consequently, it is unlikely that $EC_{0.3V}$ will equal $EC_{0.3H}$. This fact presents a problem because, in order to arrive at a relationship between $EC_{0.03}$ and $EM_{0V}$ and $EM_{0H}$ using Eq. [1] and Eq. [2], it is necessary to equate $EC_{0.3V}$ and $EC_{0.3H}$. This problem was overcome when it was found that $EM_{0H}$ could be adjusted so that $EC_{0.3V}$ calculated from Eq. [1] would equal $EC_{0.3H}$ for a large number of sites where $EC_{0.3V}$ and $EM_{0V}$ were measured. Adjustment of $EM_{0H}$ was made as follows:
Fig. 1—Cumulative relative 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) position.

Values of EC\(_{>0.3,\text{V}}\) were calculated with Eq. [1] using EC\(_{>0.3}\) as measured with the four-electrode probe, and of EM\(_{0,\text{V}}\) as measured with the EM-38 device. It was assumed that EC\(_{>0.3,\text{V}}\) is a better estimate of actual EC\(_{>0.3}\) than EC\(_{>0.3,\text{H}}\) because it contributes 85% of the EM\(_{0,\text{V}}\) reading, whereas EC\(_{>0.3,\text{H}}\) only contributes 56.5% of the EM\(_{0,\text{H}}\) reading. The adjusted EM\(_{0,\text{H}}\) for the 0- to 0.3-m depth increment was then calculated from Eq. [2] using the measured values of EC\(_{>0.3}\) and the calculated values of EC\(_{>0.3,\text{V}}\). A plot of measured and adjusted EM\(_{0,\text{H}}\) values for each depth increment of all 16 sample sites revealed a set of linear relations (Fig. 3). Therefore, it appears that these relations can be used, irrespective of the site of measurement, to adjust measured values of EM\(_{0,\text{H}}\) for a specified depth increment (0-h meters) so that EC\(_{>0.3,\text{H}}\) as demonstrated in Eq. [3] and Eq. [4] for the 0- to 0.3-m increment:

\[
EM_{0,\text{V}} = 0.15 \times EC_{>0.3} + 0.85 \times EC_{>0.3,\text{V}}, \quad [3]
\]

\[
EM_{0,\text{H(adjusted,0-0.3m)}} = 0.435 \times EC_{>0.3} + 0.565 \times EC_{>0.3,\text{V}}, \quad [4]
\]

Equations [3] and [4] can now be reduced by substitution to a single equation:

Thus, the bulk soil electrical conductivity of the 0- to 0.3-m depth of any site can be determined from two electromagnetic measurements made above ground.

Following the same rationale, two sets of equations can be obtained (Table 1) which provide different types of conductivity-depth profile information. One set of equations permits the determination of average EC\(_a\) for composited 0.3-m increments (i.e., 0 to 0.3, 0 to 0.6, 0 to 0.9, and 0 to 1.2 m), while the second set permits the calculation of EC\(_a\) for successive 0.3-m increments (i.e., 0 to 0.3, 0.3 to 0.6, 0.6 to 0.9, and 0.9 to 1.2 m). Since it is easy to derive electrical conductivities for successive increments from calculated composite increment apparent electrical conductivities (e.g., EC\(_{0.3-0.6} = 2 \times EC_{>0.6} - EC_{>0.3}\)), an alternate means of determining soil electrical conductivity-depth relations for successive incremental depths is provided.

### Table 1—Equations used to calculate electrical conductivity for soil increments from electromagnetic conductivity measurements.

<table>
<thead>
<tr>
<th>Depth, m</th>
<th>Equations for electrical conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-0.3</td>
<td>( EC_{0-0.3} = 2.982 \times EM_{0,\text{H(adjusted,0-0.3m)}} - 1.982 \times EM_{0,\text{V}} )</td>
</tr>
<tr>
<td>0-0.6</td>
<td>( EC_{0-0.6} = 2.286 \times EM_{0,\text{H(adjusted,0-0.6m)}} - 1.286 \times EM_{0,\text{V}} )</td>
</tr>
<tr>
<td>0-0.9</td>
<td>( EC_{0-0.9} = 2.133 \times EM_{0,\text{H(adjusted,0-0.9m)}} - 1.133 \times EM_{0,\text{V}} )</td>
</tr>
<tr>
<td>0-1.2</td>
<td>( EC_{0-1.2} = 2.054 \times EM_{0,\text{H(adjusted,0-1.2m)}} - 0.946 \times EM_{0,\text{V}} )</td>
</tr>
</tbody>
</table>

**Composite depths**

**Successive depths**

\( EC_{0-0.3} = 2.982 \times EM_{0,\text{H(adjusted,0-0.3m)}} - 1.982 \times EM_{0,\text{V}} \)

\( 0.3-0.6 \quad EC_{0.3-0.6} = 4.571 \times EM_{0,\text{H(adjusted,0-0.6m)}} - 2.983 \times EM_{0,\text{H(adjusted,0-0.3m)}} - 0.5889 \times EM_{0,\text{V}} \)

\( 0.6-0.9 \quad EC_{0.6-0.9} = 6.400 \times EM_{0,\text{H(adjusted,0-0.9m)}} - 4.571 \times EM_{0,\text{H(adjusted,0-0.6m)}} - 0.829 \times EM_{0,\text{V}} \)

\( 0.9-1.2 \quad EC_{0.9-1.2} = 8.216 \times EM_{0,\text{H(adjusted,0-1.2m)}} - 6.400 \times EM_{0,\text{H(adjusted,0-0.9m)}} - 0.384 \times EM_{0,\text{V}} \)

\( EC_{>0.3} = 2.982 \times EM_{0,\text{H(adjusted,0-0.3m)}} - 1.982 \times EM_{0,\text{V}} \)

Fig. 2—Geonics EM-38 prototype electromagnetic soil conductivity meter (top) lying in the horizontal position with its coils parallel to the soil surface, and (bottom) lying in the vertical position with its coils perpendicular to the soil surface.
EXPERIMENTAL PROCEDURE

A total of 16 sites were sampled in three different areas of southern California: Lakeview, San Joaquin Valley (Lost Hills, Calif.), and Imperial Valley (Imperial, Calif.). The sites were selected in order to provide a wide range of electrical conductivity-depth relations on different soil types. Electromagnetic conductivity measurements were taken with the EM-38 device positioned in horizontal and vertical positions at the soil surface (Fig. 2). As a precaution, any metal objects that might come within the field of influence of the electromagnetic device were removed. Direct measurements of EC were then taken at 0.3-m increments through the soil profile using a four-electrode salinity probe (Rhoades and van Schilfgaarde, 1976).

To evaluate the validity of the equations in Table 1, linear regressions were performed on the electrical conductivity values derived from electromagnetic conductivity measurements compared with values for corresponding electrical conductivities measured with the four-electrode probe.

RESULTS AND DISCUSSION

Table 2 provides a summary of statistical parameters performed on calculated electrical conductivities obtained from electromagnetic conductivity measurements and their corresponding "ground truth" values as measured with the four-electrode probe. These statistical parameters provide an indication of the agreement between calculated electrical conductivities and ground truth conductivities. Two different calculation methods were compared: the previously used multiple regression coefficient method (Rhoades and Corwin, 1981) and the newly developed established coefficient method described herein.

A comparison of the two different approaches (Lakeview site only) used in the calculation of conductivity for successive 0.3-m increments reveals that the multiple regression approach has a slightly better one-to-one correspondence since the dispersion of values about the line of regression, as reflected by the standard error of estimate, is less (1.101 vs. 1.773 and 1.858). Nevertheless, the electrical conductivities for successive 0.3-m increments and for successive 0.3-m increments obtained from composite increments as determined from the established coefficient approach are clearly within acceptable limits for survey and diagnostic purposes. Though less accurate, the established coefficient approach only requires two electro-

Table 2—Comparison of linear regression analysis of predicted and measured soil electrical conductivities at three test areas.

<table>
<thead>
<tr>
<th>Method</th>
<th>Site†</th>
<th>No. of entries</th>
<th>Slope</th>
<th>Intercept</th>
<th>$R^2$</th>
<th>Standard error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple regression approach</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3-m increments</td>
<td>LV</td>
<td>32</td>
<td>0.990</td>
<td>0.051</td>
<td>0.975</td>
<td>1.101</td>
</tr>
<tr>
<td></td>
<td>IV, SJV</td>
<td>64</td>
<td>0.940</td>
<td>0.113</td>
<td>0.947</td>
<td>0.626</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.971</td>
<td>0.077</td>
<td>0.971</td>
<td>0.604</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.977</td>
<td>0.015</td>
<td>0.965</td>
<td>0.061</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.880</td>
<td>0.353</td>
<td>0.871</td>
<td>0.299</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>0.857</td>
<td>0.205</td>
<td>0.840</td>
<td>0.019</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.000</td>
<td>0.000</td>
<td>1.000</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.868</td>
<td>1.451</td>
<td>0.572</td>
<td>1.044</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.937</td>
<td>0.246</td>
<td>0.937</td>
<td>1.341</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.935</td>
<td>0.356</td>
<td>0.935</td>
<td>1.773</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.803</td>
<td>0.172</td>
<td>0.779</td>
<td>0.313</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.183</td>
<td>0.681</td>
<td>0.681</td>
<td>0.898</td>
</tr>
</tbody>
</table>

†LV = Lakeview, Calif.; IV = Imperial Valley (Imperial, Calif.); SJV = San Joaquin Valley (Lost Hills, Calif.).
multiple regression coefficient approach. From these magnetic measurements as opposed to five for the
induced evidence between measured and calculated EC.
combination of all of the sampling areas does not signif-
computer memory requirement. The fact that the com-
mined with less involved computation and a lower
mag problem was used in the previous approach to obtain coefficients relating soil electromagnetic conductivity measurements to bulk soil electrical conductivity, the es-
subsequent curve (as shown in Fig. 3) need to be determined, but they appear general in their application; conse-
belief coefficient approach relies upon coefficients which are derived from inherent EM-38 response curves for homogeneous media. Initial adjustment curves (as shown in Fig. 3) need to be determined, but they appear general in their application; conse-
the established coefficient approach appears to be quite general.
There is some sacrifice of accuracy when using the established coefficient approach to determine successive soil increment electrical conductivities. The loss of accuracy may be related to the influences of varying quantities and types of magnetic materials present in different soil types. It has also been cited as a possible reason for the site specificity noticed in the multiple regression coefficient approach. Future work will be directed toward understanding the effect of magnetic susceptibility upon both approaches to see if compensating for these magnetic materials in soils will improve their accuracy.

SUMMARY

The measurement of bulk soil electrical conductivity using the EM-38 soil electromagnetic conductivity meter has been facilitated by the development of a new calculation approach, referred to as the established coefficient approach. This approach requires fewer electromagnetic readings and is less involved than previous methods. Whereas multiple regression was used in the previous approach to obtain coefficients relating soil electromagnetic conductivity measurements to bulk soil electrical conductivity, the established coefficient approach relies upon coefficients which are derived from inherent EM-38 response curves for homogeneous media. Initial adjustment curves (as shown in Fig. 3) need to be determined, but they appear general in their application; consequently, the established coefficient approach can be programmed on any hand-held calculator allowing 300 to 400 programmable steps. Furthermore, the multiple regression coefficient technique has the limitation of being site-specific in its application, while the established coefficient technique appears to be quite general.

There is some sacrifice of accuracy when using the established coefficient approach to determine successive soil increment electrical conductivities. The loss of accuracy may be related to the influences of varying quantities and types of magnetic materials present in different soil types. It has also been cited as a possible reason for the site specificity noticed in the multiple regression coefficient approach. Future work will be directed toward understanding the effect of magnetic susceptibility upon both approaches to see if compensating for these magnetic materials in soils will improve their accuracy.

REFERENCES