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CONSIDERATIONS ON VERY LOW FREQUENCY ELECTROMAGNETIC TECHNIQUES FOR CONTACTLESS SOIL CONDUCTIVITY MEASUREMENTS IN PEDOLOGY

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Abstract: *To put into practice the* ***c****onventional determination of resistivity by the galvanic method, requires a relatively large amount of labor and is, therefore, expensive. At the basis of any interpretation are the lateral or vertical variations of resistivity. The high cost of resistivity maps execution generally means that fewer measurements are made than desirable, with the result that, either (i) the explored area is not large enough to establish a reasonable background, against which the anomaly areas are to be delineated, or (ii) the anomaly areas are obscure and lack definition. The application of electromagnetic techniques (EM) for measuring soil resistivity or conductivity has been known for a long time. Conductivity is preferable in inductive techniques, as instrumentation readings are generally directly proportional to conductivity and inversely proportional to resistivity. The operating principle of this method is: a Tx coil transmitter, supplied with alternating current at an audio frequency, is placed on the ground. An Rx coil receiver is located at a short distance, s, away from the Tx coil. The magnetic field varies in time and the Tx coil induces very small currents in the ground. These currents generate a secondary magnetic field, Hs, which is sensed by the Rx receiver coil, together with primary magnetic field Hp. The ratio of the secondary field, Hs, to the primary magnetic field, Hp, (Hs/Hp) is directly proportional to terrain conductivity. Measuring this ratio, it is possible to construct a device which measures the terrain conductivity by contactless, direct-reading electromagnetic technique (linear meter). This latest technique for measuring conductivity by electromagnetic induction, using Very Low Frequency (VLF), is a non-invasive, non-destructive sampling method. The measurements can be done quickly and are not expensive. The Electromagnetic induction technology was originally developed for the mining industry, and has been used in mineral, oil, and gas exploration, groundwater studies, and archaeology. In these applications, differences in conductivity of subsurface layers of rock or soil may indicate stratified layers or voids that could be of interest.*

Key-words*: electromagnetic, inductive, conductivity, contactless*

1. INTRODUCTION

To put into practice the **c**onventional determination of resistivity by the galvanic method, requires a relatively large amount of labor and is, therefore, expensive. At the basis of any interpretation are the lateral or vertical variations of resistivity.
The high cost of resistivity maps execution generally means that fewer measurements are made than desirable, with the result that, either (i) the explored area is not large enough to establish a reasonable background, against which the anomaly areas are to be delineated, or (ii) the anomaly areas are obscure and lack definition.

2. ELECTROMAGNETIC METHOD FOR MEASURING SOIL RESISTIVITY.

The application of electromagnetic techniques (EM) for measuring soil resistivity or conductivity is known for a long time. Conductivity is preferable in inductive techniques, as instrumentation readings are generally directly proportional to conductivity and inversely proportional to resistivity.
Figure 1 presents the principle of electromagnetic method for measuring soil conductivity.

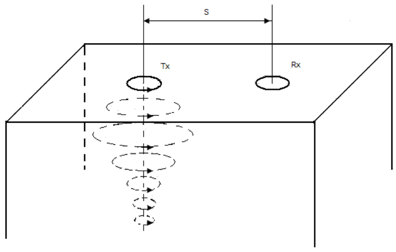

Figure 1: Principle of electromagnetic soil conductivity measurement

The operating principle of this method is: a Tx transmitter coil supplied with alternating current at a frequency audio is placed on the ground. A Rx receiver coil is located at a distance s from Tx coil.

The magnetic field varies in time and the Tx coil induces very small currents in the ground. These currents generate a secondary magnetic field, Hs, which is sensed by the Rx receiver coil, together, with primary magnetic field Hp.

The current induced in the coil receiver Rx is directly proportional to the conductivity of the soil:

$$\frac{H_s}{H_p} \cong \frac{i\omega\mu_0\sigma S^2}{4} \qquad (1)$$

where :

H_s = secondary magnetic field at Rx coil; μ_0 = permeability of vacuum;

H_p = primary magnetic field at Rx coil; σ = soil conductivity;

ω = 2 π f (pulsation); s = distance between coils;

f = frequency; i = $\sqrt{-1}$

Since the ratio of the secondary magnetic field and the primary magnetic field is directly proportional to the soil conductivity, can write apparent conductivity indicated by the instrument as defined by the equation:

$$\sigma_a = \frac{4}{\omega\mu_0 S^2}\left(\frac{H_s}{H_p}\right) \qquad (2)$$

The unit for conductivity is Siemens per meter or, more conveniently, milli Siemens per meter (mS / m).

3. CHARACTERISTICS OF THE DEVICE ACCORDING TO THE TYPE OF POLARIZATION

Table 1 shows the penetration depth depending on the type of polarization and the distance between the coils.

Table 1: the penetration depth depending on the type of polarization and the distance between the coils

Distance between coils (meters)	The penetration depth (meters)	
	Horizontal dipole (HD)	Vertical dipole (VD)
1	0,75	1,5
2	1,5	3
4	3	6

Consider the following initial conditions:

For a homogeneous or stratified horizontal ground current flow is entirely horizontal. In addition, the current flow at any point in the ground is independent of current flow at any point and the magnetic coupling between the current loops are negligible. Accordingly the depth of penetration is limited only by the distance between the coils.

The response of the device as a function of depth (in a homogeneous halfspace):

Whether on a homogeneous halfspace surface which are located the Tx and Rx coils at distance s. Consider a thin layer dz at a depth z.

The thin layer dz at a depth z is presented in figure 2.

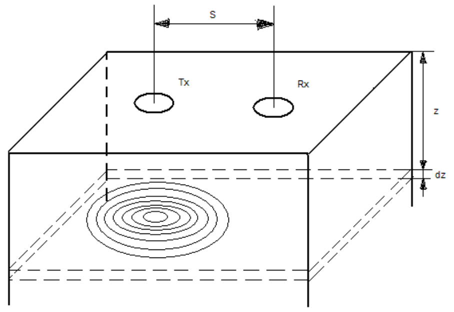

Figure 2: The thin layer dz at the depth z

The depth plotted as fractions of s - distance between coils, is represented on O_x :

$$z = \frac{depth}{s} \qquad (3)$$

It can be built, so for the vertical polarization, the function $\phi_V(z)$, which describes the relative contribution of the secondary magnetic field due to a thin layer at a depth z.

In figure 3 is presented the function $\phi_V(z)$ for the vertical polarization.

It is observed that the layer located at a depth of about 0.4s gives maximum contribution of secondary magnetic field, but that layer to a depth of 1.5s, yet contribute significantly.

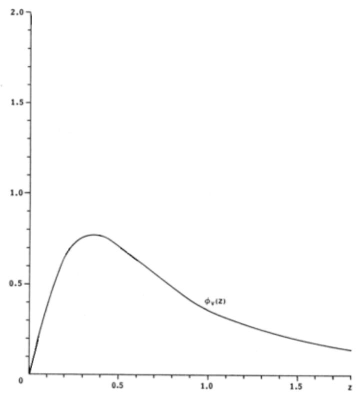

Figure 3: Operation of the device in vertical polarization mode (VD)

It is interesting to note that in the neighborhood of the surface layer has a very small **s** contribution to the secondary magnetic field and, therefore, this configuration is insensitive to changes in conductivity near the surface.

In figure 4 is presented the function $\phi_H(z)$ for the case when the transmitter and receiver operate in the operating mode to horizontal coplanar dipoles.

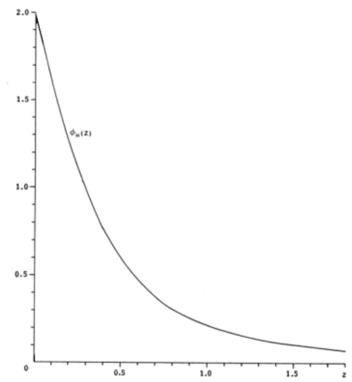

Figure 4: Operation of the device in horizontal polarization mode (HD)

For comparison of the different ways to respond to layers at different depths, now are shown in the same coordinate system, both functions: vertical polarization (VD) and horizontal polarization (HD). In figure 5 are presented both functions: $\phi_V(z)$ and $\phi_H(z)$.

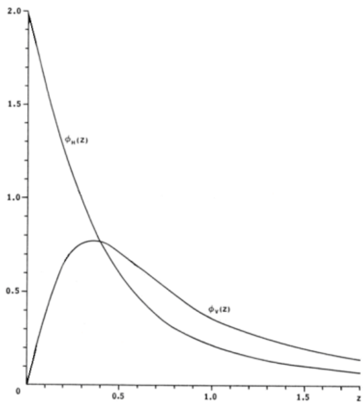

Figure 5: Representation of both functions: $\phi_V(z)$ and $\phi_H(z)$ (to highlight how different the response of different layers)

It is noted that at depths slightly smaller than the distance between the coils, the signal measured by the device is about twice higher for vertical polarization to horizontal polarization case.
The horizontal dipole orientation, the instrument is more sensitive to soil layers in the vicinity. The vertical dipole orientation device is more sensitive to the deeper layers.
Thus, by performing measurements in both modes, it is possible to measure the increase or decrease in conductivity with depth.

4. ADVANTAGES AND DISADVANTAGES OF ELECTROMAGNETIC METHOD

4.1. Advantages of electromagnetic method

The advantages of electromagnetic:
- *Excellent conductivity resolution*. Opening side swept volume of earth inductive technique is about the same as the depth. The result is that small changes in conductivity, for example, of the order of 5% or 10% are accurately measured.
A problem in the conventional method of measuring the resistivity was that this inhomogeneity located near the electrodes causes large errors. Examining the current flow in a homogeneous space for inductive technique described here that, near the emitter current density is very high and we can expect that the presence of an inhomogeneous conductors are here to have a big effect. However, if the current density is high, the radius of the current loop is low and their distance from the receiver coil is large, so that the loops are tightly coupled with the receiver. Thus errors due to local conductivity variations are negligible.
- *Current injection*. Specific problems encountered with conventional current injection materials such as gravel, bedrock, snow and ice, etc. are not found in current injection instruments using induction.
- *Quick and easy measurements*. The classical method for each measurement, four electrodes are inserted into soil and measurement is relatively close to the space between the electrodes. Making repeated maneuvers presents numerous opportunities for breakage. These problems are avoided and an inductive magnetic measurement technique can be performed five to ten times faster using this technique.

4.2 Disadvantages of electromagnetic method

As with all geophysical instruments the use of inductive technique has several disadvantages as follows:
- *Limited dynamic range* (1-1000 mS / m). For low values of conductivity land, obtaining of sufficient soil to produce a detectable magnetic field coil reception is difficult. On the other hand, if high values of soil conductivity, the EM measurements are no longer linearly proportional to the conductivity of the soil.
- *Establish and maintain the zero of the instrument*. Ideally, when zero adjustment tool, it should be suspended in space. In this case, a region of the ground looking very resistant to accurately measure its conductivity using

conventional techniques, and to adjust to zero the instrument.
It requires zero setting of the instrument to be accurately maintained at zero for long periods and temperature variations encountered during geophysical measurements in different areas of the Earth. Zero can be calibrated with an error of up to ± 0.2 mS per meter. Such an error would be negligible in the normal range of soil conductivity. However, if the measurements are carried out on a very strong field, the error may become significant.

5. BLOCK DIAGRAM OF THE DEVICE BASED ON THE METHOD OF ELECTROMAGNETIC (EM)

Figure 6 presents a block diagram of the device and the types of polarization used: vertical dipole (VD) and horizontal dipole (HD).

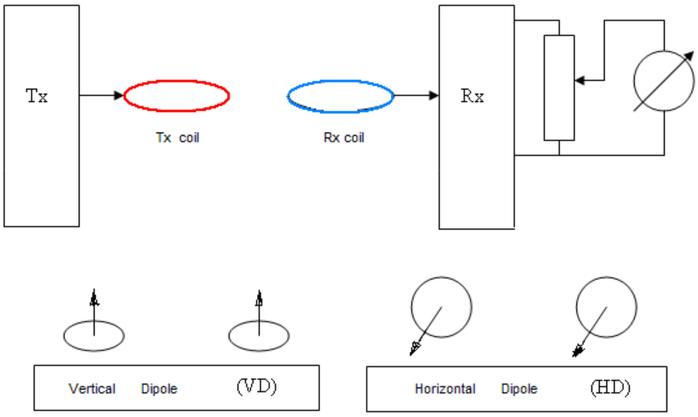

Figure 6: Block diagram of the device and polarization types used:
Vertical dipole (VD) and horizontal dipole (HD)

The device is composed of two parts. The emission consists of a transmitting coil that receives signal Tx emission module (a square wave generator of fixed frequency of 10-20 kHz). The reception desk is made of Rx coil and receiver (amplifier with one or more floors, followed by a detector). Receiver modulator output is connected to a measuring instrument (mA) through a potentiometric circuit. Level zero is set in the potentiometer.
The polarization is selected by positioning the two coils, Tx coil and Rx coil. It uses horizontal polarization dipole when the coil axis is parallel to the soil surface and vertical dipole when the coil axis is perpendicular to the soil surface.

6. MEASUREMENT TECHNIQUE

In agriculture, the device is used to measure the salinity and soil moisture. Other agricultural applications currently include mapping, depth estimation topsoil, sand deposition depth after flood damage estimation due to herbicides, etc.
For each of the applications mentioned above, a relationship must be established between the value determined by device and soil characteristic of interest. Once the relationship is established, measurements can be made quickly.
To establish a relationship between the value determined by using the soil and the characteristic of interest for selected points on the ground, are taken simultaneously: soil samples (using a probe) and the apparent conductivity of the soil (through measurement device EM) . The data from these points is made EM calibration device. Thus, the final map is drawn deep fertile soil.
Experimental correlations were found in moderate to good conductivity between the apparent conductivity and the results of the classical method, the soil samples, the most accepted and precise method for determining soil salinity.
A mobile data collection unit is mounted on a wooden trailer away from metal objects and away from the vehicle engine interference, which could affect determinations.
In figure 7 is presented the humidity device configuration for s = 1m and maximum sounding deep 1,5 m.

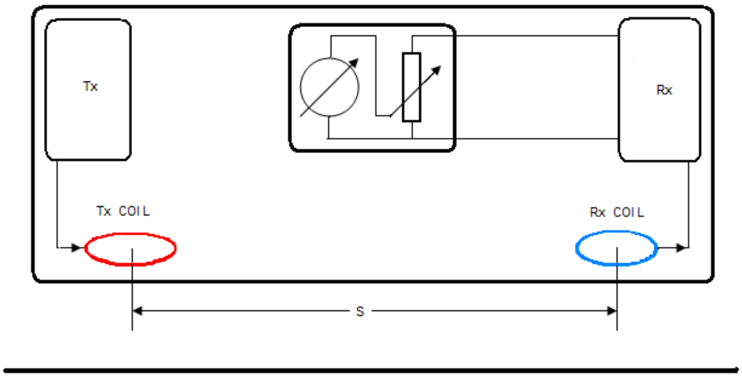

Figure 7: Configuration for s = 1m and maximum sounding deep 1,5 m.

The coils are air-cored for bouth: transmitter and receiver. These coils are in fact magnetic antennas.
The mobile unit consists of EM device coupled to an analog to digital convertor, a computer and a receiver of differential global positioning system (DGPS).
The unit operates as follows: the analog signal coming from EM is converted into a digital signal and recorded by computer. Together with this information the computer also records your location (where the measurement was performed) received from the DGPS receiver.
Using this device, data of entire fields can be collected quickly, and then, with appropriate software, you can make maps of soil conductivity. For 1 hectar field data can be collected about one hour.
After drawing the map of the land, for confirmation, it can be compared with aerial photograph (of the same pitch) made in the vegetation season.
In the early 1980s, electromagnetic induction method (EM) has been accepted as a useful method for getting maps of soil salinity. The method provides assessment tools to monitor the salinity.
Information about the depth of topsoil are a valuable tool in choosing appropriate crop management needs.

7. EXPERIMENTAL RESULTS

EM device indicate areas where higher electrical conductivity (soil more fertile) are marked on the map with dark green - green crops. Soil areas with lower conductivity, are marked with color light brown - areas where coverage is less dense crop yellowing occurs due to moisture stress.
Using aerial photography to see plant cover is easy to see differences in productivity potential and how well models of potential productivity are correlated with measurements of soil conductivity using EM device.
The EM behave linearly proportional to the conductivity of the soil when the distance between the coils is less than the depth of penetration. However, in soils with a higher apparent conductivity of 80 mS / m, EM measurements are not linearly proportional to the conductivity of the soil.
However, in soils having a higher bulk conductivity of 80 mS / m, the EM measurements are no longer linearly proportional to the conductivity of the soil.

8. CONCLUSIONS

The device for measuring the conductivity of materials by electromagnetic method (without contact) has a wide range of applications.
Its usefulness in areas such as geology (search for metal ores, oil, salt, etc.), archeology, agriculture (for measuring humidity, salinity) was confirmed in time.

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