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Using the Spectral Induced Polarization technique for estimating soil texture and moisture content

Mostafa Moawad[1*], Mohamed M. Gomaa[2], Ahmed M. Elshenawy[3], Alhussein A. Basheer[1], and Adel Kotb[1]

[1] *Geology Department, Faculty of Science, Helwan University, Cairo, Egypt.*
[2] *Head of geophysical exploration Lab., Geophysical Sciences Department, National Research Centre, Cairo, Egypt.*
[3] *Geophysical Exploration Department, Desert Research Centre, Cairo, Egypt.*

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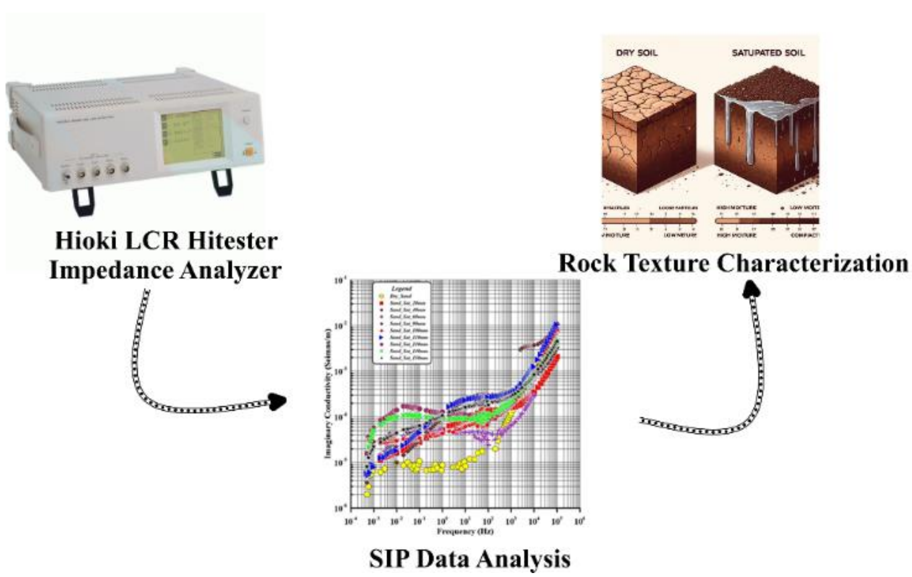
Graphical Abstract



Abstract

* **Corresponding author E-mail:** mostafa_mawaed@science.helwan.edu.eg

Information about soil texture and moisture content are necessary for cultivation, hydrology, hydrogeology and geotechnical engineering. Spectral Induced Polarization (SIP) is a promising non-invasive geophysical method for assessing soil properties critical to hydrology, agriculture, and geotechnical engineering. This study evaluates the efficiency of SIP in estimating soil texture and moisture content across varying saturation levels in semi-arid environments. Measurements were conducted over a frequency range of 0.0005 Hz to 100 kHz, using controlled laboratory experiments of dry to wet sand synthetic samples. SIP method is useful for monitoring soil humidity and moisture. The electrical characteristics of soil are influenced by water, leading to alterations in impedance spectra. Results indicate strong correlations between water content and SIP parameters, particularly quadrature conductivity, phase angle, and chargeability. With increasing water content, the resistivity decreases with good separation response below 100 Hz while the imaginary conductivity increases. In addition to the phase shift between current and potential response become closer, then starting to become wider, so it's made the phase shift decrease then increase. In the context, chargeability decreases as the conduction passes increase between grains so the storage energy transport via these passes' links increases. The findings demonstrate the potential of SIP for soil monitoring, contributing to enhanced agricultural productivity. In addition to considering soil texture characteristics and sustainable soil management practices.

1. Introduction

Soil texture and moisture content are considered as a significant parameter and have a large impact on the performance and outcomes for many environmental and agricultural processes. These processes include plant development, moisture content and soil erosion. In order to sustain life on Earth, soils are necessary. Accurately measuring these parameters is vital for proper soil management and for monitoring the state of the environment, as well as for the productivity of agriculture.

The application of geophysics in hydrologic investigations has been growing quickly over the past ten years due to advancements in groundwater modeling programs and the sensitivity of geophysical instrumentation [1]. By identifying spatial patterns of petrophysical parameters and connecting them to hydrologic qualities or states, these applications aim to aid in understanding of aquifer heterogeneity. In fact, one of the most significant and difficult objectives in hydrogeophysics is to be able to accurately estimate the hydraulic properties of subsurface formations using a non-invasive technique. Furthermore, any future hydrogeological or environmental initiative must be able to forecast or evaluate the spatial variability of these characteristics. Because the porous media is inevitably disturbed, using traditional methods to determine these qualities is still challenging and occasionally impractical [2,3]. In the context, substantial advancements in subsurface hydrogeological characterization would arise from the ability to consistently measure, track, and map important hydraulic parameters using geophysical instruments [4-11].

The Spectral Induced Polarization (SIP) technique allows the soil texture to be characterized, and soil moisture determined with a method that is accurate, non-destructive, and straightforward. SIP is a technique that evaluates the frequency-dependent electrical properties of soils to gain knowledge of the physics of those soils. The use of spectral analysis enables researchers to assess the textural and moisture characteristics and hence the soil quality, with high accuracy results. Such an introduction of the SIP technique in terms of characterization of soils shows that this study will very much improve the way soils are monitored and managed since real-time soil property information will be available in detail [12-14]. Soil management has progressed to a better level through the incorporation of SIP in the study of soil as it enhances the efficiency of soil management activities. Due to this encouraging feature, the SIP method has been identified as a theoretical tool that could non-invasively provide information about variations in soil texture and water content. SIP quantifies the frequency-dependent complex electrical impedance of soil, which consists not only in its magnitude but also to a significant extent by its phase with respect to an induced polarization signal. SIP technique depends on many conditions like mineral composition, pore fluid chemistry and presence of organic matter. Accurate data on soil properties over field-relevant scales, such as soil grain size, permeability, cation exchange capacity (CEC), and water content, is necessary for the best possible protection and management of the soil for conservation, geotechnical engineering, water resources, and agriculture [15].

All specialists in the potential field of geophysics are interested in SIP investigations to determine soil properties with low cost and short time by this effective technique [15-17]. This literature extended to follow the previous studies and continue the effective experiments in laboratory scale.

a) b)

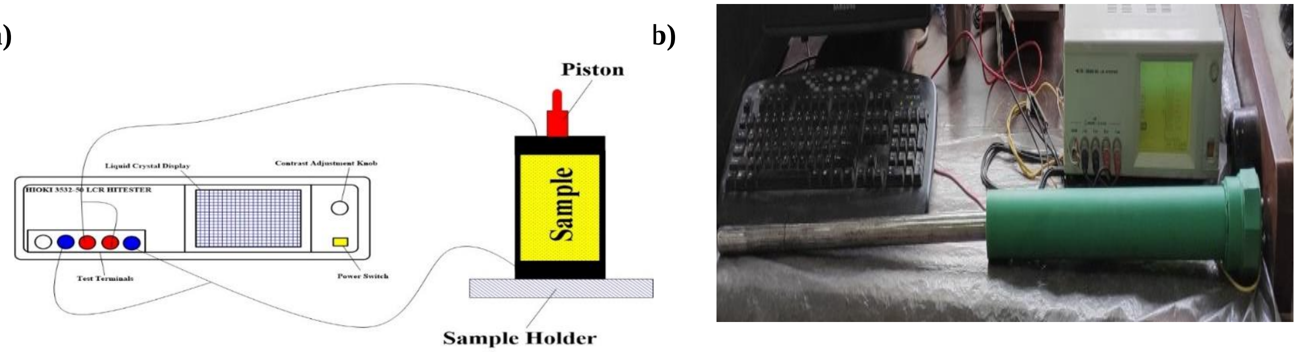


Fig.1: a) Schematic representation and b) instrument of connected electrode

2. Materials and Methods

Electrical properties measurements were taken on a thin disk-shaped unsaturated to fully saturated sandstone by water of thickness 25 mm, diameter 40 mm. Hioki 3522-50 LCR Hitester Impedance Analyzer connected to the electrodes (Fig.1) was used to collect data in the frequency (f) range from 0.0005 Hz to 100 kHz across a voltage of 1 V was applied [18].

The measured electrical characteristics parameters are series and parallel capacitance (C_s and C_p) and series and parallel resistance (R_s and R_p), respectively. The complex impedance can be calculated as $Z^* = Z' + iZ''$, where $Z' = R_s * (\frac{A}{d})$, and $Z'' = (\frac{1}{\omega C_s})(\frac{A}{d})$ are real and imaginary (quadrature) component of impedance, respectively. Note that A is cross-sectional area of sample and d is the thickness of sample. After that phase angle $\theta = \arctan\frac{Z''}{Z'}$ can be measured.

The complex relative dielectric constant $\varepsilon^* = \varepsilon' - i\varepsilon''$ is must be calculated to measure the real and imaginary (quadrature) conductivity, then the complex component of dielectric constant can be calculated as real $\varepsilon' = \frac{C_P}{C_0}$ where, geometrical capacitance $C_0 = \left(\frac{A}{d}\right)\varepsilon_0$ (F) and ε_0= 8.85 × 10^{-12} (F/m), and imaginary $\varepsilon'' = \frac{G_P . d}{\omega . A . \varepsilon_0}$ where, Parallel conductance $G_P = \frac{1}{R_P}$ and angular frequency $\omega = 2\pi f$.

The real part of complex conductivity is $\sigma' = \varepsilon'' * \omega * \varepsilon_0$, while the imaginary part is $\sigma'' = \frac{\sigma'}{\tan\delta}$, where $\tan\delta = \frac{\varepsilon''}{\varepsilon'}$ is dielectric loss. According to polarization phenomena, chargeability can be calculated from the graph of impedance (Argand) plane as $\mathrm{M} = \frac{\rho_0 - \rho_\infty}{\rho_\infty}$, where ρ_0 and ρ_∞ are resistivities at low and high frequencies, respectively.

Ten synthetic samples (dry to wet sand) are prepared to be ready for the measurements of electrical properties. Sand is completely dried at oven 100 °C for 2 days.

After that, sample weight dry was measured, and at different saturation levels. Subsequent measurements with the determination of weight were made with increasing water saturation.

The saturation levels (% by weight) were calculated as $W_s = \frac{W_W - W_D}{W_D} * 100$, where W_W is weight of wet sample and W_D is weight of dry sample.

3. Results

Electrical measurements were made on dry and wet sand synthetic samples from dry to different water saturation levels by the electrode shown at (Fig.1) in the frequency range from 0.0005 Hz up to 100 kHz. Samples were prevented from air evaporation by putting it in the isolated chamber (Desiccator) where the relative atmospheric humidity is ~ 64% and at room temperature (24 ºC). At low saturations, the change in electrical conductivity and dielectric permittivity is rapid; at high saturations, the change is slower.

Figure 2 shows the variation of resistivity values with frequency according to water saturation levels increase. With the increase of frequency, resistivity decreases. Values of resistivity at low frequency are 10^5 Ω.m (dry) and 10^4 Ω.m (fully saturated).

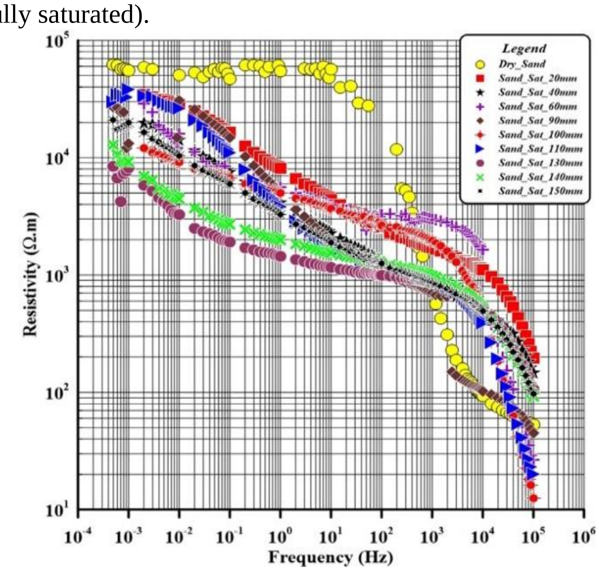


Fig.2: Change in resistivity with frequency as a function of different water saturation levels.

According to SIP measurements, the imaginary part of conductivity represents the storage energy in the grains. Figure 3 shows the relationship between imaginary conductivity and frequency according to the increase of water. With the increase of frequency, imaginary conductivity makes a peak of relaxation and starts to increase at 0.1 Hz. Values of conductivity at low frequency are $2x10^{-6}$ S/m (dry) and 10^{-5} S/m (fully saturated).

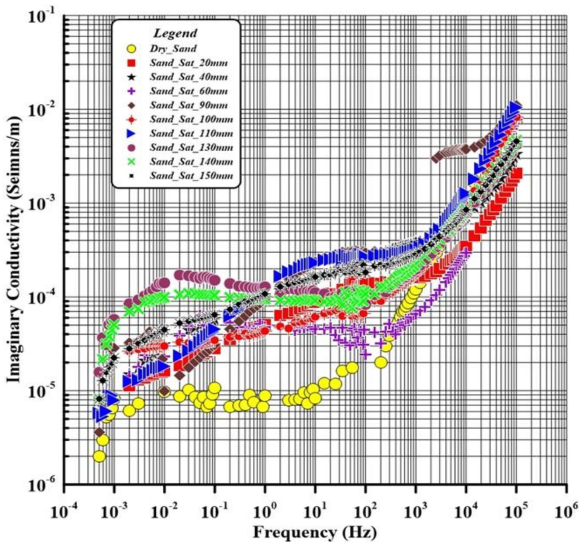


Fig.3: Change in imaginary conductivity with frequency as a function of different water saturation levels.

There is a clear separation between dry and saturated samples in the phase angle detection in the frequency range between 10 to 10^5 Hz (Fig.4), in the context, with the increase of frequency, the phase angle decreases until the critical point at 10^2 Hz then starts to increase. Values of phase angle at low frequency are 0.7 rad. (dry) and 0.9 rad. (fully saturated).

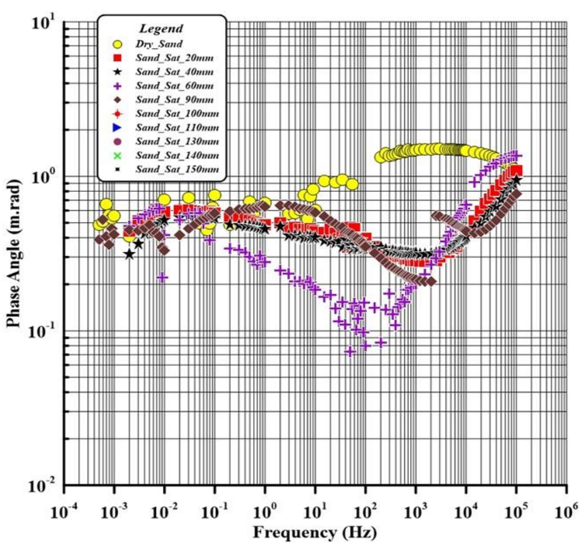


Fig.4: variation in phase angle with frequency as a function of different water saturation levels.

Figure 5 shows the relationship between chargeability and water saturation levels. No charges will accumulate in the water so there is an inverse relation between these quantities. Chargeability values of this kind of sample range from 10^3 to 10.

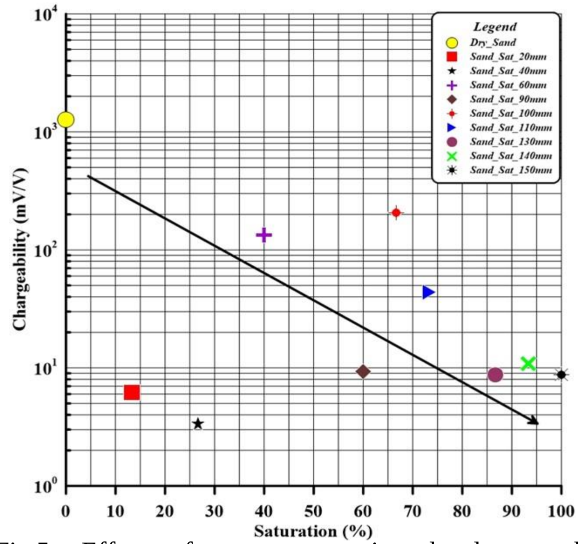


Fig.5: Effect of water saturation levels on the chargeability of sample.

4. Discussion

In this study, results perform the effectiveness of SIP technique to detect the possible soil texture and its moisture content. As partially saturated rocks like those in the vadose zone become a more popular area of field study, characterization and understanding of some electrical properties under partial saturation conditions are important. This analysis supports the understanding, monitoring, and prediction of water flow/pollutant transport. Because the unsaturated zone is difficult to study, accurate geophysical methods require calibration with laboratory tests. Wherever reservoir rocks are located, assessed, and exploited is of significant oil well logging techniques: Each rock response in different circumstances must be known concerning its petrophysical properties. Geophysical methods extensively based on Archie's [19] empirical relationship have been used for petrophysical characterization measured from well logs, such as electrical resistivity and polarization measurements.

The resistivity relationship with frequency (Fig.2) shows that as water increase makes the conducting pass ways between grains, so it's made the resistivity decrease. Therefore, as water content increases the resistivity decreases, and with increasing water content the slope of decreasing changed from gentle slope (-0.76) to steep slope (-2.45), the negative sign refers to decreasing. So, the difference between water bearing formations and dry formations and in between can be detected in the frequency range 10^{-3} and 10^3 Hz.

One of the most important parameters of SIP is the quadrature conductivity in the relationship with frequency (Fig.3) performance that as water increases makes the charges accumulate to store and after a short time starts to leak these charges rapidly. This can be distinguished between the same frequency range as resistivity (10^{-3} and 10^{3} Hz). It notices that by increasing water content, the imaginary conductivity increases. In the same frequency range, the phase angle changes with frequency (Fig.4) as water increase makes the phase shift between current and potential response become closer, then starting to become wider, so it's made the phase shift decrease then increase.

When an electrical field is applied, some of the ionic charges in the pore water of the soil begin to move producing an electrical current. Not all the ions, however, can move freely but are caught at impermeable boundaries within the soil. This collection of ionic charges is known as induced polarization because electric dipole moments are generated within the rock. The term "chargeability" designates a description and measurement of the formed induced polarization under the action of the electric field and its intensity. Water saturation highly affected on soil electrical characteristics; with increasing water saturation levels the chargeability decreases as the conduction passes increase between grains so the storage energy transport via these passes' links increase (Fig.5).

Conclusion

As the SIP method is sensitive to the presence of water in the soil matrix, it is especially useful for monitoring soil humidity and moisture. The electrical characteristics of soil are influenced by water, leading to alterations in impedance spectra. The following results were obtained:

(1) Water-bearing formation can be detected in the frequency range 10^{-3} and 10^{3} Hz in the resistivity and conductivity measurements.

(2) As water levels increase, there are clear effects on electrical properties. With the increase of frequency, the resistivity decreases at low frequencies are 10^{5} Ω.m (dry) and 10^{4} Ω.m (fully saturated). In this context, the imaginary conductivity makes a peak of relaxation and starts to increase at 0.1 Hz at low frequencies are 2×10^{-6} seimns/m (dry) and 10^{-5} seimns/m (fully saturated).

(3) In the phase angle measurements, the frequency range for detecting the saturated and unsaturated zones becomes between 10^{1} to 10^{5} Hz at low frequencies are 0.7 rad. (dry) and 0.9 rad. (fully saturated).

(4) Chargeability is a common parameter that describes the IP effect, so as the water level increases in the soil the chargeability will decrease.

In the future work, results suggest that combining SIP with remote sensing techniques and existing hydrological models, researchers can achieve a comprehensive understanding of soil moisture dynamics across various spatial and temporal scales. The use of satellite-based remote sensing, for instance, allows for large-scale monitoring of surface moisture, while SIP offers the necessary subsurface insights to complement this data. Additionally, incorporating SIP into groundwater studies enhances the ability to map aquifer properties, monitor changes in groundwater storage, and detect zones of preferential flow. This integrated approach not only improves the accuracy of hydrological assessments but also supports adaptive management strategies in response to climate variability, fostering more resilient and sustainable environmental practices. The potential of SIP to be integrated into broader environmental monitoring frameworks is substantial, given its capability to provide detailed and non-destructive data on soil properties.

Finally, results represent that when the water content rises, the quadrature conductivity goes up, but the chargeability and phase angle go down. The findings demonstrate the potential of SIP for real-time soil monitoring, contributing to enhanced agricultural productivity, considering soil texture characteristics and sustainable soil management practices.

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