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Assessment of Soil Petrophysical Parameters Using Electrical Resistivity Tomography (ERT) and Induced Polarization Techniques

Ahzegbobor Philips Aizebeokhai, Kehinde D. Oyeyemi and Olusola T. Kayode
Department of Physics, College of Science and Technology, Covenant University,
1023 P.M.B., Ota, Ogun State, Nigeria

Abstract: Electrical Resistivity Tomography (ERT) and time domain Induced Polarization (IP) techniques has been used to assess the spatial variability of the soil petrophysical properties in Covenant University Farm, Ota, Southwestern Nigeria. Apparent resistivity and chargeability of the induced polarization effect were concurrently measured along six traverses using Wenner array. The observed data were inverted to produced 2D electrical resistivity and chargeability models of the soil. The inverse models were used to delineate the tilled layer from the untilled layer and qualitatively assess the degree of compaction and lateral thickness of the soil. Other petrophysical properties such as amount of clay volume, moisture content and organic matter in the soil which are related to the electrical conductivity of the soil were also inferred. The study demonstrates the effectiveness of ERT and time domain induced polarization techniques for accessing the variations of soil conditions in large tracts of land for precision agriculture.

Key words: Electrical resistivity, induced polarization, soil properties, precision farming, Nigeria

INTRODUCTION

The knowledge of the petrophysical properties of soil is useful for agricultural practices and environmental impact assessments. Agricultural practices often indicated spatial variability in the sub-soil among nearby parcels of land and this is usually manifested as differences in crops productivity. Many techniques have been used to determine soil properties and their spatial distribution or/and temporal variability. The distribution of these properties can be exploited in more efficient ways to allow for increased crops yield without necessarily applying chemical fertilizers and pesticides (Robert, 2002; Rodriguez *et al*., 2010). Consequently, the environmental impacts of agricultural activities on soils, surface water and groundwater can be considerably reduced. However, the mapping and characterization of soil properties as rapidly and accurately as possible can be very challenging. Geophysical techniques are effective and relatively inexpensive tools that can be used for rapid and accurate characterization of the spatial distribution and temporal variability of soil petrophysical parameters. Electrical Resistivity Tomography (ERT) is one of such geophysical techniques that can be used to map and characterize the spatial distribution and temporal variability of soil properties (Williams and Baker, 1982; Mckenzie *et al*., 1989; Corwin and Lesch, 2003; Lizarraga, 2007; Sudha *et al*., 2009). ERT survey makes use of the variations in the electrical properties of the soil.

Soil conductivity (or its inverse, resistivity) is controlled by a variety of factors including the salinity, clay volume, moisture content, porosity, mineralogy organic matter, bulk density and temperature. Thus, soil conductivity is a complex physio-chemical property that results from the inter-relationship and interactions of these soil properties. ERT measurements can be used to assess the spatial distribution and temporal variability of any or a combination of these soil properties. Soil conductivity has been used to map and characterize the spatial distribution of soil salinity (or total solute concentration) and assess other soil properties such as clay content, porosity and Cation Exchange Capacity (CEC) (Shevnin *et al*., 2006, 2007) which correlates well with soil conductivity. In this study, ERT and time domain Induced Polarization (IP) geophysical techniques were used to map and characterized the petrophysical properties of the soil in Covenant University Farm, Ota, Southwestern Nigeria. Most parts of the farm are usually water-logged during the raining season due to underlying relatively impermeable near-surface lateritic clay layer which has been characterised in previous studies (Aizebeokhai and Oyebanjo, 2013; Aizebeokhai and

Corresponding Author: Ahzegbobor Philips Aizebeokhai, Department of Physics, College of Science and Technology, Covenant University, 1023 P.M.B., Ota, Ogun State, Nigeria

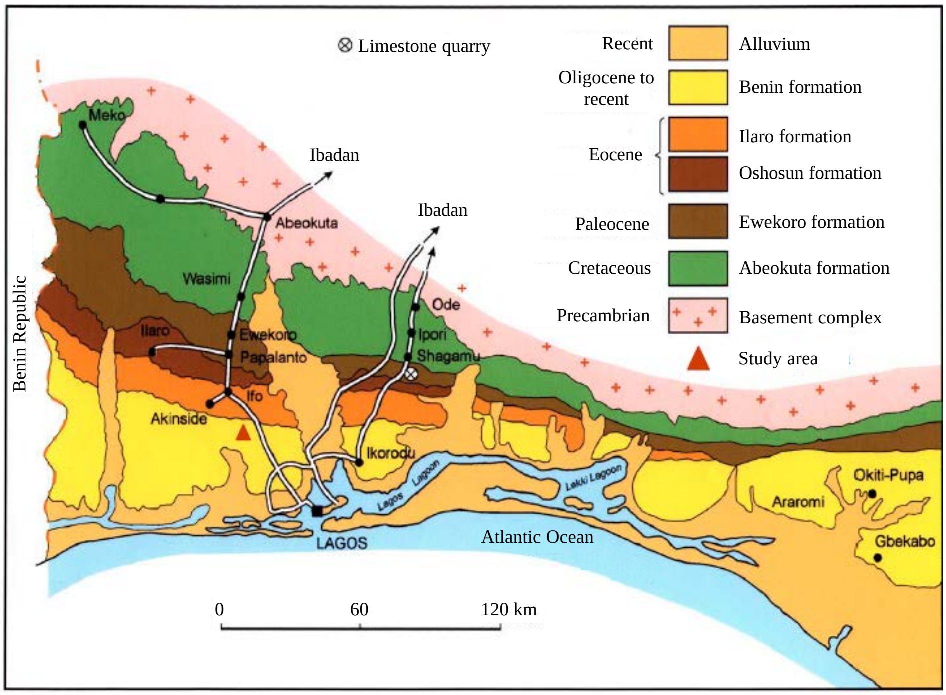

Fig. 1: Geological map of the Nigerian part of the Dahomey embayment (modified after)

Oyeyemi, 2014) this is expected to lead to increased soil salinity in the area. The inverse models of the resistivity and chargeability were used to delineate the tilled soil and assess the degree of compaction as well as the spatial variability in the soil thickness. Other petrophysical properties of the soil including clay volume, moisture content and organic matter which are related to soil conductivity are inferred.

Site description: Covenant University Farm (Lat. 6.67°N and Long. 3.16°E) is located in the eastern part of the Dahomey Basin, Southwestern Nigeria (Fig. 1). The basin is a combination of inland, coastal and offshore basins and stretches along the continental margin of the Gulf of Guinea. The area is generally gently sloping low-lying and is characterized by two main climatic seasons the dry season that spans from November to March and raining (or wet) season between April and October. Occasional rainfalls are often witnessed within the dry season due to its proximity to the Atlantic Ocean. Rainfall forms the major source of groundwater recharge in the area; mean annual rainfall is >2000 mm. The mean monthly temperature ranges from 23°C in July to 32°C in February. Because of its proximity to the coast, the area is under the influx of sea water and other types of aerosols sprayed from the Atlantic Ocean this can potentially increase the salinity of the subsoil.

The local geology is consistent with the regional geology and is predominantly Coastal Plain Sands and Recent sediments. The Coastal Plain sands consists of poorly sorted clayey sand, reddish mud/mudstone, clay lenses, sandy clay with lignite of Miocene to Recent. The Coastal Plain sands are underlain by a sequence of coarse sandy estuarine, deltaic and continental beds characterised by rapid changes in facies. The top soil is mainly sandy loam which is rich in organic matter and underlain by unconsolidated sand with varying thickness ranging from about 1.0-2.0 m across the farm land. This unconsolidated sand is underlain by more consolidated lateritic clay unit which is largely impermeable. This causes runoff water to settle in most parts of the area after rainfall. At the time of the survey, the farm land has been tilled and cultivated with maize and plantain already growing on it. Observation shows evidence of application of organic fertilizer on the farm land. The aquifer system is confined and relatively deep with depth ranging from about 45->65 m as characterized from previous studies (Aizebeokhai and Oyebanjo, 2013; Aizebeokhai and Oyeyemi, 2014).

MATERIALS AND METHODS

Six 2D ERT and time domain IP profiles were conducted with the aid of ABEM Terrameter (SAS

1000/4000 series). Traverses 1-4 are 100 m in length while Traverses 5 and 6 are 70 m and 80 m in length, respectively due to limited access. The 2D traverses were conducted in the West-East direction and are separated from each other with an inter-line spacing of 15 m. Wenner array with minimum electrode spacing of 1.0 m was used for the data measurements and a data level of 5 (electrode spacing of 5.0 m) was achieved in each of the profiles. These survey parameters (minimum electrode spacing and data level) ensure that the effective depth of investigation is confined to the root zone (about 2.0 m depth). Care was taken to minimize electrode positioning error in the measurements throughout the survey. To ensure data quality and minimized error in the data collection, the measurements were stacked for each observation and the data stacking was set for a minimum 3 to a maximum of 6. The root-mean-squares error in the measurement was generally <0.3%. Data measurements with root-mean-squares error up to 0.5% or higher were repeated after ensuring that the electrodes were in good contact with the ground. The apparent resistivity and apparent chargeability were measured concurrently.

The observed apparent resistivity and chargeability data sets were inverted with RES2DINV computer code (Loke and Barker, 1996) which uses a non-linear optimization technique that automatically determines the 2D resistivity model of the subsurface for the input apparent resistivity data or/and apparent chargeability data (Griffiths and Barker, 1993; Loke and Barker, 1996).

The program divides the subsurface into a number of rectangular blocks according to the spread of the observed data. Least-squares inversion with standard least-squares constraint which attempt to minimize the square of the difference between the observed and the calculated apparent resistivity or apparent chargeability values was used to invert the observed datasets. Smoothness constraint was applied to the model perturbation vector only and appropriate damping factor was selected for each profile data set using trial and error methods.

RESULTS AND DISCUSSION

The inverse resistivity and chargeability models obtained from the data inversion are presented in Fig. 2-7, the effective depth of investigation is about 3.0 m. The root-mean-squares errors observed in the inverse resistivity models range between 4.2 and 7.2%. Correlation between measured chargeability data and calculated ones shows low level of noise in the IP data. The root-mean-squares errors observed in the chargeability inverse models are much less than those of the resistivity inverse models and range from 0.11-0.29%. The inverse resistivity models are generally characterized with low resistivity values in all the traverses, ranging from about 40-700 Ωm. Low resistivity (<100 Ωm) values are particularly pronounced in the west end of the farm. On the whole, the inverse model resistivity is averagely

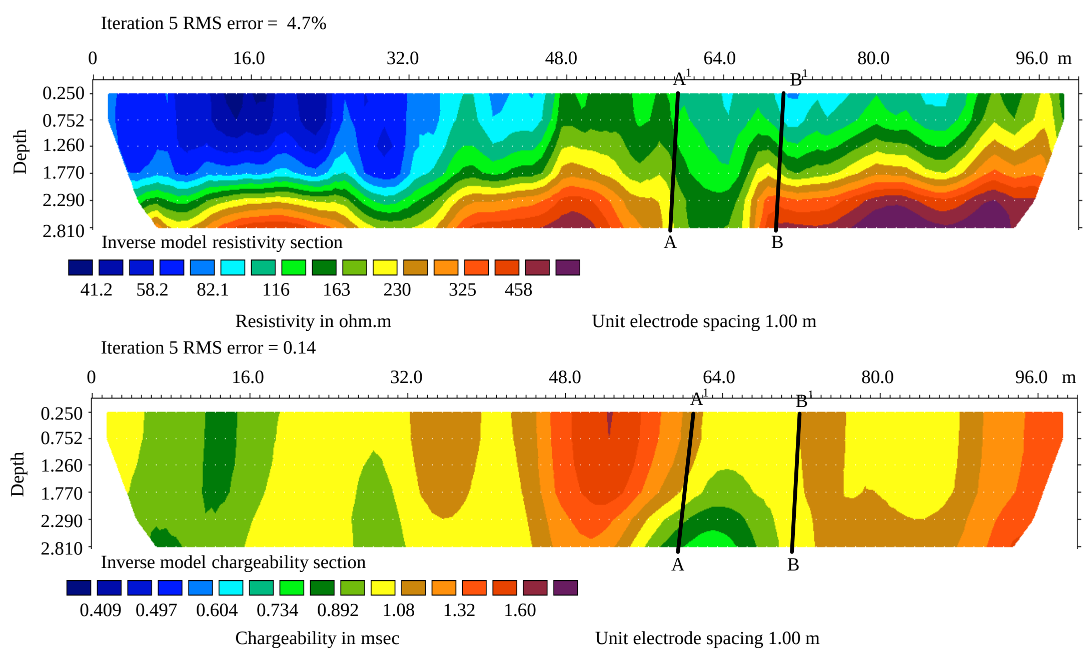

Fig. 2: Inverse resistivity and chargeability model sections for Traverse 1

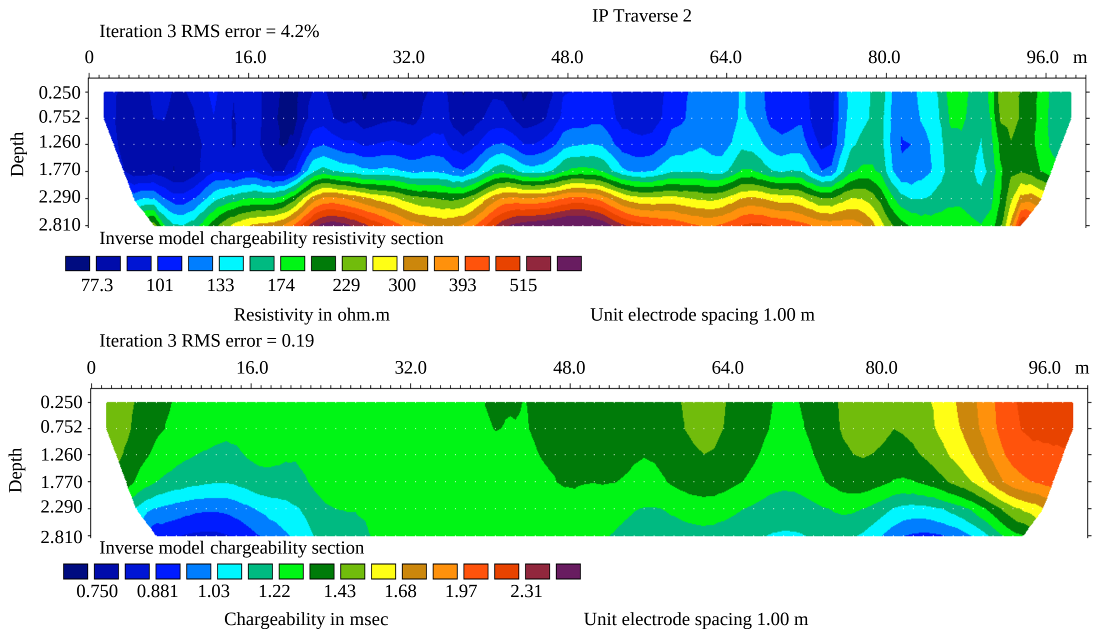

Fig. 3: Inverse resistivity and chargeability model sections for Traverse 2

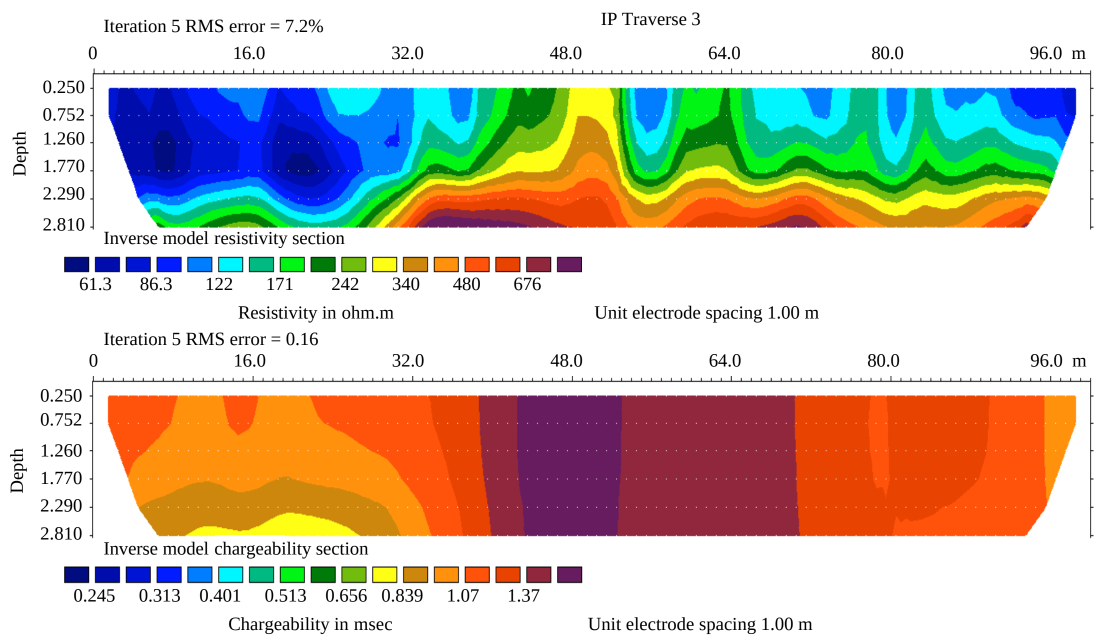

Fig. 4: Inverse resistivity and chargeability model sections for Traverse 3

<100 Ωm to an average model depth of about 2.2 m. This relatively low model resistivity indicates high moisture content and unconsolidated soil within this depth range. Consequently, the tilled layer is largely characterised with low resistivity anomaly and a sharp anomaly contrast is observed between the tilled layer and the relatively consolidated or untilled layer. The tilled layer can therefore, be easily discriminated from the untilled layer on the ERT images. However, relatively higher model resistivity values are observed in Traverse 4. Field observation shows that the subsoil in this area is more compacted than most parts of the survey farm. This indicates that the subsoil in the study site is generally conductive.

Soil moisture, porosity, degree of consolidation and organic matter are thought to be the dominant factors that

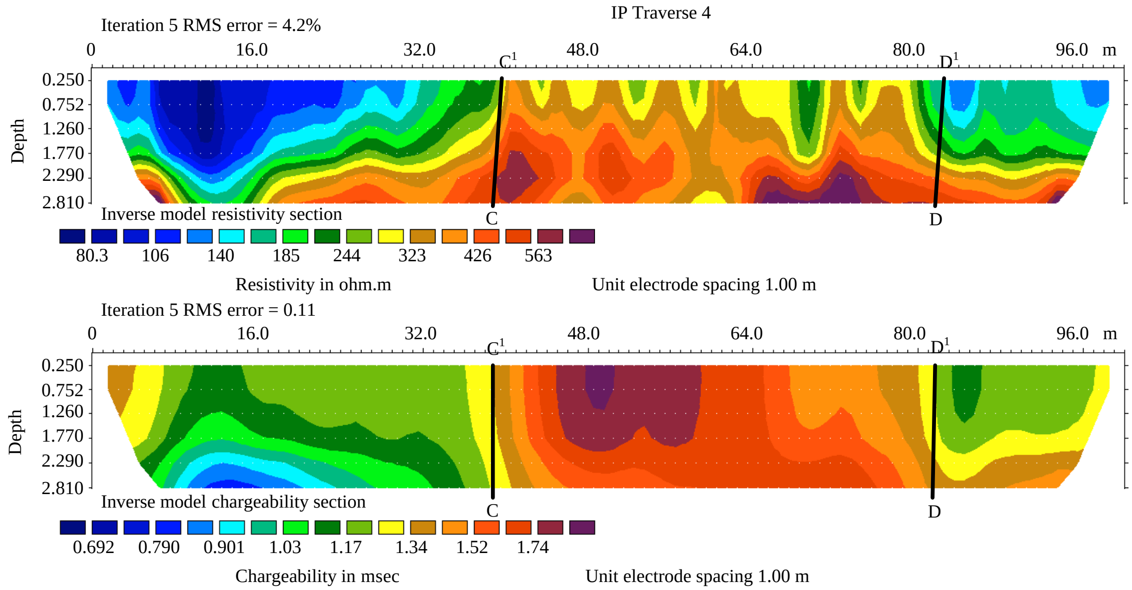

Fig. 5: Inverse resistivity and chargeability model sections for Traverse 4

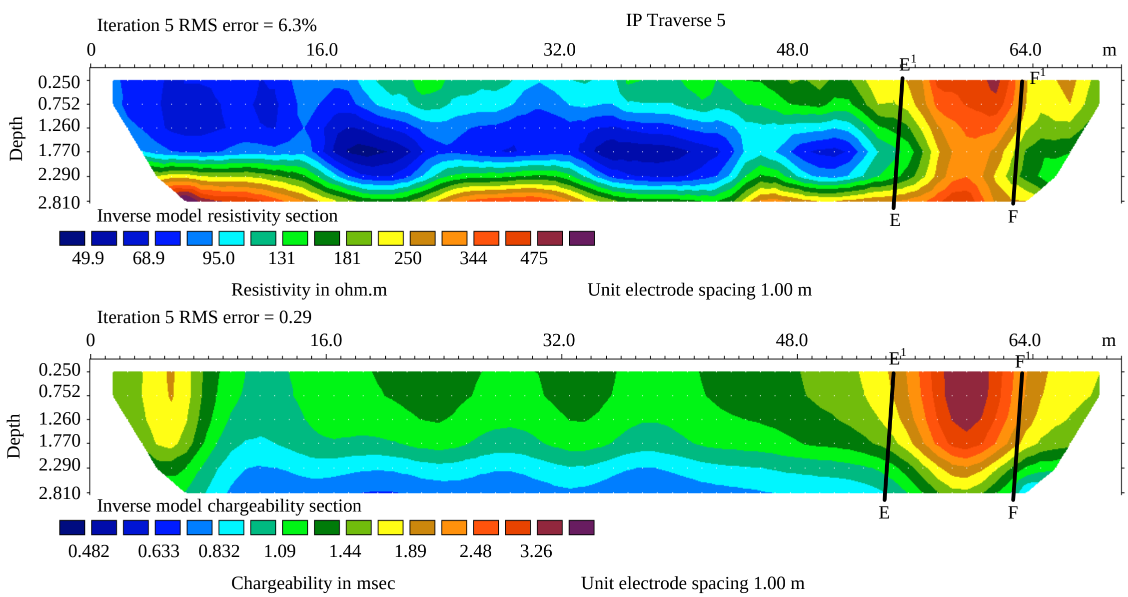

Fig. 6: Inverse resistivity and chargeability model sections for Traverse 5

determine the observed model resistivity distribution in the farm land. Areas with loosed soil are generally more porous and permeable and therefore contain higher soil moisture content than the more consolidated untilled soil. The loosed soil is largely characterised with low resistivity anomalies (<100 Ωm) were generally observed in these areas. High organic matter or soil nutrient is thought to also contribute significantly to the observed low resistivity anomaly in the west end of the farm. The plants (maize and plantain) in the West end of the farm were observed to be growing better than those in the Eastern part indicating better tillage and more soil nutrients in the Western part of the farm. Although, soil salinity could significantly decrease model resistivity values, the contribution soil salinity to the observed low resistivity anomalies in the ERT images is thought to be minimal.

The model chargeability observed in the IP images is generally low, ranging from 0.4-3.5 msec. Strong correlations are observed between the resistivity and

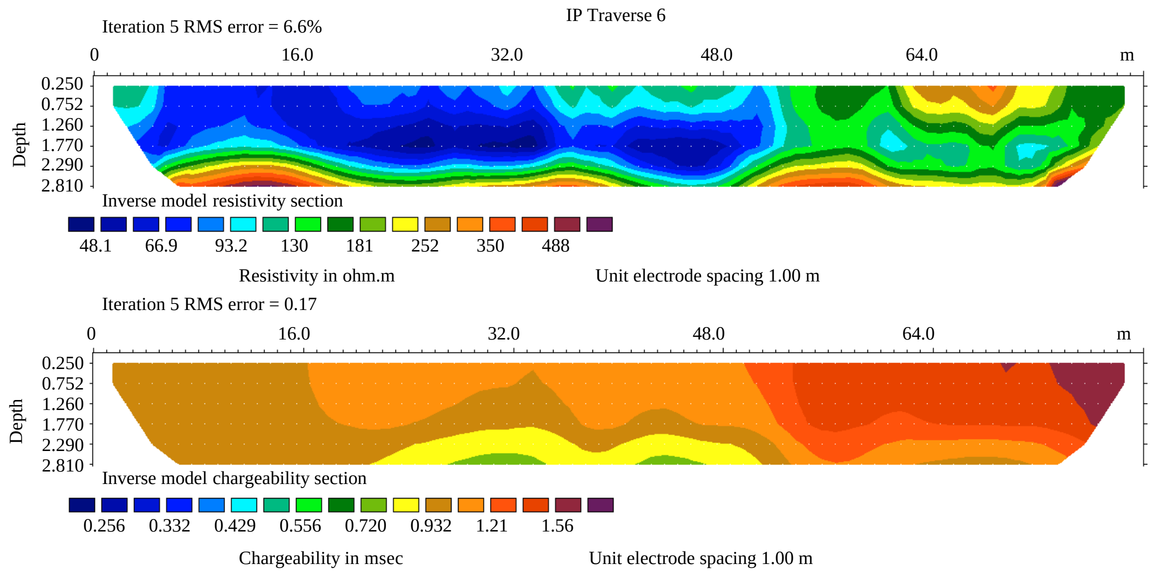

Fig. 7: Inverse resistivity and chargeability model sections for Traverse 6

chargeability anomalies in the inverse model sections for Traverses 2, 5 and 6 (Fig. 3, 6 and 7) with high resistivity values corresponding to relatively low chargeability values. Areas with relatively high resistivity anomalies (>100 Ωm) are thought to be regions with more consolidated soil materials, consisting mainly of lateritic soil. The relatively high resistivity zone (more consolidated soil material) generally occurs at depths >2.0 m. However, some high resistivity anomalies are also observed to produced high chargeability anomalies; for example, the anomaly marked CC^1 and DD^1 in Traverse 4 (Fig. 5) and that marked EE^1 and FF^1 in Traverse 5 (Fig. 6). The anomaly marked AA^1 and BB^1 in the model section for Traverse 1 (Fig. 2) is thought to be a fractured zone which serves as conduit path for groundwater infiltration and percolation.

The chargeability of a given medium is a measure of the discharge of polarization effect in the medium. Thus, chargeability is related to the permittivity and electrical resistivity of the subsurface materials as well as the porosity and moisture/water content in the subsurface media. Other factors that can significantly influence the chargeability of surface materials are grain size and shape of the constituent particles, mineral volume fraction and mineral conductivity. Strong IP effects are commonly observed in sediments containing clays disseminated on the surface of larger grains. Hence, clayey sand and clayey sandstone typically displays large IP effects. In contrast, compacted clays are usually associated with low IP effects as the ohmic conduction dominates current flow. Small measurable IP effects are associated with clean sand and gravel (Vanhala, 1997). The IP images generally show low chargeability values ranging from 0.4-3.5 msec. This indicates that the soils are mainly composed of sandy materials and less disseminated clayey materials. A careful analysis of the 2D resistivity and chargeability images show that the observed low resistivity anomalies did not show distinct and relatively high chargeability anomalies. Thus, the observed low resistivity anomalies are not principally due to increased clay volume or clay mineral dissemination in the subsoil. This is because clay is expected to produce high chargeability anomaly due to cationic exchange capacity. Hence, the observed low resistivity anomaly is mainly due to increased porosity and high moisture content in the sub-soil.

CONCLUSION

The knowledge of the spatial distribution of soil petrophysical properties is useful for precision agriculture as well as environmental impact analysis. In this study, 2D ERT and time domain IP images were used to qualitatively assess the spatial distribution of soil petrophysical properties in Covenant University Farm. Clay volume, moisture content, degree of compaction and organic matter which are related to the soil conductivity were inferred from the ERT and IP images. The low resistivity anomalies observed in the inverse models are attributed principally to the effect of tillage, moisture content and presence of organic matter in the soil. The study demonstrates that ERT can be effectively used to map and access the saptial distribution of soil properties in large tracts of land for precision agricultures and environmental impact assessment. The degree of relaibility of soil resistivity model can be significantly improved if ERT is combined with other geophysical methods such as self potential, induced potential and electromagnetic methods which are equally sensitive to these parameters.

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