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Relationship between Soil Plasticity Index and Resistivity of Geomaterials

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Abstract: *This study explores the applicability of the resistivity method in estimatinggeotechnical index properties in parts of Bayelsa State. Representative soil samples were obtained from twelve boreholes, while geoelectrical soundings were conducted with array centres positionedat the location of each borehole in order to generate data for the analysis. The recovered soil samples were subjected to laboratory testing to determinetheir geotechnical properties. Relationship between the engineering properties and the processed geoelectric parameters was examined by plotting resistivity values against the moisture content and plasticity index of each soil layer and sample across the study area. From the results, a non-linear, inverse relationship was observed between soil moisture content and electrical resistivity values which implies that higher water content enhances higher electrical conductivity and conversely lower resistivityof subsoil materials.A regression coefficient of 0.25 was obtained for the dominantly clay and silt soils, 0.36 for the clayey-silty sands, and 0.58 for the poorly graded sands. This indicates that the trend of soil resistivity values tends to be more predictable in soils with a lower percentage of moisture. Similarly, graphical plots of soil resistivity and plasticity index show fair to moderate correlation for the clays and clayey sands with a correlation coefficient of R^2 = 0.4513 and R^2 = 0.5182 respectively.The analysis also shows that soils with high plasticity index tend to clay and generally have higher values of natural moisture content and liquid limit. The established quantitative relationships can thus be used to complementsubsoil data acquired via conventional methods and for geotechnical appraisal of soil suitability before the construction of civil engineering projects in the study area.*

Keywords: *Geotechnical, geoelectrical, sounding, plasticity index, liquid limit*

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I. Introduction

A basic requirement prior to the construction of civil engineering projects like roads and buildings is a report of an accurate assessment of the underground material, its geotechnical quality, and general physical properties. The conventional method of boring for the determination of geotechnical properties such as moisture content, liquid limit, plasticity index, permeability, compressibility, and shear strength are invasive, expensive, and time-consuming [1,2]. They usually involve a long period of field acquisition by various methods and a long period of rigorous laboratory work. In addition, soil properties are subject to strong spatial and temporal variations. To this end, geophysical methods are sometimes used to complement geotechnical measurements for site investigations. The geophysical methods that suit such investigations are seismic refraction, electrical resistivity, and gravity prospecting [3]. Among these, those in view of the electric properties like the vertical electrical sounding (VES) technique, appear to be preferred. This is in light of the fact that soil materials and properties are emphatically corresponded and can be evaluated through their geoelectrical properties. Electrical resistivity surveys thus provide a non-destructive and less expensive way of assessing soil properties via the determination of reliable correlations obtained with laboratory test results.

Moisture content and plasticity index are important parameters that can be used as a guide for soil classification. The moisture content of a soil sample is defined as the mass of water in the sample expressed as a percentage of the oven-dried mass. Water is present in most naturally occurring soils and has a profound effect on soil behaviour. It is also used as a subsidiary to almost all other field and laboratory tests of soils. From literature, Atterberg limit results show that clay soils tend to have high plasticity indices. The addition of water to such soils may cause unusually large and frequent slope failures. Lower values of plasticity index of fine soil sediments suggest that the soils are more likely to be silt than clay. Soil with zero value of plasticity index is considered to have little or no clay and silt and is referred to as non-plastic. Clean sands are good examples of non-plastic soils. Generally, clays have low resistance to deformation when wet, but they dry to hard, cohesive masses. They are virtually impervious, difficult to compact when wet, and impossible to drain by ordinary means. Large expansion and contraction with changes in water content are characteristics of clays. The small size, flat shape, and mineral composition of clay particles combine to produce a material that is both compressible and plastic [4].

The resistivity of a geological material can vary significantly, depending on the lithology, porosity, water content, and the concentration of salts in its pore water [5]. Several attempts have been made by many researchers to explore the phenomenon of electrical resistivity in soils and its relationship with other soil properties such as water content, thermal resistivity, salinity, cation exchange capacity (CEC), and hydraulic conductivity. Electrical current flows in soil by electronic and electrolytic conduction. Some specific soil minerals usually metallic minerals conduct current through electronic conduction. However, conducting minerals rarely exists in sufficient quantity to have a considerable effect on the electrical properties of soil. Electrolytic conduction is mainly responsible for the flow of current in soils through the movement of ions in pore fluid. The quantity and quality of water in soil has a significant effect on electrical resistivity. According to [6], electrical resistivity decreases with increasing moisture content in soil and electronic conduction is more likely to occur in clayey soil than in sand. The chemical composition of water contained in pore spaces of soil material also affects resistivity. A higher concentration of dissolved ions in pore fluids facilitates the conduction of electric current thus reducing the resistivity. Resistivity of water may vary from 0.2 to over 100Ωm depending on its ionic concentration and the amount of dissolved solids. Resistivity of natural water and sediments without clay varies from 1 to 120Ωm [7].

The focus of this present study is to investigate the relationship between moisture content and plasticity index determined via laboratory analysis and bulk resistivity of soils obtained from geoelectric field survey so that the latter can be integrated into the routine appraisal of soil index properties.

II. Location of Study

The study area is located within the coastal region of the Niger Delta sedimentary basin. Geographically, it lies between latitudes 4^0 55'N and 5^0 51'N and longitudes 6^0 10'E and 6^0 25'E (Figure 1). A network of motorable roads exists within the study area that links the different investigation sites. A detailed geology of the area has been described by [8,9]. The tertiary section of the Niger Delta is divided into three formations Benin, Agbada, and Akata, representing prograding depositional facies distinguished mainly based on sand-shale ratio and further divided into depobelts as progradation proceeds into deeper waters.

The Benin formation is the water-bearing zone of the stratigraphic units. It is overlain by Quaternary deposits (40-150m) thick and generally consists of rapidly alternating sequences of sands and salty clay which becomes increasingly prominent seaward [10]. Generally, multi-aquifer systems have been identified in the Delta based on strata logs [11]. The average annual rainfall is about 2500 mm and this serves as the major source of groundwater recharge. The geomorphology of the area is monotonously flat and the regional slope is towards the south [12].

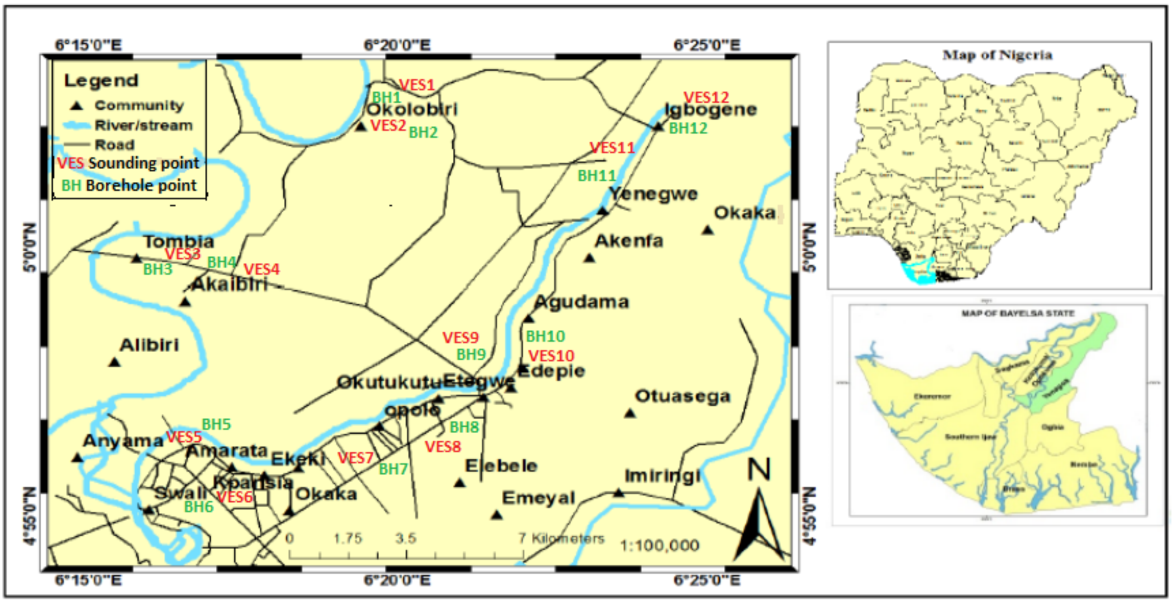

Figure 1: Map of the study area showing VES and borehole locations

III. Materials and Methods

The study methods include field geoelectric surveys, soil boring operations, and laboratory tests for soil characterization. Vertical electrical sounding (VES) using the Schlumberger array with current electrode half-spacings (AB/2) ranging between 50 and 150 m was conducted across the study area (Fig 1) with the ABEM SAS 1000 Terrameter. VES is a simple resistivity survey technique that provides one-dimensional resistivity values of sub-surface soil. Other equipments used for the 1D resistivity sounding include a D.C. power source, insulated wires, measuring tapes, and stainless steel electrodes. Electrodes were properly hammered into the ground to ensure firm contact. The process of measuring resistance values of the geomaterials materials was by injection of controlled current through two electrodes and measuring resulting potential difference by another pair of electrodes. The positions of the VES locations were also recorded during the survey with a GPS receiver. Apparent resistivity of the soil layers was evaluated as the product of the layer resistance and a geometric factor that depends on the particular electrode configuration deployed in the field survey. The true layer resistivity and depth of the soils were processed using the IP2WIN, 1-D inversion software. All depth interpretations were constrained with the lithological log data from the nearest borehole.

Soil boring was performed using a hand auger and manual percussion rig. Auger boring was conducted in 4 locations with depth limited to approximately 6m while percussion drilling was executed in 8 locations to a depth of 30m. The soil samples were secured in waterproof bags and brought to the laboratory for soil characterization tests. The tests performed on the samples include determination of moisture content, liquid limit, plastic limit, and grain size distribution using ASTM standard procedures [13,14]. The plasticity index of the cohesive soil samples was determined as the difference between the liquid limit and the plastic limit. Based on the analytical results the samples were subsequently classified using the Unified Soil Classification System (USCS).

IV. Results and Discussions

Fifty two soil samples were obtained from 12 boreholes and grouped into 3 categories denotedby the letters A, B, and C after laboratory determination of their geotechnical index properties. The categories were defined based on the USCS classification of the analysed samples. Group A, essentially comprised of soils that plot on the CH, MH, and CL sections of the Cassagrande plasticity chart and are basically fine-grained soil sediments. Samples that were classified as SC, SM, SC-SM, and SP-SM based on their geotechnical index results were categorised into Group B, while Group C, comprised of Poorly Graded Sands (SP). Figure 2 is a stacked column chart showing the average moisture content of each soil group across the boreholes, while figure 3 shows the Cassagrande plasticity chat of the soils.

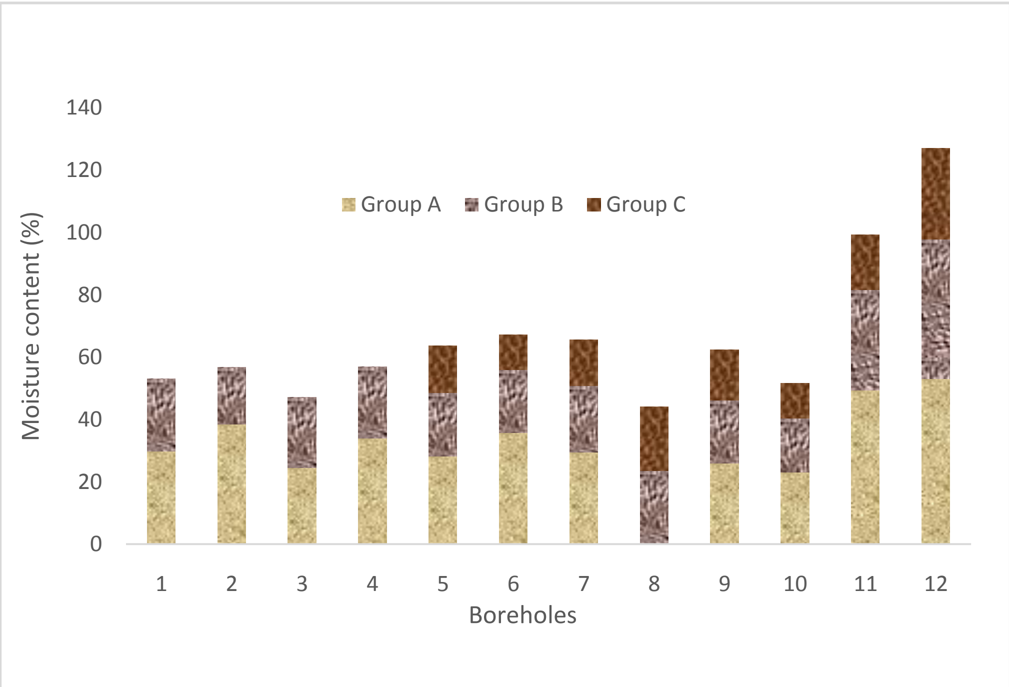

Figure 2: Stacked average moisture content across boreholes

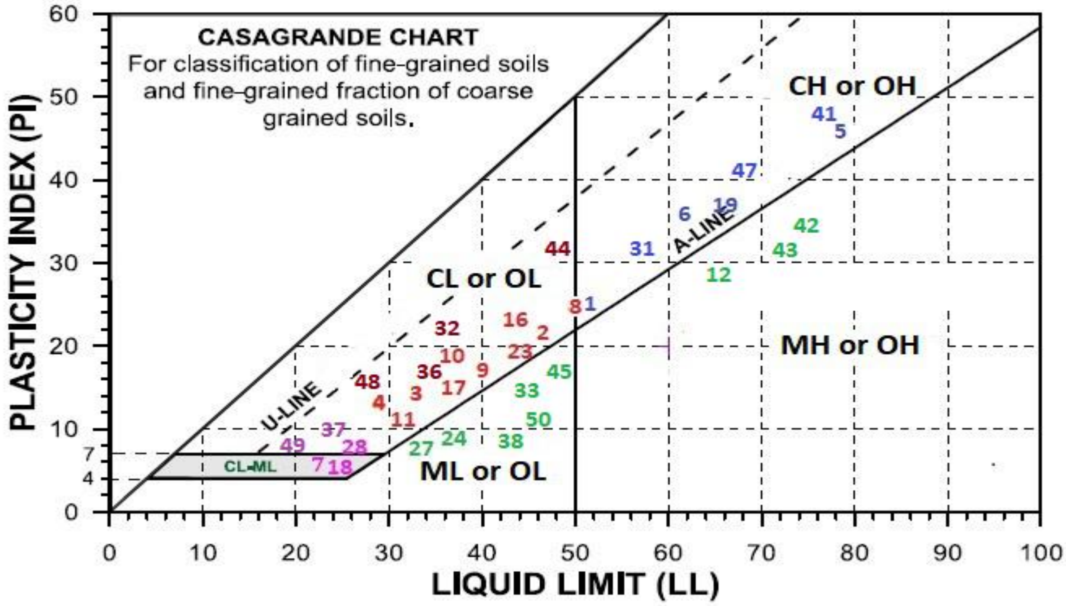

Figure 3: Plasticity versus liquid limit chat of soil samples

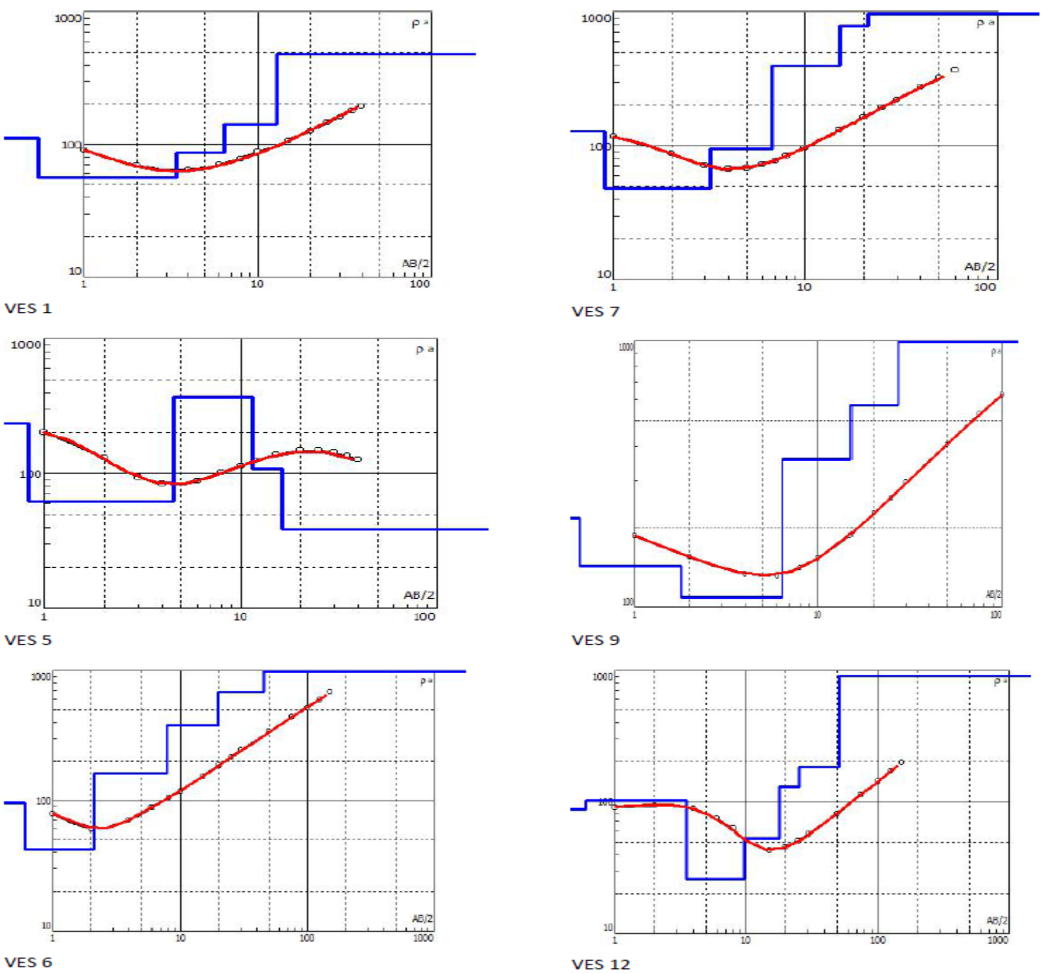

Figure 4: Resistivity curves of selected borehole locations

Twelve vertical electrical soundings were also conducted with electrode array centred close to each borehole locations. The modeled geoelectric curves showing true resistivity and depth of soil layers for selected investigation sites are presented in figure 4. The relationships between the geotechnical properties and the

resistivity of the subsoils were examined by plotting resistivity values against the moisture content and plasticity index determined for each soil layer and sample respectively in all the study locations.
Results of the correlation between layer resistivities of subsoils and moisture content are shown in figures 5 - 8, while results resistivity versus plasticity index of the fine-grained and cohesive soil samples are presented in figures 9 - 11.

Resistivity and Moisture Content

A non-linear, inverse relationship trend is observed between soil moisture content and soil electrical resistivity values obtained in the field. The observed correlations were variable with respect to location and soil sample category. Regression coefficients of R^2=0.25, R^2=0.36, and R^2=0.58 were obtained for groups A, B, and C respectively (figures 5 - 8). Generally, electrical resistivity increases with decreasing water content in soils.

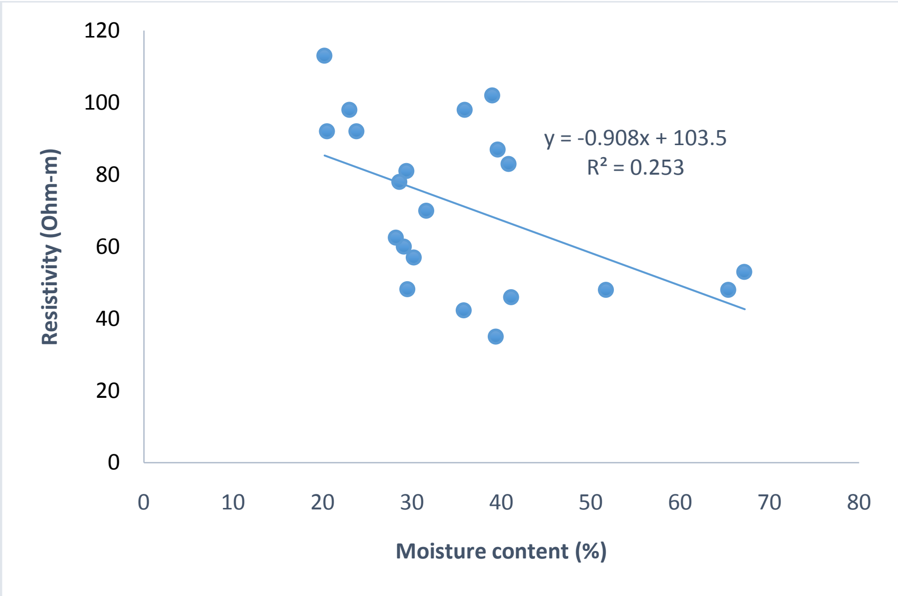

Figure 5: Relationship between resistivity and moisture content for Group A samples

Higher moisture content in soils facilitates the conduction of electrical current through the movement of ions in pore water. This implies that increasing water content will result in higher electrical conductivity and conversely lower resistivity values. Plots of resistivity against water content in this investigation (Table 1) shows that a greater correlation exists between resistivity and water content for sands without fines, while the least correlation is observed in the dominantly clay and silty soils.

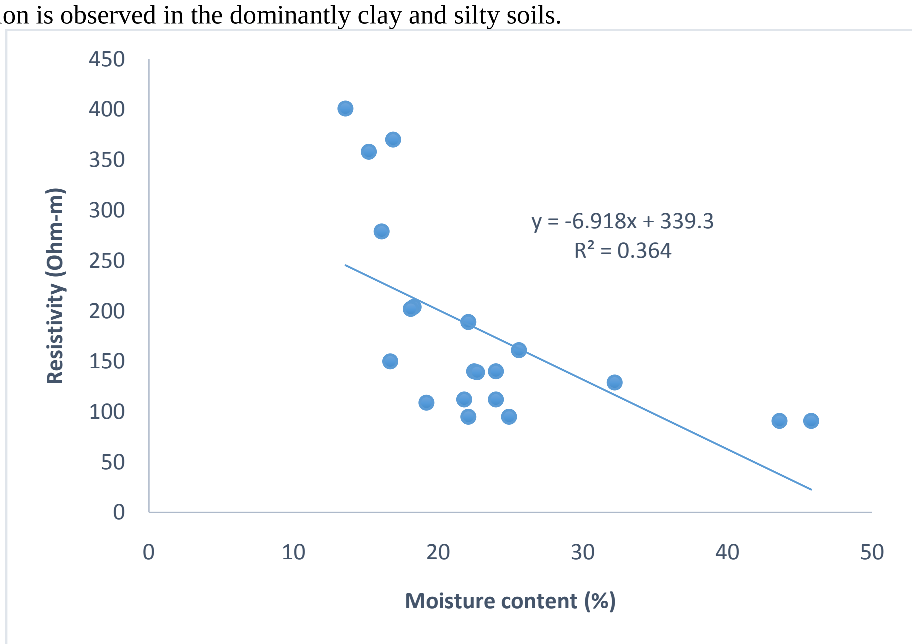

Figure 6: Relationship between resistivity and moisture content for Group B samples

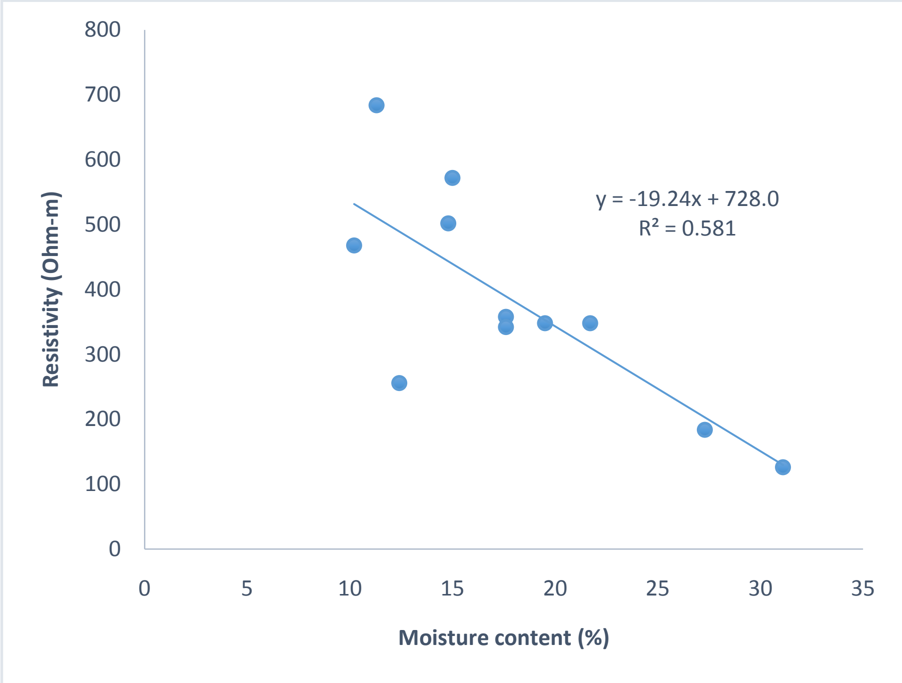

Figure 7: Relationship between resistivity and moisture content for Group C samples

The reason for the relatively higher correlation coefficient of the sands is due to their lower moisture content relative to clays. According to [15], at lower percentages, the effect of pore water content on resistivity is significant and shows a consistent trend, whereas, at higher moisture content, its effect on resistivity is less significant.

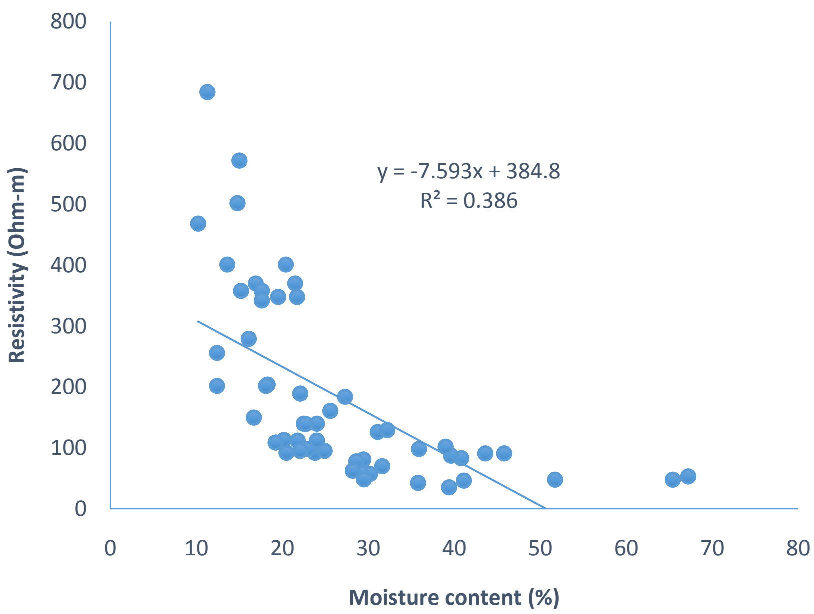

Figure 8: Relationship between resistivity and moisture content for all samples

Table 1: Quantitative relationship between resistivity and moisture content

Sample group	Empirical equation	Correlation coefficient
Group A	y = -0.9084x + 103.58	R^2 = 0.2537
Group B	y = -6.9182x + 339.34	R^2 = 0.3646
Group C	y = -19.245x + 728.01	R^2 = 0.5817
All samples	y = -7.5936x + 384.81	R^2 = 0.3861

Resistivity and Plasticity Limit:

Results of soil resistivity and plasticity index show fair to moderate correlation respectively for the clayey-silty (Group A) soil samples and those of Group B (clayey-silty sands). Correlation coefficients for Group A and B were evaluated to be R^2 = 0.4513 and R^2 = 0.5182 respectively. No correlation was established for the poorly sorted sand (Group C) samples since they are basically non-plastic soils. It can be seen that soils with high plasticity index tend to clay and generally have higher values of natural moisture content and liquid limit. The lower R^2 value for Group A relative to Group B could again be attributed to the non-linear relationship between resistivity and water content beyond approximately 25%, noting that plasticity index is a function of both clay and water content.

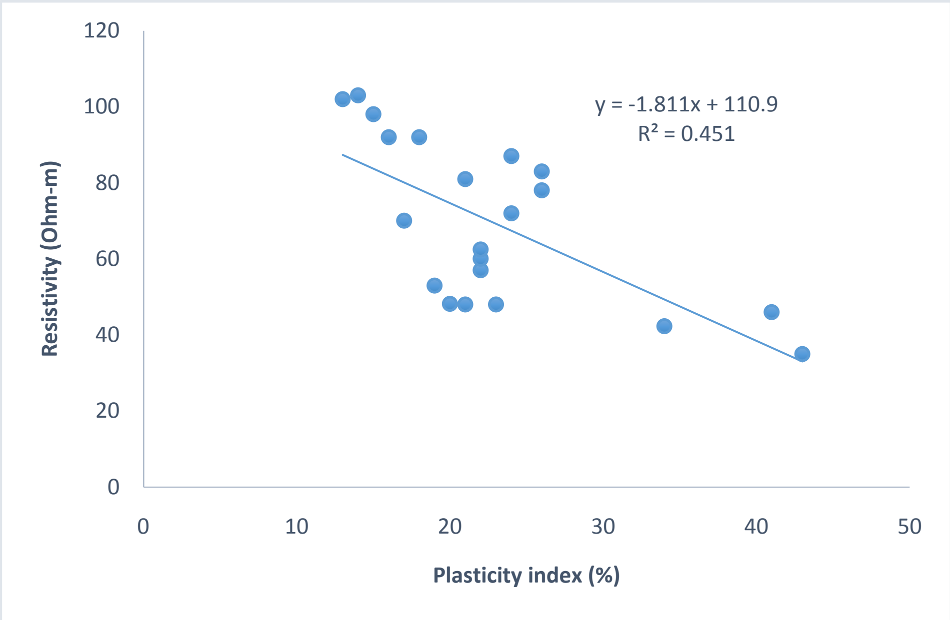

Figure 9: Plot of resistivity against plasticity index for Group A samples

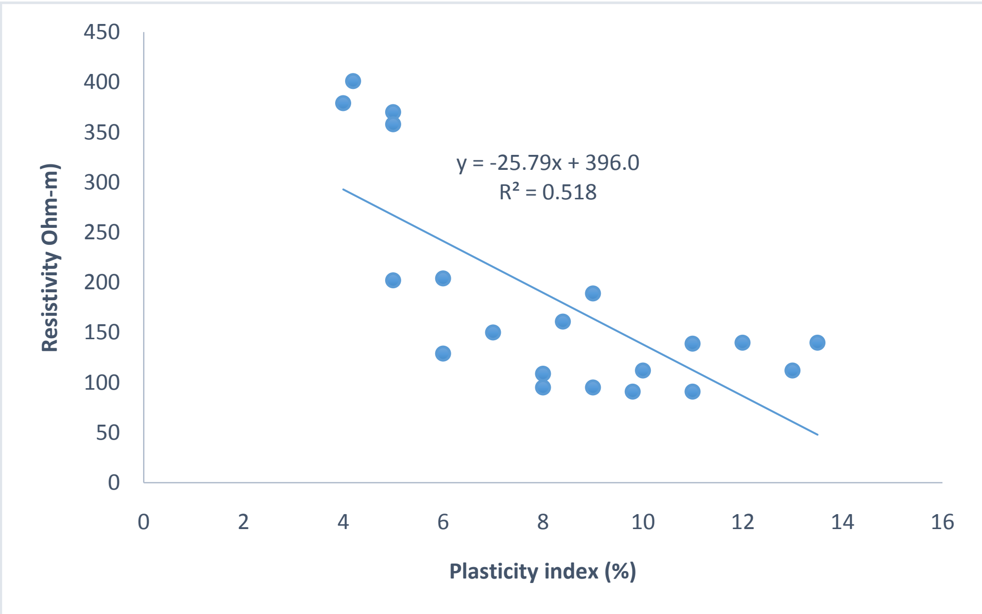

Figure 10: Plot of resistivity against plasticity index for Group B samples

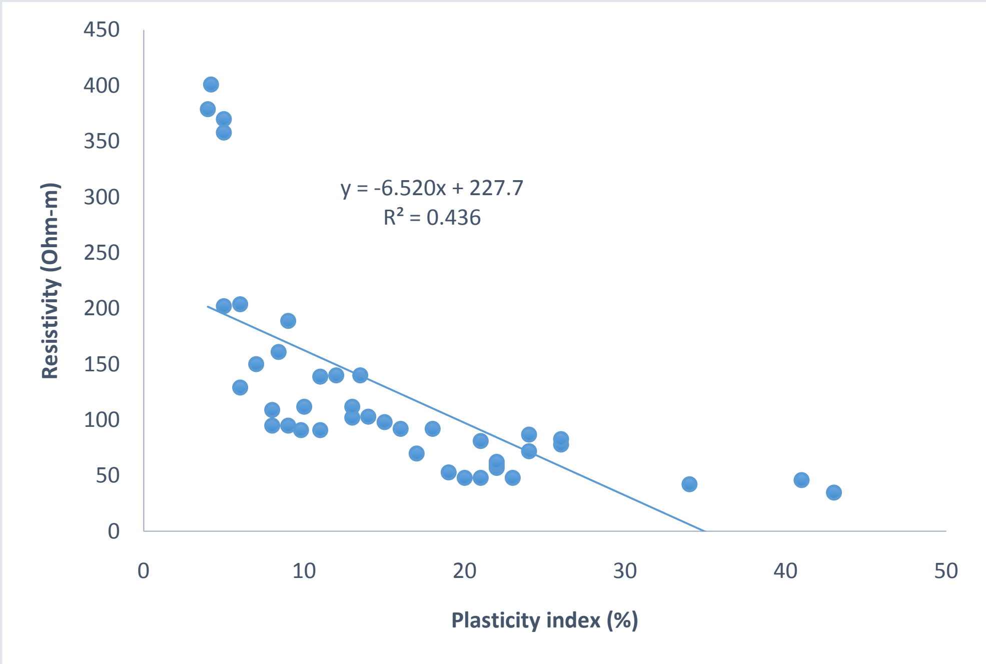

Figure 11: Plot of resistivity against plasticity index for Group A and B samples

Table 2: Quantitative relationship between resistivity and plasticity index

Sample group	Empirical equation	Correlation coefficient
Group A	y = -2.2818x + 119.63	R^2 = 0.5885
Group B	y = -20.348x + 336.98	R^2 = 0.4622
Group A + B	y = -7.0462x + 230.35	R^2 = 0.4797
Group C	Non-plastic	

V. Conclusion

The study has investigated the effect of moisture content and plasticity index on the value of electrical resistivity of soils with the intent of establishing a nexus for the use of the latter as a reliable means of acquiring data for routine soil investigations.A non-linear, inverse trend is observed between soil moisture content and soil electrical resistivity values obtained in the field. The results show a higher correlation for the poorly graded sands and least regression coefficient for the clay and silt category. Similarly, graphical plots of soil resistivity and plasticity index show fair to moderate correlation respectively for both the clays and silts and the clayey-silty sands with no correlation established for the poorly sands since they are basically non-plastic.The established quantitative relationship between resistivity with moisture content and plasticity index can be used to constrain field geoelectric measurements. This approach will ensure that the resistivity measurements are reliable enough to complement subsoil data acquired by other conventional means in the study area. However, a more cautious application of resistivity measurements in determination of soil properties in predominantly clay and silty layers is advised as their resistivity measurements above certain moisture content is less predictable.

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