Quest Journals
Journal of Research in Humanities and Social Science
Volume 13 ~ Issue 5 (May 2025) pp: 197-205
ISSN(Online):2321-9467
www.questjournals.org

Research Paper

Geoelectrical And Geotechnical Characterization of Oil Spill Areas in Agbura

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Abstract
Soil investigation and characterization within an oil spill location in Agbura was carried out via the conduct of vertical electrical sounding (VES) and geotechnical analysis in order to determine both lateral and vertical spread of the spill. The VES and boreholes were sited at specific positions with respect to the primary spill point and samples were collected at designated depths for physical examination, geotchnical appraisal and determination of the rate of infiltration. From the results, the resistivity values of the soil profile at the impact site shows that the first geolelectric layer had a high resistivity of 1558 Ohm-m and was composed of sandy clay based on laboratory tests. The second layer was clayey with resistivity of 679 Ohm-m. The third and fourth layers were fine - medium grained sands with resistivity values of 925 ohm-m and 1280 Ohm-m respectively. The unsually high resitivity values at the impact site comparative to the control site is attributed to the hydrocarbon content in the sediments. Further analysis of the geoelectric data show that resistivity values of VES sites within 150m downslope of the impact point were similar to resistivity values at the spill impact point, whereas VES sites within the same lateral distance upslope were comparatively lower and relatively similar to values obtained at the control site. From the geotechnical results, permeability values of the first and second layers of the soil based on Hazen and Kozney-Carmen empirical formulae ranges between 2.51×10^{-6} to 3.94×10^{-6} m/s and 2.26×10^{-6} to 4.14×10^{-6} m/s respectively, with an average of 3.11×10^{-6} m/s. while permeability based on Kozney-Carman formula ranged between. The permeability values indicate that the spill could infiltrate to an approximate depth of 3m within a period of 1 month. The occurrence of the clayey layers acted as natural barriers to the infiltration process, hence, most of the oil seem to be trapped in the second geoelectric layer (approximately 0.8 - 3.2m). Proactive measures should therefore be put in place to prevent incessant occurrence of oil spills, while rapid response to cases of spill is strongly advocated to mitigate widespread contamination.

Received 13 May., 2025; Revised 25 May., 2025; Accepted 27 May., 2025

I. INTRODUCTION

Environmental hazards resulting from oil spills, obstructs the maximum functioning of plants and animals and creates environmental states incompatible for a healthy living (Ugwu, et al., 2021). If not checked or effectively managed, spills from oil facilities can lead to total annihilation of the ecosystem. According to Oyem, 2001, life in the Niger Delta region is increasingly becoming unbearable due to the ugly effects of oil spills, and many communities continue to groan under the degrading impact of this menace.

The amount of pollution in the environment, has culminated in huge human and material losses, environmental degradation and poor air quality. Numerous studies have reported that soil and shallow groundwater in the area contain significantly high concentrations of hydrocarbon related contaminants (Nwankwoala & Mzaga, 2017). In addition, activities of oil and gas exploration raise a number of issues such as depletion of biodiversity, gas flaring, noise pollution, wastewater pollution, land degradation, soil fertility loss and deforestation, which are all major environmental issues.

Aquifer properties such as porosity, permeability, and hydraulic conductivity, control the infiltration and redistribution of oil spill within the subsurface (Abidoye & Wairagu, 2013). Incidentally, soil resistivity values are controlled by similar soil properties like texture, permeablity, fluid and matrix conductivity, and the presence of clay materials (Nwankwo & Emujakporue, 2012). Surface resistivity sounding technique can therefore be applied as a non-invasive, rapid, and cost effective tool in mapping and predicting the extent of contaminants distribution within the subsurface. Geophysical methods offer efficient process for characterizing hydrocarbon contaminant plumes in the subsurface. Hydrocarbons, often exhibit very high resistivity in natural environments but change to conductive behaviour with time due to biodegradation (bacterial activities and other biological processes) producing carbonic and organic acids, which contribute to enhancing the conductivities (Oki et al, 2015).

Porosity and permeability are two physical characteristics of soil/aquifers which control groundwater flow and contaminant transport mechanism. Porosity is the percentage of the volume of pores in a given soil divided by the total volume of the soil, while the permeability is a geologic property which refers to the ease with which a fluid can flow through the soil. It depends upon the porosity of the soil. Mathematically hydraulic conductivity (K) is:

$$K = k\,\rho g / \mu$$

Where k = intrinsic permeability of the medium, while ρ and μ are the density and dynamic viscosity of the flowing fluid respectively. Permeability is a direct function of average grain size distribution of granular porous media. Therefore, as the average grain size decreases from sand to clay, $k_{sand} > k_{silt} > k_{clay}$ (Oborie, et al, 2018). Permability determination can be done by different techniques such as pumping test of wells, constant head permeameter (CHP) and falling head permeameter (FHP) methods and calculations from empirical formulae (Todd and Mays, 2005). However, the field methods are limited for accurate estimation of hydraulic conductivity due to aquifer geometry and precise knowledge of hydraulic boundaries as well as the cost of well construction and operations (Uma, 1989). Alternatively, empirical formulae for estimating the permeability based on grain-size distribution characteristics have been developed and adopted in a number of studies. Grain-size distribution methods are comparably less expensive and do not depend on the geometry and hydraulic boundaries of the aquifer. Soil is often made up of grains of many different sizes and textures. Since pore size distribution is very difficult to determine, the potential alternative is the grain size distribution as a substitute which is easy to measure and used for the approximation of hydraulic properties and estimation of hydraulic conductivity (Oborie, et al, 2018). Several formulae have been established by many researchers and scientists based on experimental work using the hydraulic conductivity and grain size relationship, such as Hazen, Kozeny, Carman, Terzaghi, Shepherd, Alyamani and Sen (Alyamani and Sen 1993; Shepherd, 1989). The aim of this study is to map the extent of lateral migration and depth infiltration of hydrocarbons into the soil in the spill sections of the study area using geoelectrical sounding technique and geotechnical analysis.

II. LOCATION OF STUDY

Agbura is located within 15 kilometer radius of Yenagoa, the capital city of Bayelsa State Capital. It is geographical coordinates are between latitude 4°50' 30'' and 4° 52' 0'' N and longitude 6°15' 30'' and 6°17' 30'' E.

The study area is the host community of the 16” Nun River-Kolo creek BVS Riser - a pipeline transporting crude oil at Agbura-Otuokpoti in Yenagoa local government area of Bayelsa State. A number of oil spill incidents have been reported at various sections of the pipeline on different occasions over the years but no proper remediation or cleanup have been carried out in the area.

The area is generally a flat lowland plain characterized by tidal flats and coastal beaches, beach ridge barriers and floodplains. The broad plain is gentle-sloping and the elevation decreases downstream. The area has an average elevation of 5m above sea level. It is drained basically by the Ikoli creek, Epie creek and the Nun River.

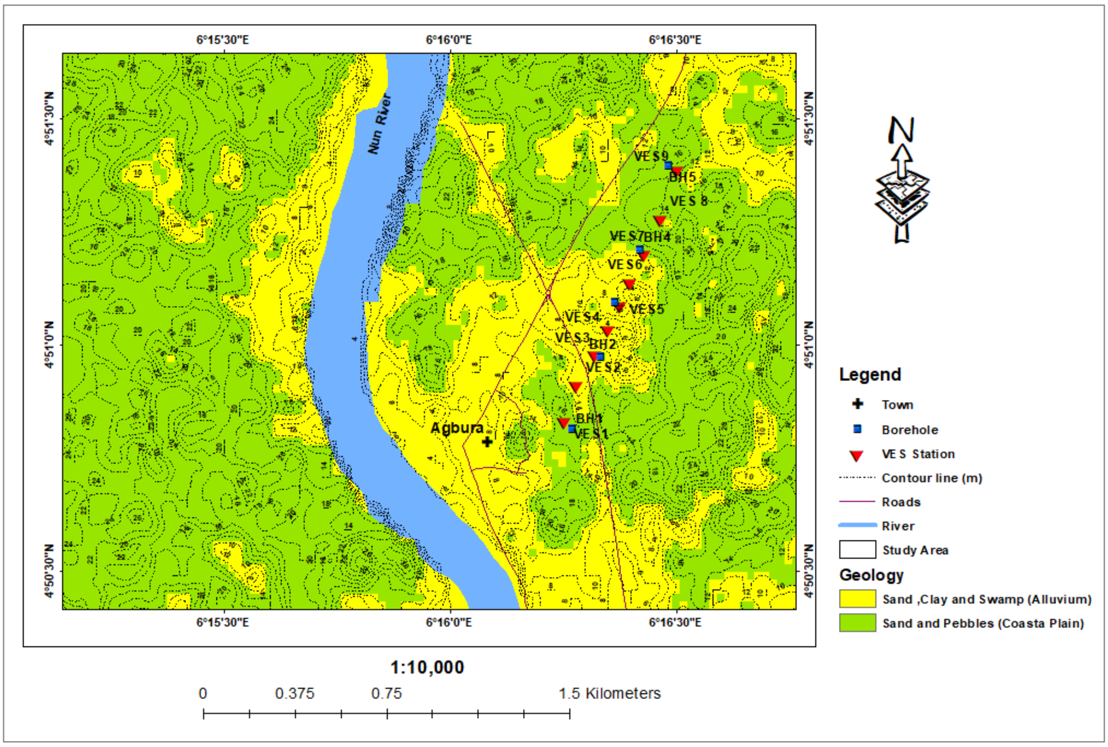

Figure 1: Borehole and VES locations within the study area

III. MATERIALS AND METHOD

Nine (9) Vertical electrical sounding (VES) using the Schlumberger electrode configuration were used in the investigation. The ABEM terrameter SAS 1000, a self-averaging digital device was used for the field operation. The potential electrodes were maintained at the same relative spacing, while the current electrodes are progressively expanded about a fixed central point. Consequently, readings are taken as the current reaches progressively greater depths. A computer aided modelling technique using IP2Win software was used for the data interpretation.

Soil borings (BH1- BH5) were executed to a depth of 6m from which samples were obtained using hand auger. The boreholes were positioned at specific points with respect to the primary point of impact (BH3) of the oil spill. BH1 and BH2 were located downslope at distances of 100m and 500m with respect to BH3, while BH4 and BH5 were sited upslope of BH3 at lateral distances of 100m and 500m respectively. Soil samples were collected at an interval of 0.5m for visual examination and laboratory analysis. The borings were carried out close to specific VES stations to enable correlation of the acquired data.

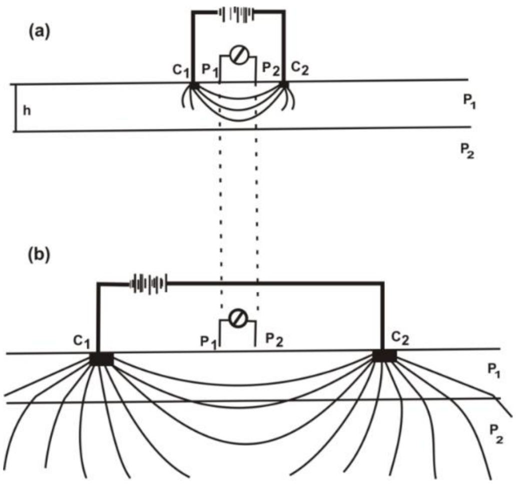

Figure 2: VES and Schlumberger configuration

Relationship between resistivity and plasticity index was analysed, while the derivatives of the grain size distribution of the soils were used in the determination of porosity and permeability using Hazen and kozney-Carmen empirical formulae (average taken as representative permeability).

IV. RESULTS AND DISCUSSION

Geoelectric sounding and data analysis

The results of the vertical electrical sounding (VES) data obtained from various locations in the study area showing the resistivity and thickness of the geoelectric layers are presented in Table 4.1, while the computer processed models for VES 1 and VES 9 are presented in Fig. 3.

Table 4.1: Geoelectric layer results in the study area

VES No.	Location	Thickness of layers (m)					Resistivity of layers (Ωm)					
		h_1	h_2	h_3	h_4	h_5	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6
1	VES1	0.6	1.9	3.7	5.5	11.9	106	78	124	192	401	1270
2	VES2	0.5	2.8	5.0	7.3	10.1	270	104	178	375	896	1464
3	VES3	0.5	3.6	6.1	9.6		964	535	209	461	1233	
4	VES4	0.7	2.7	5.6	10.7		1102	581	193	413	1368	
5	VES5	0.6	2.9	5.3	12.4		1584	769	325	680	2171	
6	VES6	0.4	3.3	6.1	11.7		127	85	190	321	986	
7	VES7	0.5	3.1	5.8	7.5		133	72	195	306	852	
8	VES8	0.6	3.3	7.6	12.1		128	84	170	287	713	
9	VES9	0.7	3.0	5.9	15.7		54	138	215	331	1005	

Discussion of geoelectric results

The oil spill in Agbura study area occurred at the VES 5 (BH3) location (Fig 1). The map of the study area also shows that VES 1- VES 4 were sited southwest of the reference/primary impact site (VES 5) location, while VES 6 - VES 9 are located northeast VES 5. Groundwater flow direction based on the calculated hydraulic heads at the borehole locations shows that although the slope of the flow is very gentle, VES 1-VES 4 are located downslope of the reference spill location, while VES 6 - VES 9 are situated upslope.

The geolectric data obtained from the VES survey and the soil profiles from the boreholes (Fig. 4.) were compared to determine the influence of the soil type, hydrocarbon content and distance from impact on the resistivity measurements.

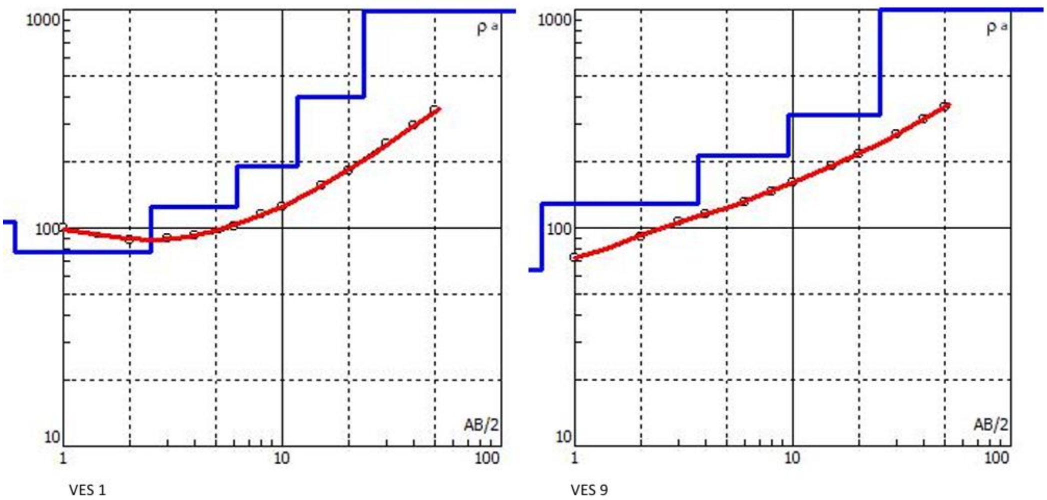

Figure 3: VES curve at stations 1 and 9

Resistivity values at the non-spill (control) sites

The configuration of the entire VES set up was such that VES 1 and 9 were situated 500m away from the impact site of the spill and served as control sites. VES 1 was positioned southwest (downslope) of the primary spill site (VES 5), while VES 9 was situated northeast (upslope) of the primary spill site. Correlation of the resistivity values and the lithologic composition of corresponding soil layers as determined from visual inspection and laboratory analysis of the samples recovered from the boreholes is presented in Fig. 4.

Fig. 4 shows that the non spill impacted soil profiles both downslope and upslope have similar resistivity values which were significantly different from resistivity values of soil at the spill location. Soil predominantly composed of clay and silt had resistivity values that were generally less than 90 Ohm-m. Resistivity values greater than 90 Ohm-m but less than or equal to 130 Ohm-m correspond to sandy clay soil samples. The third category of soil samples encountered at the non spill (control) sites were sands with some clayey/silty proportions. Their resisitivity values ranged between greater 130 Ohm-m and less than or equal to 180 Ohm-m. The fourth soil types were the non-plastic sands with resitivity values of greater 180 Ohm-m. These values compare favorably with geoelectric results of prestine, unconsolidated sediments as published by Okiongbo and Akpufure (2015), Oborie and Nwankwoala (2012).

Resistivity values at impact site (VES 5/BH3)

The resistivity values of the soil profile at the impact site shows that the topsoil was composed sandy clay but had a very high resistivity value of 1558 Ohm-m. The second layer was a clayey with resistivity of 679 Ohm-m. The third and fourth layers were fine - medium grain sands with resistivity values of 925 ohm-m and 1280 Ohm-m respectively. The unsually high resitivity values are attributed to the hydrocarbon content in the sediments. Hydrocarbons are poor conductors of electricity and therefore exhibit high resistivity when electric current is passed through them.

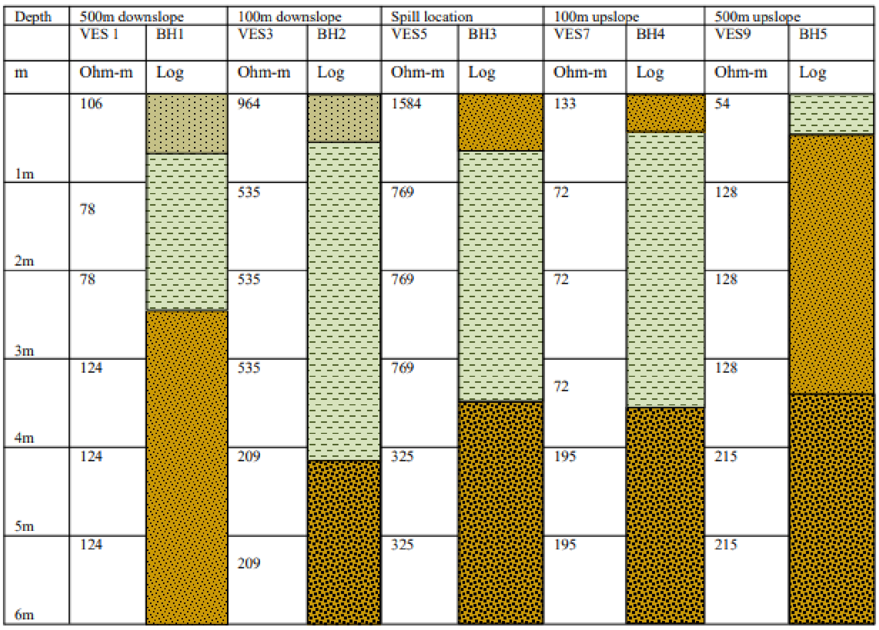

Fig 4: Correlation between VES and borehole logs in the study area

Resistivity values of soil profiles within 150m downslope of the impact site

The VES and borehole locations within 150m lateral distance (downslope) of the impact site include VES 4, VES 3 (BH2), and VES 2. VES 4 was located 50m away from the primary spill site, while VES 3 and VES 2 were located 100m and 150m from the primary spill site respectively. Visual examination of the soil samples within these locations showed that they contained variable amounts of oil which seemed to reduce with lateral distance from the impact site. Measured values of the geoelectric layers show that the first (top) layer had resistivity values of 270, 964, and 1102 Ohm-m at VES 2, VES 3 and VES 4 locations at depths of 0.5, 0.5 and 0.7m respectively. Geotechnical laboratory test results show that the top layer sediments of VES 2, VES 3 and VES 4 are lithologically characterised as clayey sand and sandy clay. A simple compasrison between the corresponding layer at the control sites shows that the resistivity values are significantly higher. This points to the fact that the resistivity is a function of not just the lithology but the composition of the contained fluid which in this case is oil.

The second layer resistivity values for the soil profiles in this category shows that resistivity range between 104 - 581 Ohm-m with an average thickness of 3.5m. Soil samples recovered from layer 2 of VES 3 (BH2) reveal that the samples are clays as per their lithology with visible hydrocarbon content, hence the elevated resistivity values which are not characteristic of prestine clay sediments. Layer 3 based on the geoelectric results show that resistivity ranged from 178 - 209 Ohm-m. The thickness of the layer ranged from 5.0 - 6.1m, bringing the average depth of this geoelectric layer to 9.2m approximately. Both visual and laboratory analysis shows that the lithology of the strata is fine - medium sand. However, the resistivity values of layer 3 is less than that of the overlying clay which must have trapped most of the percolating oil. Consequently, the unsual phenomenon of a clay layer exhibiting higher resistivity than sand within the same soil profile results. The resistivity values of both oil infiltrated soil layers and unaffected zones are presented in Fig 4.

Resistivity values of soil profiles within 150m upslope of the impact site

Three VES points and one borehole were located within 150m of the primary impact site (VES 5/BH3). The field survey points comprise VES 6, VES 7 (BH4) and VES 8. The top layer resistivity values for these VES locations range between 127 - 133 Ohm-m, having a thickness range of 0.4 - 0.6m. The second layer resistivity ranged between 72 - 85 Ohm-m with a thickness range of 3.3 - 4.0m, while the third geoelectric layer restivity was between 170 - 195 Ohm-m and had a thickness range of 5.8 - 7.6m. It is noteworthy to observe that the resistivity values in this sub-section of the study shows a sharp contrast with resistivity values obtained within the same lateral distance (150m) in the opposite (downslope) direction of the primary spill site. In addition, the values seem to correlate with resistivity values obtained at the control sites located 500m away from the impact site. This is attributed to the fluid flow direction which indicates that flow in the study area is from north east to southwest. Further implication of this observation is that boreholes, plants and other inhabitants of the ecosystem downslope of the impact point are more likely to be affected by the spill than ecosystems in the upslope positions.

Plasticity Index and Resistivity

The relationship between soil resistivity and plasticity index was determined by plots of resistivity values against plasticity indices under three categories (Figs. 5-7). Fig. 5 is a plot of resistivity against plasticity index in both spill impacted areas and unaffected areas. Figure 6 is a graph of resistivity against plasticity index in the non-spill impacted geoelectric layers, while Figure 7 shows resistivity against plasticity index of spill impacted geoelectric layers.

Incase case 1 the cluster zones are separated into 3 distinctively different segments with an overall very low, approximately zero correlation (R^2 = 0.0718), indicating that the factors controlling the resistivity are multidimensional. Three distinct zones were identified in the graphical plot of case 1. At the bottom of the graph is a zone in which resistivity is between 50-200 Ohm-m corresponding to soil samples in the zones unaffected by the spill or areas with negligible infiltration of oil spill. The 2nd zone has restivity values greater than 500 Ohm-m but less than 1000 Ohm-m, corresponding to samples infiltrated by the hydrocarbons in the second geoelectric layer at a depth between 0.8-3.2m as delineated by the geoelectric sounding results and laboratory analysis. The 3rd segment belong to samples within the topsoil and most impacted by the oil spill and within 100m downslope of the impact point. Resistivity of the samples in the 3rd segment range between greater than 1000 Ohm-m but less than 2000 Ohm-m. Coefficient of determination (R^2 = 0.7803) in Fig. 6 and (R^2 = 0.7031) in Fig 7. The results suggest lithology and the type of contained fluid significantly affects the resistivity, while the effect of plasticity is neglible in resistivity values of soils affected by oil spill.

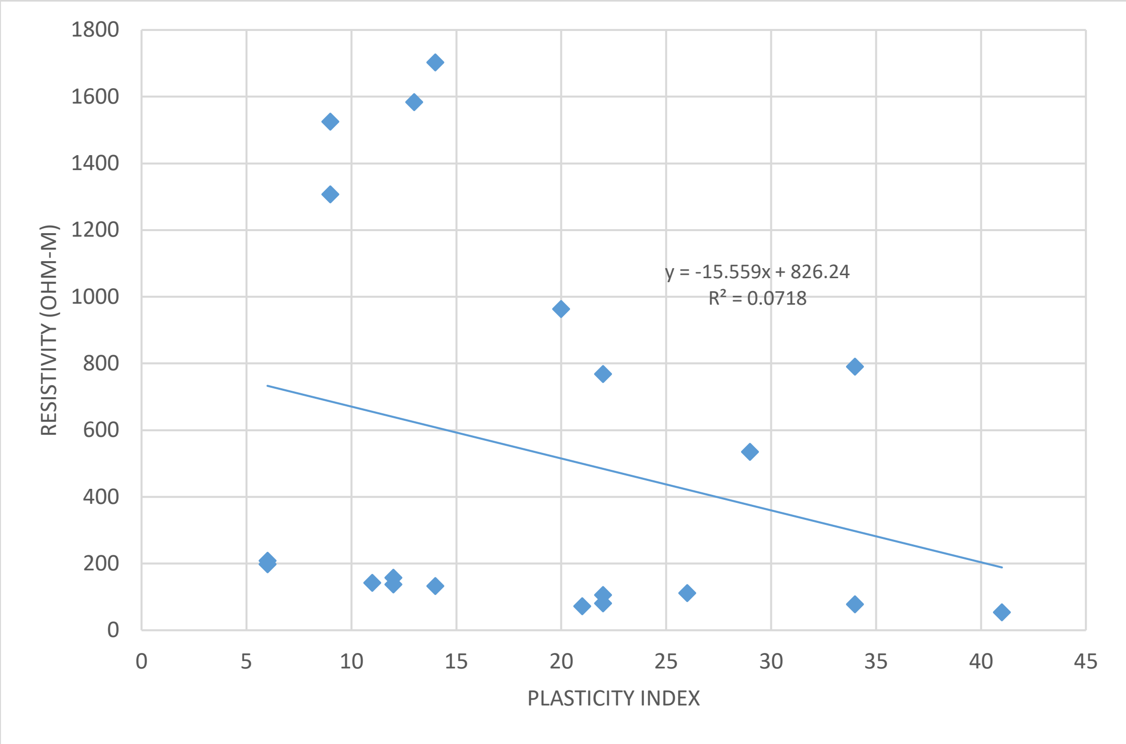

Figure 5: Resistivity against plasticity index in spill impacted and unaffected areas

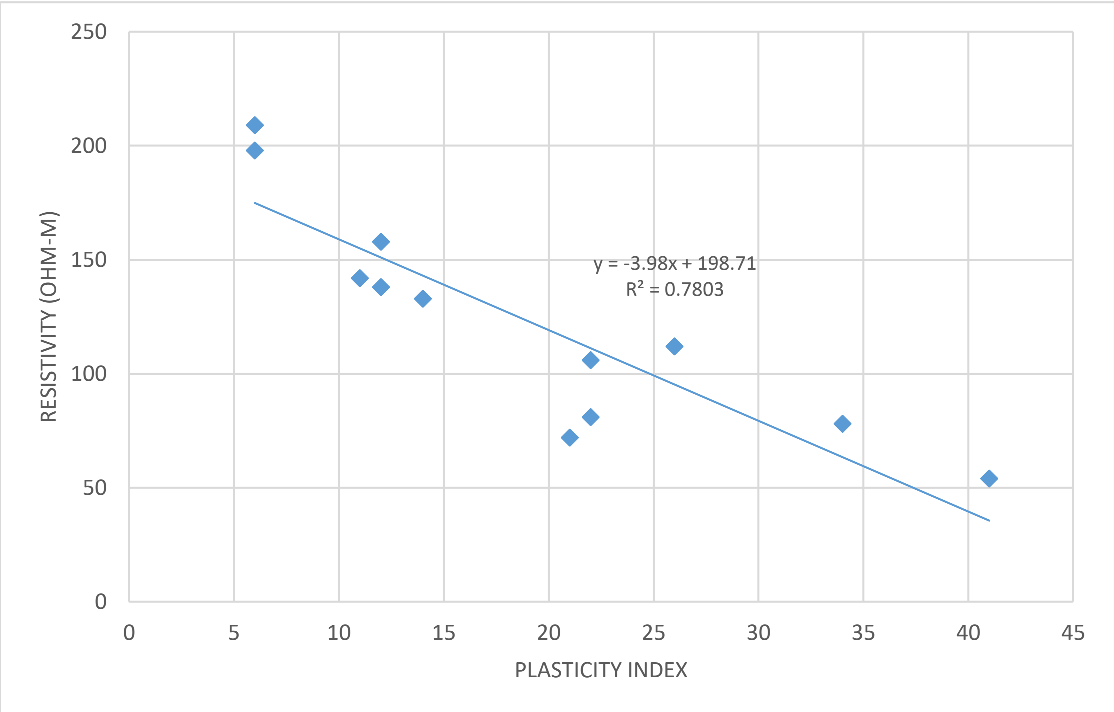

Figure 6: Resistivity against plasticity index of non-spill impacted geoelectric layers

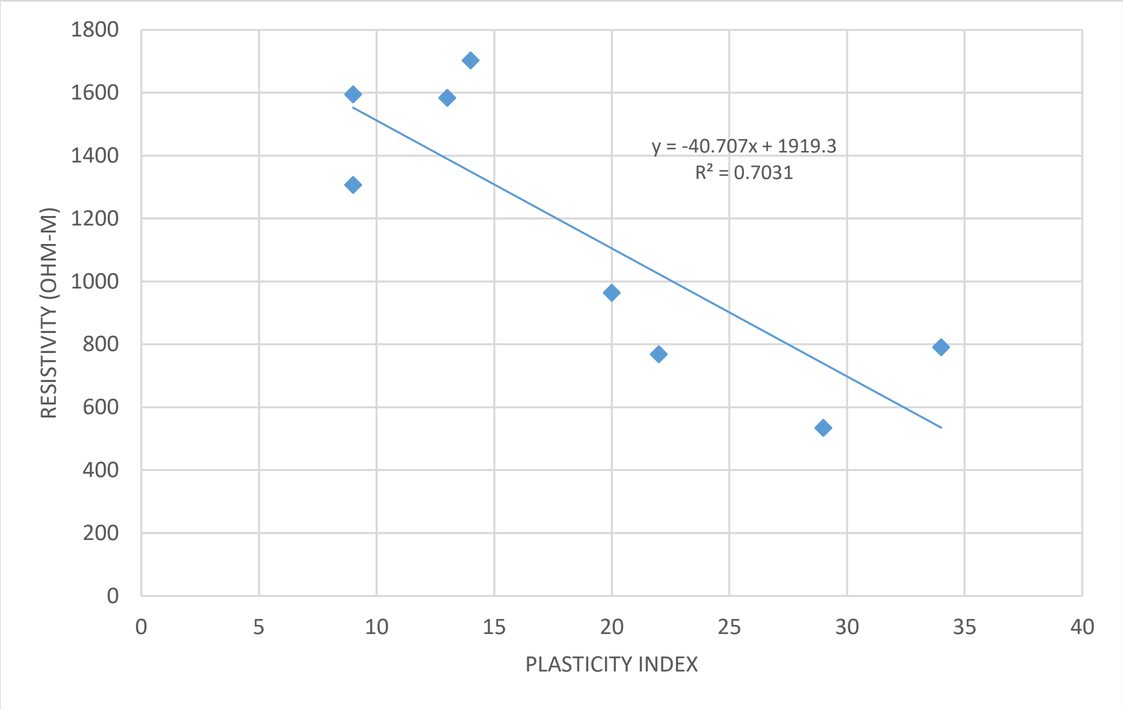

Figure 7: Resistivity against plasticity index of spill impacted geoelectric layers

Determination of Soil porosity and permeability

The Hazen and Kozeny-Carmen formulae for permeability (k) were chosen and used in this study because of their range of applicability, while porosity (n) was determined using Vukovic and Soro (1992) formula. The mathematical expression of the formulae are given below:

$n = 0.255\ (1+0.83^{u})$

$k_H = \quad 6 \times 10^{-4} \times [1 + 10\ (n - 0.26)]\ (d10)^2$

$k_{K\text{-}C} = 8.3 \times 10^{-3} \times [n^3 /(n - 1)^2]\ (d10)^2$

Where n = porosity and u = coefficient of uniformity
k_H - permeability based on Hazen's empirical formula
$k_{K\text{-}C}$ = permeability based on Kozeney-Carmen's empirical formula

Table 2 shows the coefficient of uniformity and coefficient of gradation derived from quantitative values of D_{10}, D_{30}, D_{60}.

Table 2: Derived geotechnical parameters

BH No.	D10	D30	D60	Cu	Cc
A3	0.044	0.08	O.18	3.8	1.4
A4	0.052	0.09	0.15	2.9	1.0
A10	0.046	0.07	0.15	3.3	0.7

The quantitative analysis of the grain size distribution was based on the determined grading characteristics such as d_{10}, d_{30}, and d_{60}. From these geometric values, the effective size, uniformity coefficient, and coefficient of gradation were derived. Uniformity coefficient (Cu) is equal to d_{60}/d_{10}. Soils with Cu less than or equal to 3 are considered to be "poorly graded" or "uniform". Coefficient of gradation (Cc) = $(d_{30})^2\ /(d_{60}\times d_{10})$. For well−graded soils, Cc is approximately equal to 1. The parameter d_{10} is referred to as the "effective size" of the soil. Empirically, d_{10} has been strongly correlated with the permeability of fine−grained sandy soils.

Table 3: Calculated values of permeability values using Hazen and Kozney fomulae

BH No.	n	Hazen (m/s)		Kozney-Carman (m/s)		Average	
A3	0.3806	0.00000251	2.51×10^{-6}	0.00000226	2.26×10^{-6}	0.00000239	2.38×10^{-6}
A4	0.4035	0.00000394	3.94×10^{-6}	0.00000414	4.14×10^{-6}	0.00000404	4.04×10^{-6}
A10	0.3929	0.00000293	2.93×10^{-6}	0.00000287	2.87×10^{-6}	0.00000290	2.90×10^{-6}

Using the Hazen formula, permeability results in Agbura ranged from 2.51×10^{-6} to 3.94×10^{-6} m/s, while permeability based on Kozney-Carman formula ranged between 2.26×10^{-6} to 4.14×10^{-6} m/s. Average permeabity values based on the two formulae across the study area is evaluated as 3.11×10^{-6} m/s. The permeability values indicate that the spilled oil could infiltrate to an approximate depth 3m within a period of 1 month. The evaluated depth of infiltration are also evident from visual inspection and laboratory analysis of the recovered soil samples which show oil soaked sediments to depth of 3.2m in the study area.

V. CONCLUSION

The study has successfully delineated the extent of the lateral migration and depth of oil infiltration into the soil in Agbura via the conduct of geoelectrical sounding and geotechnical investigation. The VES results show that the non spill impacted soil profiles both downslope and upslope have similar resistivity values which were significantly different from resistivity values of soil at the spill location. Unsually high resitivity values were recorded at the spill impact sites.

The calculated permeability values of the upper layers of the soil profile indicated that the spill could potentially infiltrate to an approximate depth of 3m within a period of 30 days. The predominance of less permeable near surface silty and clayey sediments impeded the downward transport mechanism, hence most of the oil seem to be trapped in the second geoelectric layer across the study area. (approximately 0.8 - 3.2m).
Proximity to the spill site, depth of sampling and flow direction with respect to the position of the contaminant's source were seen as the most critical factors which affected the soil resistivity/quality in this study. Proactive measures should be put in place to prevent incessant occurrence of oil spills, while rapid response to cases of spill is strongly advocated to mitigate widespread contamination of soil and water resources of the study area.

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