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Assessment of Soil Homogeneity using Geoelectrical Diametrix in Layered and Weathered Rocks

Tamunoene K.S. Abam* Ferdinand D Giadom+ Robert Egwu Otu Iduma++ and Ifeyinwa L Nwankwo.**
*Institute of Geosciences and Environmental Management
Rivers State University of Science and Technology, P.M.B. 5080, Port-Harcourt, Nigeria
+ Department of Geology, University of PortHarcourt, Choba-PortHarcourt, Nigeria
++Department of Surveying and Geoinformatics, Akanu Ibiam Federal Polytechnic, Unwana, Ebonyi State, Nigeria
** Groundscan Services Nigeria Limited, Lydia Abam Lane, Trans-Amadi Industrial Layout, Port-Harcourt, Nigeria

Abstract:- This paper explores the use of diametrically aligned vertical electric sounding VES in assessing homogeneity and anisotropy in layered sedimentary soils and in weathered rock formation. Both Wenner and schlumberger electrode configurations were used in the sedimentary and weathered rock formation respectively, and augmented by geotechnical boring to 30m. The Mann-Whitney U-test was applied to the diametrically aligned VES data where the presence of significant differences between the data sets suggested degrees of uniformity in ground resistivity and by extension compositional quality and structure. Similarly, characteristic values of electrical resistivity in diametrically opposite directions of the geo-layers were determined and compared. By evaluating the differences in apparent resistivity at the same depth, a measure of homogeneity was derived. Various degrees of homogeneity were established at both the sedimentary and weathered formation.

I. INTRODUCTION

Spatial variability in soil type and properties is a natural consequence of the geologic processes of sedimentation and rock formation. In sedimentary areas, the energy of the depositional environment to a large extent determines the soil type, uniformity in grain sizes and homogeneity of the soil (Pettijohn 1965). Inhomogeneity within the same soil type can occur due to differences in composition and microstructure. Techniques, such as Ground Penetrating Radar have been developed to explore the sub-soil (Arcone, et al 1998a &b), however some have argued that the technique is more suited for detecting buried objects with significant structural and density contrasts (Hussain et al 2020).

The Resistivity technique has also been used for characterizing the sub-surface materials in terms of their electrical properties (Maciej Maślakowski et al 2014). Variations in electrical resistivity typically correlate with variations in lithology, water saturation, fluid conductivity, porosity and permeability, which may be used to map stratigraphic units, geological structure, sinkholes, fractures and groundwater. For this reason, resistivity techniques have not only used to identify soil types and determine properties of underlying soils needed for the design of suitable foundations, they have also provide needed data for the installation of optimum cathodic protection systems (Banton, et al 1997 and Mazac, et al 1990), where geoelectric resistivity surveys assess the aggressivity of soil/water, corrosion potential and assist with information for cathodic protection of buried steel components (Keller and Frischnecht; 1970, Beck; 1981).

Advanced applications of electrical resistivity methods as in ERT calibrated with lithologs have successfully modeled geologic cross-sections. According to (Qinbo Cheng et al 2019, Muhammad Hasan et al 2021), ERT interpretations, supported by borehole data or alternate geophysical data, accurately represent the geometry and lithology and/or hydrology and/or petrology of subsurface geologic formations.

Although geo electrical resistivity procedures of profiling and depth sounding capture spatial and vertical heterogeneities, the idea to investigate heterogeinity and anisotropy is novel. Consequently, this study is intended to explore the use of geoelectrical diametrix as a means to assessing heterogeneity and anisotropy.

II. METHOD OF STUDY

The acquisition of resistivity data involves the injection of current into the ground via a pair of electrodes and then the resulting potential field is measured by a corresponding pair of potential electrodes. The field set-up requires the deployment of an array of regularly spaced electrodes, which are connected to a central control unit via multi-core cables. Resistivity data are then recorded via complex combinations of current and potential electrode pairs to build up a pseudo cross-section of apparent resistivity beneath the survey line. The depth of investigation depends on the electrode separation and geometry, with greater electrode separations yielding bulk resistivity measurements from greater depths.

In this case, resistivity was measured by passing a current of known value into the ground (C_1 C_2) and measuring the induced potential difference between two intermediate points in the ground using another set of electrodes (P_1, P_2). The mean ground resistivity measured comprised essentially that between the voltage electrodes (P_1, P_2) up to a depth (ID) equal to about $^1/_3$rd of the distance between C_1 and C_2 (total electrode spread) and a width equal to about $^2/_3$rd of the distance C_1 and C_2. As the electrode spread (C_1, C_2) increases, depth of probe increases, thereby, giving a vertical electrical sounding, VES. The equivalent soil resistivity, ρ , was calculated using the relationship derived from ohms law(Burger, 1992).

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$\rho = \pi.Ra\,(^b/_a + b^2/a^2)$

Where R = resistance value read on by the resistivity – meter (Ω)

a = distance between both inner pins (m)
b = distance between inner and outer pins (m)
ρ = average resistivity (Ωm) of an equivalent soil layer which depth is equal to 75% of the distance between the inner and outer electrodes (0.756)

Temperature corrections are usually applied in cases where ambient soil temperature is greater or less that 18°C using the formula:

$$\rho t = \frac{\rho}{1 + Xo\,(To - T)}$$

Where:
ρt = average resistivity at 18°C (Ωm)
ρ = average resistivity at the soil temperature (Ωm)
T_o = reference temperature, 18oC
T = actual soil temperature (°C)
X_o = Correction coefficient 0.02 for t > 18°C and 0.03

for t < 18°C

Two measurements were taken perpendicular to each other in two (x , y) directions at each test point. The, mean resistivity of the top layer (r^o_{1m}) and the mean resistivity of the subsoil (r^o_{2m}) were computed and used to determine the thickness (LTH) and average depth (LD) of the geological strata.

Mean resistivity of top layer (r^o_{1m}) was obtained with the following relation (Burger, 1992) :

$$r^o_{1m} = \frac{\sum^n_1 r^o_i}{n} \quad \text{(ohm.m)}$$

$$X_k = X_m(1 - K_n \times COV)$$

Where :

n = number of test points
r^o_i = mean value of the two values measured along the two directixes in the point I, given in (ohm.m).

Mean resistivity of subsoil layer (r^o_{2m}) was computed with the following relation :

$$\mathbf{r^o_{2m} = \frac{\sum^n_1 r^o_{2i}}{n} \quad (ohm.m)}$$

Where :

n = number of test points

r^o_{2i} = mean resistivity of subsoil in measurement point I, given in (ohm.m).

The thickness (LTH) and depth (LD) of Geological Strata were determined at every instance of change in strata in the subsurface as indicated by the apparent resistivity curve.

Relating the value of LTH and LD at maximum test point (MID) to the mean resistivity, r^o_{2m} , we have :

$$r^o_{2m} = \frac{\sum^n_1 r^o_L\,.\,LTH\,(MID^2 - LD^2)}{\sum^n_1 LTH\,(MID^2 - LD^2)} \quad \text{(ohm.m)}$$

Where :

r^o_L = resistivity of every geological stratum (ohm.m)
LTH = thickness of every geological stratum (m)

Where: LD = average depth of each stratum (m)
MID = maximum test depth (m)

At each test centre point geotechnical borings were made and lithologs obtained for comparison with the predicted geo-electric ground models from the VES.

The apparent resistivity values for both diametrical alignments were subjected to Mann-Whitney U test, which evaluated the significant difference between the two data sets. Since the Mann-Whitney U test is non-parametric, it is not restricted by any assumptions about the nature of the data sets (Ebdon 1985). The value of the U-test is obtained from the relationship:

$$U_x = n_x n_y + n_x(n_x+1)/2 - r_x$$

Where n_x and n_y are the number of the data points in each direction, while r_x is the ranking of the data points. A low value of U is produced when there is a large difference between the data sets.

The characteristic values of the soil apparent resistivity was obtained as cautious estimation of the variation of the mean value, standard deviation of the test results. The equation adopted was as proposed by Schneider (1999):

Where:
X_k = Characteristic value of the soil parameter

X_m = Arithmetical mean value of the soil parameter = $\frac{\sum X}{n}$

COV = Coefficient of variation = $\frac{S}{X_m}$

S= Standard deviation

$= \frac{\sum(X - X_m)^{1/2}}{(n-1)^{1/2}}$

K_n = Statistical coefficient = 0.5

III. RESULTS AND DISCUSSIONS

The lithostratigraphy for Akri and Oguta, two locations, 5km apart within the sedimentary environment of the Niger delta are presented in Fig. 1. The lithostrats in both locations are well correlated, except that Akri is on a slightly higher elevation, being closer to the levees of the Niger River system.

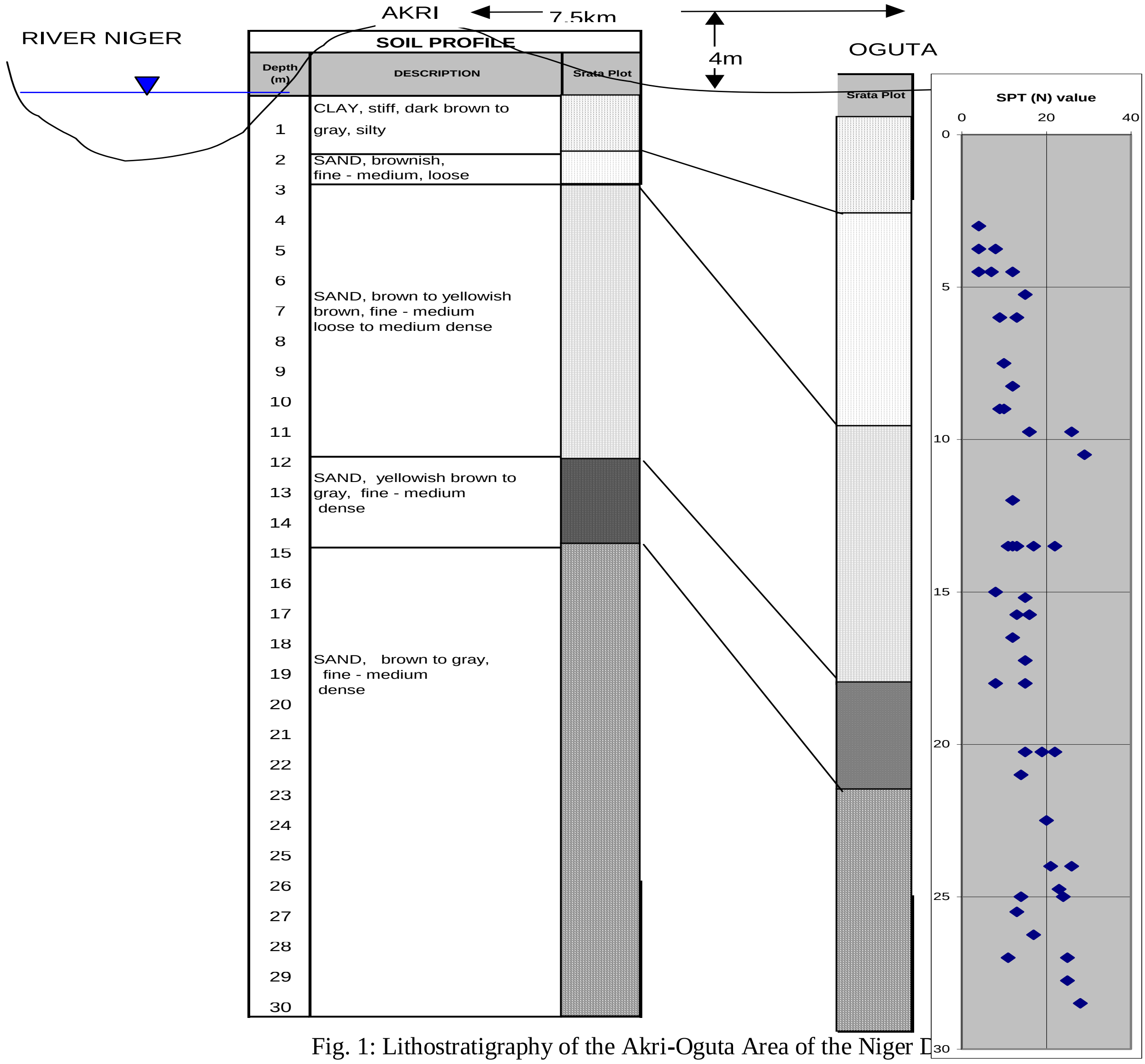

Fig. 1: Lithostratigraphy of the Akri-Oguta Area of the Niger D

The relative densities, indicated by the SPT(N) values of the various sand units show that they are mostly loose to medium dense (Tomlinson, 1999). The results of four diametrically aligned VES executed at Akri and Oguta respectively are shown in Tables 1 and 2. The result revealed a spatial variation of the subsurface resistivity across the area. This spatial distribution of the subsurface resistivity follows the heterogeneous distribution of certain influencing factors. This influencing factors includes; hydrochemical and lithological/soil changes the presence of sulphate reducing bacteria (SRB).

Table 1: Field Data For The Sub Soil Electric Resistivity Measurement For Oguta

LOCATION :	CPT 3 Area		BH 2 Area		CPT 4 Area		CPT 5 Area	
ELECTRODE	R^1_X	R^1_Y	R^2_X	R^2_Y	R^3_X	R^3_Y	R^4_X	R^4_Y
SPACING (m)	(ohm)	(ohm)	(ohm)	(ohm)	(ohm)	(ohm)	(ohm)	(ohm)
1	8.35	7.94	7.054	7.21	8.131	8.31	7.04	6.08
3	3.45	2.94	3.505	3.67	2.23	2.34	2.11	2.02
5	2.45	2.51	2.302	2.13	1.918	1.76	1.04	1.15
10	1.54	1.48	1.571	1.71	0.978	1.04	0.67	0.51
15	1.041	1.012	1.0519	0.91	0.486	0.42	0.34	0.31

Table 2: Field Data For The Sub Soil Electric Resistivity Measurement For Akri:

LOCATION :	**BH 4 Area**		**BH 3 Area**		**BH 5 Area**		**CPT 2 Area**	
ELECTRODE	R^1_X	R^1_Y	R^2_X	R^2_Y	R^3_X	R^3_Y	R^4_X	R^4_Y
SPACING (m)	(ohm)	(ohm)	(ohm)	(ohm)	(ohm)	(ohm)	(ohm)	(ohm)
1	33.8	31.72	22.26	23.2	562.94	517.8	287.8	291.1
3	2.595	4.87	24.2497	20.1	56.796	72.1	210.17	198.5
5	18.88	19.11	24.248	24.8	81.938	79.3	87.766	81.52
10	15.195	17.7	16.597	17.16	25.58	21.6	22.261	25.41
15	15.88	14.3	12.396	10.81	71.879	58.7	69.581	58.28

The corresponding resistivity values indicate a moderate soil resistivity that ranges between 40 ohm–m and 6000 ohm-m.

The apparent resistivity curves based on Zohdy (1989) and geo-electric ground models derived from Reynolds (1998) for only two cases, derived from these measurements are presented in Figs 2 and 3 for illustrative purposes. Comparison of the geo-electric ground models and the lithostratigraphy show strong agreement to the extent permitted by the depth of probe. At Oguta, the bulk of the soil resistivity profile are within the range 40 – 100Ωm (corrosive to moderately corrosive). The soil type includes the upper wet silty clay and lower saturated fine sand. The lowest resistivity was encountered at VES 4 (CPT5 Position). This section is wet, with clayey top soil, and water level less than 0.8m below ground level.

At Akri a significant number of the soil resistivity measurements are within the slightly corrosive range (120 - 6000Ωm) as indicated in Figs (2 and 3). The soil type includes the upper dry silty sand and lower saturated fine sand. The lowest resistivity was encountered at VES 1 and VES 2 corresponding to BH4 and BH3 positions with a resistivity range of 120 – 1400 Ωm. This area has a dry top soil, with sandy top soil, and groundwater level of about 1.8 to 2.2m below ground level.

Generally, Soil resistivity changes dramatically with moisture content it is expected that the soil resistivity values measured shall substantially increase when it is dry with other parameter (pH, chemical content) remaining the same. Swamp area showed a relatively acidic soil condition, which can lead to intensive local corrosion such as pitting and stress corrosion.

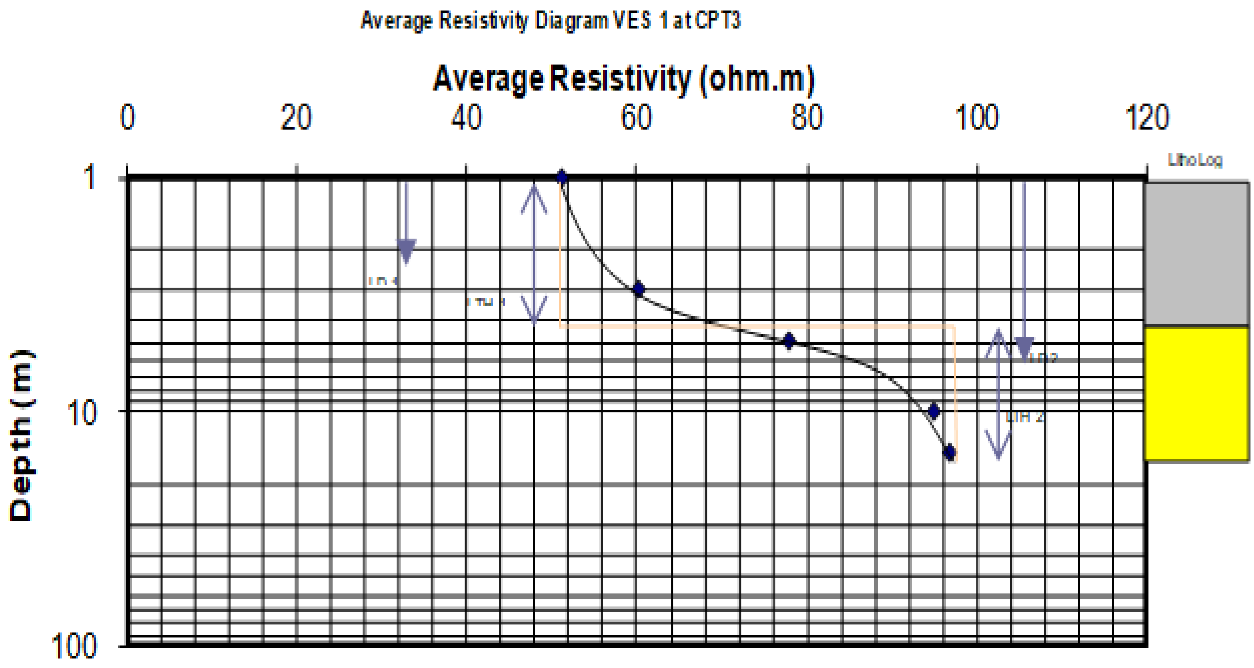

Fig. 2: Geo-electric ground model of VES1 at CPT3 location at Oguta

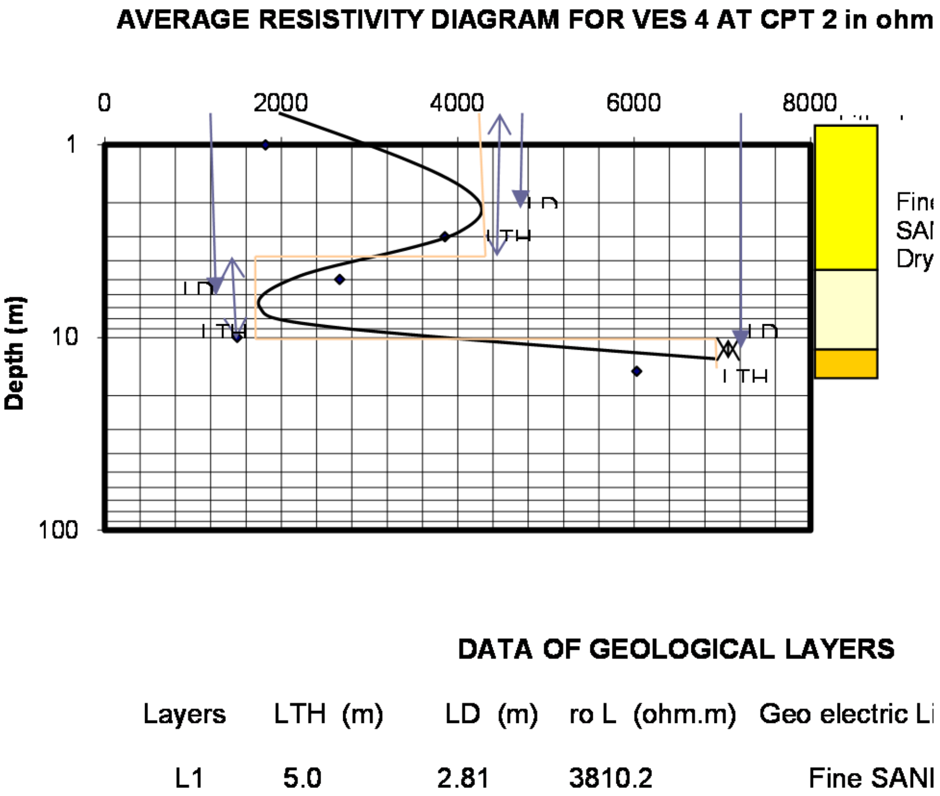

Fig. 3: Geo-electric ground model of VES1 at CPT3 location at Akri

In order to investigate heterogeneity and possible anisotropy, the Mann Whitney U-test was performed. The computation of Mann Whitney U-test which is illustrated in Tables 3 and 4, ranged from 11 to 14, while U for the apparent resistivity measurements for Oguta ranged from 11 to 13. In both cases, the U values are within the limits where the spatial differences in resistivity are considered significant at 95% confidence level. The presence of significant differences between the data sets suggest a small degree of uniformity in composition and structure.

Table 3: Mann Whitney U Computation for Oguta

LOCATION :	CPT 3 Area		BH 2 Area		CPT 4 Area		CPT 5 Area	
ELECTRODE SPACING (m)	Ranking Rx	Ranking Ry	Ranking Rx	Ranking Ry	Ranking Rx	Ranking Ry	Ranking Rx	Ranking Ry
1	10	9	9	10	9	10	10	9
3	8	7	7	8	7	8	8	7
5	5	6	6	5	6	5	5	6
10	4	3	3	4	3	4	4	3
15	2	1	2	1	2	1	2	1
Sum of Ranks	29	26	27	28	27	28	29	26
U	11	14	13	12	13	12	11	14

Table 4: Mann Whitney U Computation for Akri

LOCATION :	CPT 3 Area		BH 2 Area		CPT 4 Area		CPT 5 Area	
Depth of Probe (m)	Ranking Rx	Ranking Ry	Ranking Rx	Ranking Ry	Ranking Rx	Ranking Ry	Ranking Rx	Ranking Ry
1	10	9	6	7	10	9	9	10
3	1	2	9	5	3	6	8	7
5	7	8	8	10	8	7	6	5
10	5	6	3	4	2	1	1	2
15	4	3	2	1	5	4	4	3
Sum of Ranks	27	28	28	27	28	27	28	27
U	13	12	12	13	12	13	12	13

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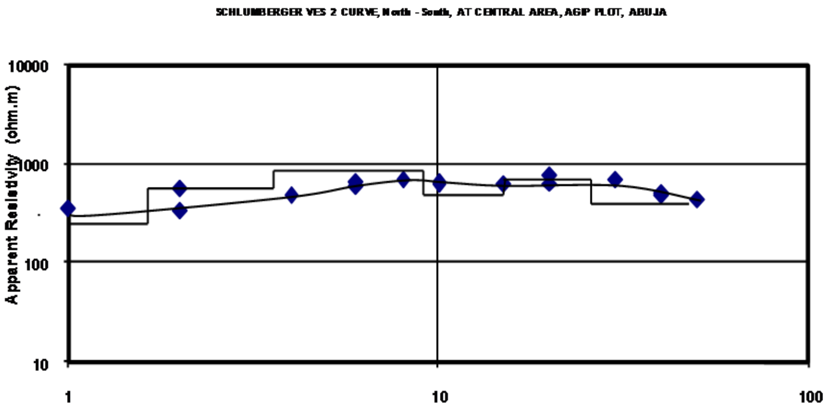
Results of another set of diametrically aligned resistivity measurements in a weathered hard rock terrain in Abuja, Nigeria are presented in Fig. 4 and 5. The apparent resistivity values which are typical of weathered hard rock terrains range from 335 to 800 Ωm. The corresponding composite weathered soil profile revealed in the geotechnical boring is shown in Fig.6.

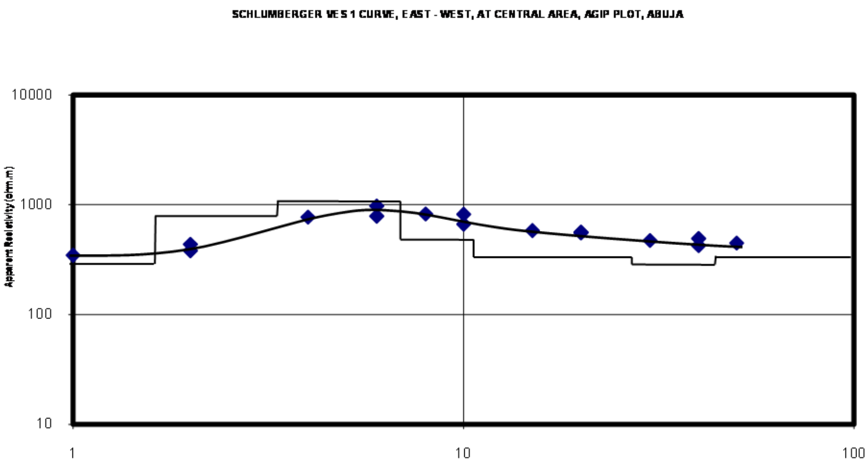


Data (File) name :	R00018.S4K	DAB/2 (m)	03-04-07
Project name:	Geotechnical soil Investigation	Direction lay out:	N - S
Code name:	VES 2	Client :	NAOC
Location:	Central Area, Agip Plot, Abuja.	Schlumberger:	O'Neill

AB/2 (m)	Rho (Ohmm)	AB/2 (m)	Rho (Ohm.m)	AB/2 (m)	Rho (Ohm.m)	AB/2 (m)	Rho (Ohm.m)	
1.0	335.6		60 0	656.1		100	631.8	30.0
584.7								
2.0	572.1		600	601.7		15.0	637.2	40.0
453.1								
2.0	337.1		800	689.4		20.0	644.6	40.0
483.0								
4.0	481.5		10.0	667.4		20.0	613.4	50.0
445.3								

Resistivity (Ohm.m)	Depth (m)
335.646	0.80
454.609	1.30
481.487	2.70
628.898	4.00

Fig. 4: Geo-electric soil data for Direction X at Abuja site



Data (File) name :	R00018.S4K	Date : AB/2 (m)	03-04-07
Project name:	Geotechnical soil Investigation	Direction lay out:	E - W
Code name:	VES 1	Client :	NAOC
Location:	Central Area, Agip Plot, Abuja.	Schlumberger:	O'Neill

AB/2 (m)	Rho (Ohm.m)	AB/2 (m)	Rho (Ohm.m)	AB/2 (m)	Rho (Ohm.m)	AB/2 (m)	Rho (Ohm.m)	
1.0	346.2		6.0 0	976.4		10.0	665.2	30.0
473.5								
2.0	437.0		6.00	784.2		15.0	581.0	40.0
424.9								
2.0	381.2		8.00	825.8		20.0	561.9	40.0
490.8								
4.0	772.5		10.0	818.1		20.0	555.0	50.0
448.5								

Resistivity (Ohm.m)	Depth (m)
346.153	0.80
409.140	1.30
772.497	2.70
880.331	4.00
825.769	5.30
741.638	6.70

Fig. 5: Geo-electric soil data for Direction Y at Abuja site

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The computed Mann Whitney U coefficient (Table 5) gave a value between 127 and 129, which when compared to the significance level, indicated no significant differences in the apparent resistivity measurements. This relatively high U-value is suggestive of a high degree of uniformity in the weathered soil profile.

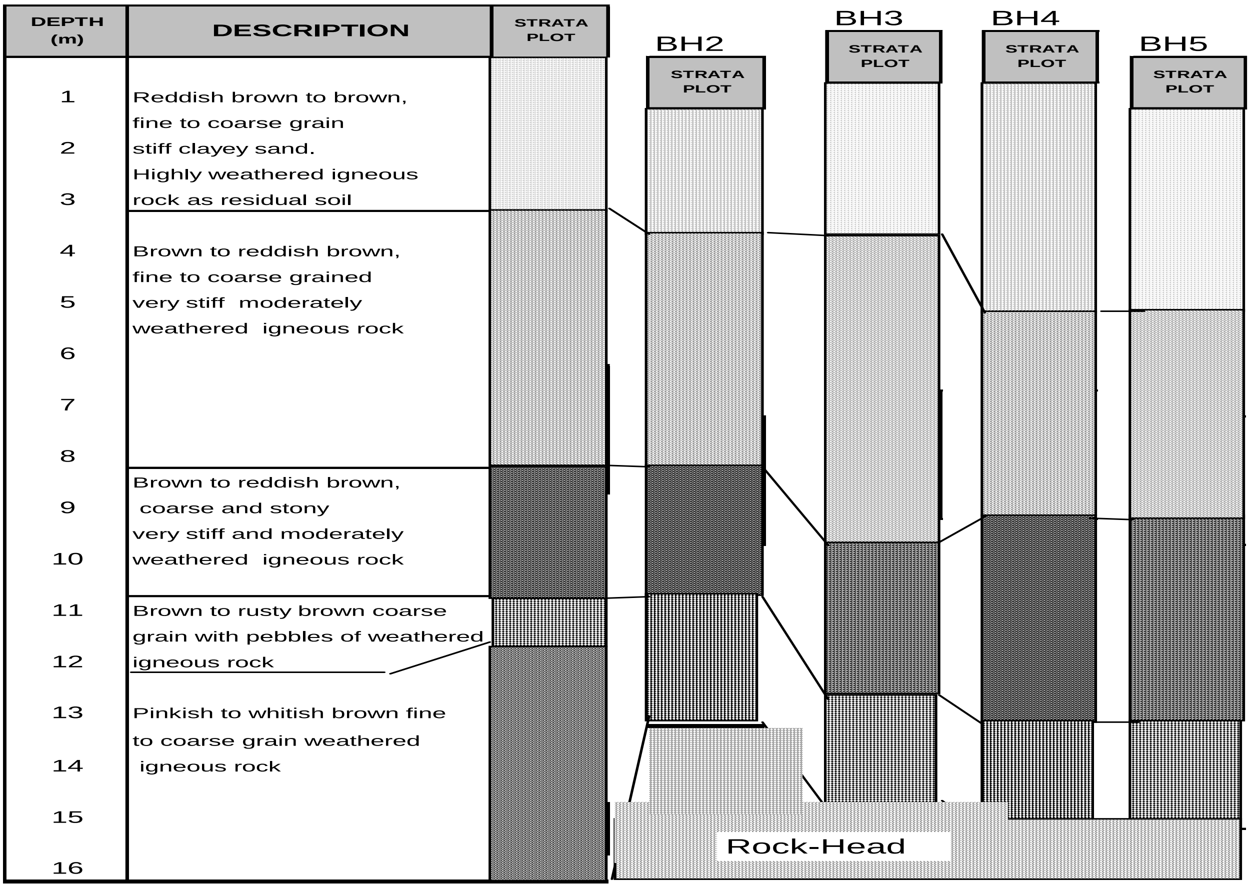

Fig. 6: Composite Soil Profile at a Weathered rock area in Abuja, Nigeria

Table 5: Mann Whitney U Computation for Abuja

Depth of Probe (m)	Resistivity-1	Ranking-1	Ranking-2	Resistivity-2
0.8	346	2	3	356
1.3	437	6	16	572
1.3	381	4	1	337
2.7	772	28	10	481
4	976	32	22	656
4	784	29	18	602
5.3	826	31	25.5	689
6.7	818	30	24	667
6.7	665	23	19	632
10	581	17	20	637
13.3	562	15	21	645
13.3	555	14	27	764
20	473	9	25.5	689
26.7	425	5	13	515
26.7	491	12	11	483
33.3	449	8	7	445
Sum of Rankings		265	263	
Man Whitney U-value		127	129	

The diametrix resistivity was further subjected to another test of similarity using the characteristic values of the geoelectric layers after Eurocode 7. In using the characteristic value, four test points each were considered in Oguta and Akri in the Niger delta (Table 6 and 7).

Table 6: Computation of characteristic for geoelectric layers in Oguta

OGUTA	**Soil type**	**Parameters**							
		Oguta	Test1	Oguta	Test2	Oguta	Test3	Oguta	Test4
		R^1_X	R^1_Y	R^2_X	R^2_Y	R^3_X	R^3_Y	R^4_X	R^4_Y
Max. Electrode		8.35	7.94	7.05	7.21	8.13	8.31	7.04	6.08
Spread	Layered	3.45	2.94	3.51	3.67	2.23	2.34	2.11	2.02
	Sediments	2.45	2.51	2.30	2.13	1.92	1.76	1.04	1.15
		1.54	1.48	1.57	1.71	0.98	1.04	0.67	0.51
		1.04	1.01	1.05	0.91	0.49	0.42	0.34	0.31
Xm		3.37	3.18	3.10	3.13	2.75	2.77	2.24	2.01
S		2.93	2.77	2.40	2.49	3.09	3.18	2.76	2.37
COV		0.87	0.87	0.77	0.80	1.12	1.15	1.23	1.18
Xk		1.90	1.79	1.90	1.88	1.20	1.18	0.86	0.83

Table 7: Computation of characteristic for geoelectric layers in Akri

AKRI	**Soil type**	**Parameters**							
		Akri	Test1	Akri	Test2	Akri	Test3	Akri	Test4
		R^1_X	R^1_Y	R^2_X	R^2_Y	R^3_X	R^3_Y	R^4_X	R^4_Y
Max. Electrode		33.80	31.72	22.26	23.20	562.94	517.80	287.80	291.10
Spread	Layered	2.60	4.87	24.25	20.10	56.80	72.10	210.17	198.50
	Sediments	18.88	19.11	24.25	24.80	81.94	79.30	87.77	81.52
		15.20	17.70	16.60	17.16	25.58	21.60	22.26	25.41
		15.88	14.30	12.40	10.81	71.88	58.70	69.58	58.28
Xm		17.27	17.54	19.95	19.21	159.83	149.90	135.52	130.96
S		11.15	9.68	5.26	5.54	226.35	206.86	109.79	110.76
COV		0.65	0.55	0.26	0.29	1.42	1.38	0.81	0.85
Xk		11.69	12.70	17.32	16.44	46.65	46.47	80.62	75.58

As with the Man Whitney test, the characteristic values in each of the four cases show slight differences reflecting some degree of heterogeneity.

IV. CONCLUSION

This study concludes that by diametrically aligning VES Resistivity the sounding uniformity of ground conditions at a site can be assessed. The Mann-Whitney U-test as well as the characteristic value can both serve as veritable tools for the quantitative assessment of heterogeneity in site conditions. The qualification of the heterogeneity in subsoil ground conditions imply that ground condition can be differentiated and categorized using the Mann-Whitney U-test and by determining the characteristic values of geolayers and can by extension be integrated into geotechnical and geophysical mapping and classification methods.

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