Adewuyi and Philips, J Geol Geophys 2018, 8:1
DOI: 10.4172/2381-8719.1000453

Journal of Geology & Geophysics
ISSN: 2381-8719

Research Article Open Access

Integrated Geophysical and Geotechnical Methods for Pre-Foundation Investigations

Ibrahim Adewuyi O[1] and Falae Philips O[2]*

[1]*Department of Geology, University of Ibadan, Ibadan, Nigeria*
[2]*Geotechnical Engineering Group, CSIR-Central Building Research Institute, Roorkee, India*

Abstract

An integrated geophysical and geotechnical investigation for a proposed building foundation of an industrial plant layout was carried out to determine the competency of the subsoil as foundation materials. Electrical Resistivity Imaging (ERI) and soil analyses techniques were adopted. Two traverses of four Vertical Electrical Sounding (VES) points were carried out and 8 Boreholes for Standard Penetration Test (SPT) were drilled. In addition soil samples were taken at 1.5 m and 10 m depths and subjected to various laboratory analyses. Three geoelectric layers were delineated from VES including topsoil, saturated sandy clay soil and limestone. The SPT N value indicates that the relative density of the soils is medium dense to very dense while the result of the geotechnical analyses shows that maximum dry density of the soils range from 1680-1900 kg/m^3 and 1600-1850 kg/m^3 respectively at 1.5 m and 10 m while the optimum moisture content range from 14-19% and 13-19% respectively at 1.5 m and 10 m. The soils are silty sand with low plasticity depiting low to medium swelling potential. Conclusively, the subsurface on which the foundation of the industrial structures will be located within the study area is safe and fairly competent for any engineering work. Owning to the water lodge nature of the area it is advice that the building should rest on pill between 5 m and 10 m depth.

Keywords: Foundation; VES; Geotechnical; Geoelectric layer, Pill

Introduction

The suitability of soils for engineering purposes depends largely on their ability to remain in place and to support either permanent or transient loads that may be placed on them [1]. A foundation is an integral part of a structure that transmits the weight of the structure to the soil underneath it. However, when the soil below does not possess the required geotechnical properties, construction problems arises which ultimately affects the structure [2,3]. Hence, site investigations are conducted to discover the characteristics of the soil at the particular location to determine their ability to support structures emplaced on them [4,5]. Often, existing civil and other engineering structures are located over anomalous subsurface zones which are significantly incompetent to bear the load of the structures. Soupios [6], Oyedele [7] noted that in recent times, failure of building structures has increased incessantly all over Nigeria and has thus become a source of serious concern for building engineers.

When failure of any structural element occurs, many factors are often responsible for it which includes: (i) improper foundation investigation, (ii) poor building design, (iii) poor materials and (iv) inexperience of the handler as the case maybe. So it's important for a precise determination of engineering properties of soil to ensure proper design and successful construction of any structure [8]. The conventional methods such as boring, pitting and trenching [9,10] for the determination of these engineering properties (Density, porosity, permeability, moisture content, Consistency, compressibility, Shear strength [11-15] are invasive, costly and time-consuming which include a long time in acquiring samples on the field by various field methods as well as a long period of rigorous laboratory work in the determination of the basic geotechnical parameters. Soil properties are subjected to high spatial and temporal variations. For an accurate assessment of soil properties, high-density sampling will be required. However, borehole sampling can be very costly and time-consuming in such conditions [9,16].

In many instances, geophysical methods enhance the reliability and speed, and also reduce the cost of a geotechnical investigation [17]. Assessing and characterizing geotechnical conditions can become complex and costly in the presence of obstacles such as difficult access, irregular terrain and ground conditions, or regulatory constraints. Results based on traditional methods such as penetration testing or direct sampling may be of limited utility [18]. Surface geophysical techniques can provide an alternate, wide-area methods for subsurface characterization and information regarding relevant material properties [19-21]. Though geophysics is not a substitute for geotechnical boring or testing, it is often a very cost-effective and efficient means of constructing continuous 2D and 3D images of the subsurface and determining in-situ bulk properties [17]. The electrical resistivity of material can be reduced by subsoil porosity and moisture contents. Therefore, the need to understand the use of electrical resistivity as indices to define subsoil competence and their engineering characterises [9,22-24].

Different site investigation methods has been employed by various scholars including Cone penetration Test, Standard penetration test, trenching and laboratory analysis of samples [6,7,10,25-32]. However they were not able to address fully the use of electrical resistivity as non-invasive method.

In this study, a non-destructive, cost-effective and rapid measurement of soil electrical properties geophysical technique involving Vertical Electrical Sounding (VES) using Schlumberger array was adopted to investigate the subsurface conditions [28,33-39] alongside with boring of holes to carry out the Standard Penetration Test (SPT) [6,32,40-43]

***Corresponding author:** Falae Philips O, Geotechnical Engineering Group, CSIR-Central Building Research Institute, Tel: +91 7895428093; E-mail: philomo08@gmail.com

Received November 06, 2018; **Accepted** December 18, 2018; **Published** December 25, 2018

Citation: Adewuyi OI, Philips OF (2018) Integrated Geophysical and Geotechnical Methods for Pre-Foundation Investigations. J Geol Geophys 8: 453. doi: 10.4172/2381-8719.1000453

and collections of samples for geotechnical properties of the samples at a proposed industrial building site in Ibese, southwestern Nigeria. In addition, reliable correlations between electrical resistivity and other soil properties will be utilized in order to characterize the subsurface soil with the aim of determining the competence of the subsurface layer which will carry the structure.

Study Area

Ibese town is about 14 km North of Ilaro town, in Yewa North Local government of Ogun state, southwestern Nigeria (Figure 1). The study area, with relatively flat to a gentle slope terrain falls within the Dahomey Basin which is a combination of inland, coastal, offshore basin that stretches from south-eastern Ghana through Togo and the Republic of Benin to southwestern Nigeria. It is separated from the Niger Delta by a subsurface basement high referred to as the Okitipupa Ridge [44-46].

Methodology

Vertical Electrical Sounding (VES) were carried out using ABEM Terameter to define the lithological arrangement of the proposed site. VES using the Schlumberger electrode configuration was carried out at eight (8) selected points (Figure 1). The electrodes were expanded from a minimum current electrode spacing (AB/2) of 1.0 m to a maximum of 100 m. Two profile lines were set out having 4 vertical electrical soundings (Figure 1). The VES data obtained were subjected to partial curve matching using two layer master curves and auxiliary curves as an initial stage of data interpretation. The layered earth model thus obtained served as input model for an inversion algorithm as a final stage in the quantitative data interpretation. The final interpreted results were used for the preparation of geoelectric sections, and maps.

Furthermore, Standard Penetration Tests (SPT) was conducted at 3 m interval. The sampling procedure consisted of driving a standard split spoon as set forth in ASTM D1586-1990 and BS 5930, using hammer 63.5 kg weight falling through 760 mm height. In each Test bore, samples were taken at 3 m and 10 m depth for laboratory analyses. Samples recovered from the borings were visually classified and geologically logged. SPT investigation was undertaken between 1.5 m and 30 m depth range. In boreholes (Figure 2), SPT results are routinely used to provide an estimate of density [8,32] (Table 1). The N value is assumed to be dependent on relative density in granular soils, and undrained shear strength in cohesive soils. Standard Penetration Test used is to identify the soil stratification and engineering properties of soil layers [7].

Results and Discussion

Geotechnical properties

SPT shows that the study area can be classified as dense to very dense having a general N value (corrected) range between 8 and 96, except a few points which are mainly at the top soil which would have been influenced by weathering and the water-logged nature of the area. Low SPT blows are mostly typical of clay soils, even those which are not pre-stressed, i.e., when they are not under a long-term process of

S/N	SPT (N) VALUE (CORRECTED)	RELATIVE DENSITY
1	0-4	VERY LOOSE
2	05-Oct	LOOSE
3	Nov-30	MEDIUM DENSE
4	31-50	DENSE
5	>51	VERY DENSE

Table 1: SPT value and there corresponding Relative density.

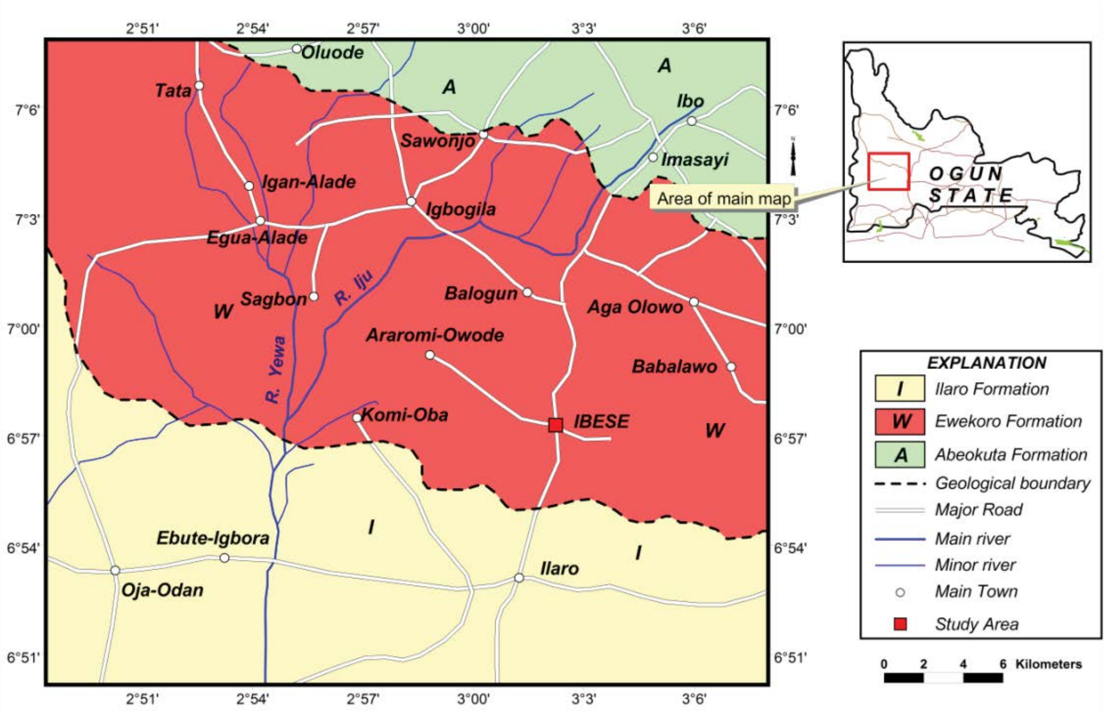
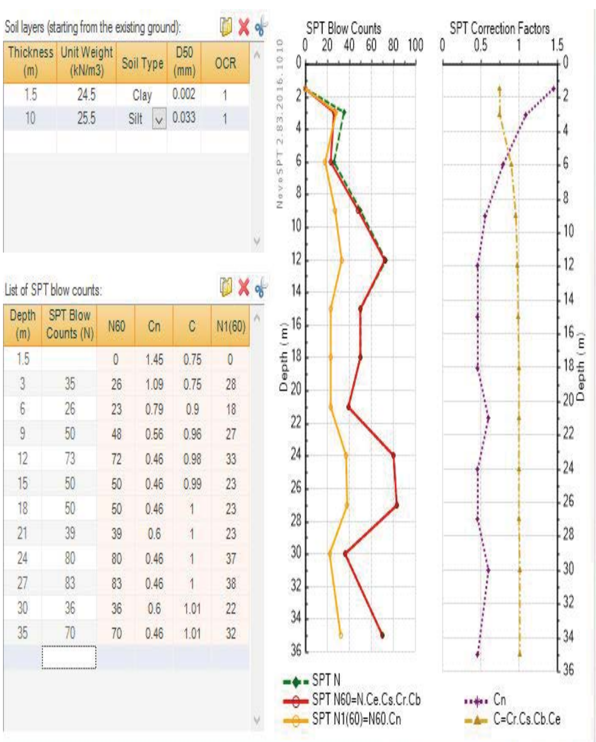


Figure 1: (a) Geological map of the Yewa in Ogun state; (b) The layout of the study area indicating the tested points.

Citation: Adewuyi OI, Philips OF (2018) Integrated Geophysical and Geotechnical Methods for Pre-Foundation Investigations. J Geol Geophys 7: 453. doi: 10.4172/2381-8719.1000453



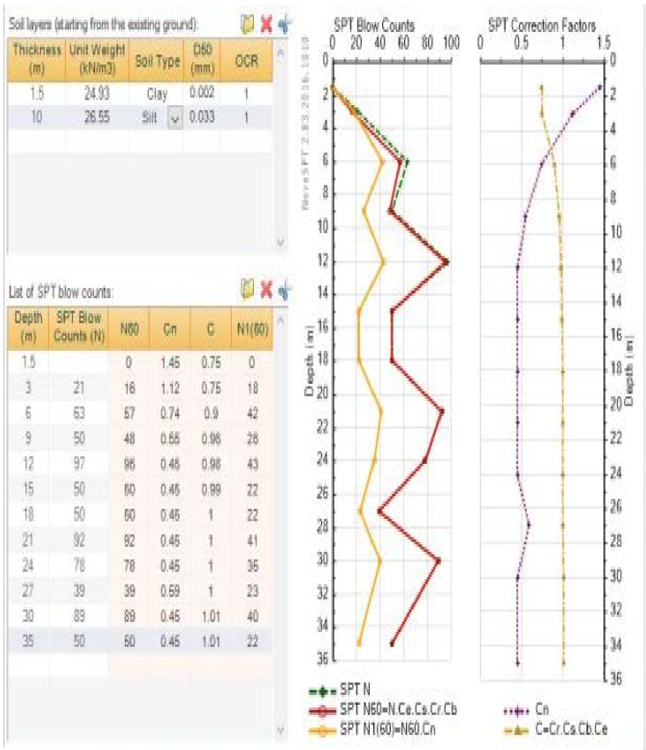
Soil layers (starting from the existing ground):

Thickness (m)	Unit Weight (kN/m3)	Soil Type	D50 (mm)	OCR
1.5	24.5	Clay	0.002	1
10	25.5	Silt	0.033	1

List of SPT blow counts:

Depth (m)	SPT Blow Counts (N)	N60	Cn	C	N1(60)
1.5		0	1.45	0.75	0
3	35	26	1.09	0.75	28
6	26	23	0.79	0.9	18
9	50	48	0.56	0.96	27
12	73	72	0.46	0.98	33
15	50	50	0.46	0.99	23
18	50	50	0.46	1	23
21	39	39	0.6	1	23
24	80	80	0.46	1	37
27	83	83	0.46	1	38
30	36	36	0.6	1.01	22
35	70	70	0.46	1.01	32

BH 1



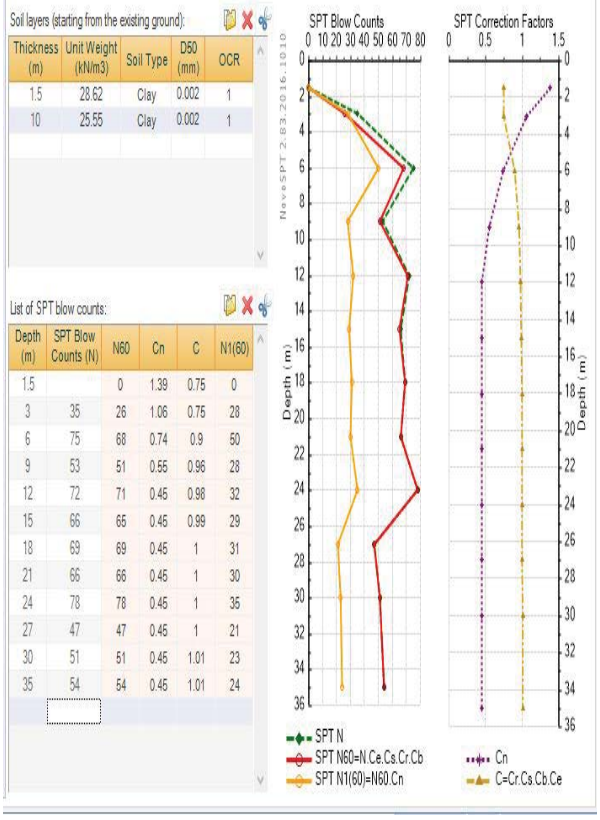
Soil layers (starting from the existing ground):

Thickness (m)	Unit Weight (kN/m3)	Soil Type	D50 (mm)	OCR
1.5	24.93	Clay	0.002	1
10	26.55	Silt	0.033	1

List of SPT blow counts:

Depth (m)	SPT Blow Counts (N)	N60	Cn	C	N1(60)
1.5		0	1.45	0.75	0
3	21	16	1.12	0.75	18
6	63	57	0.74	0.9	42
9	50	48	0.65	0.96	28
12	97	96	0.46	0.98	43
15	50	60	0.46	0.99	22
18	50	50	0.45	1	22
21	92	92	0.45	1	41
24	78	78	0.45	1	35
27	39	39	0.59	1	23
30	89	89	0.45	1.01	40
35	50	60	0.45	1.01	22

BH 2



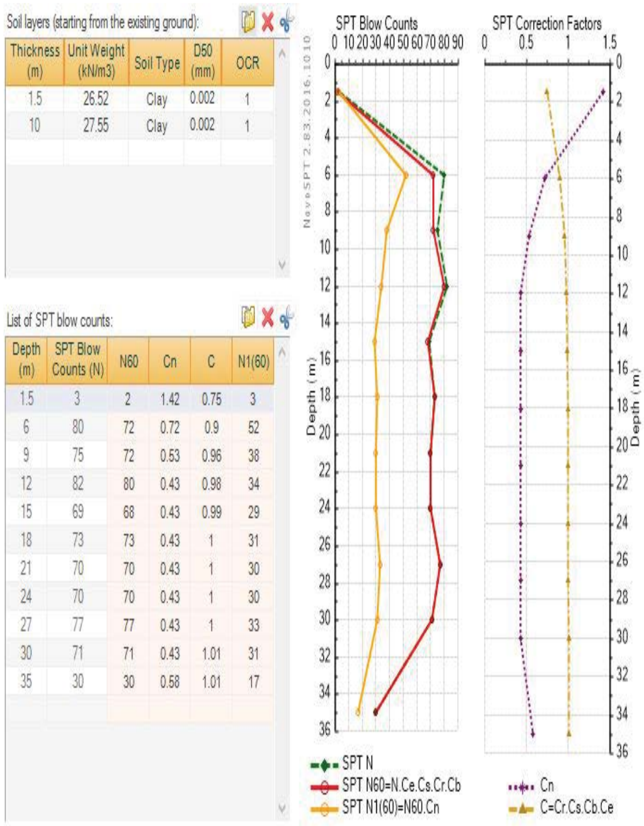
Soil layers (starting from the existing ground):

Thickness (m)	Unit Weight (kN/m3)	Soil Type	D50 (mm)	OCR
1.5	28.62	Clay	0.002	1
10	25.55	Clay	0.002	1

List of SPT blow counts:

Depth (m)	SPT Blow Counts (N)	N60	Cn	C	N1(60)
1.5		0	1.39	0.75	0
3	35	26	1.06	0.75	28
6	75	68	0.74	0.9	50
9	53	51	0.55	0.96	28
12	72	71	0.45	0.98	32
15	66	65	0.45	0.99	29
18	69	69	0.45	1	31
21	66	66	0.45	1	30
24	78	78	0.45	1	35
27	47	47	0.45	1	21
30	51	51	0.45	1.01	23
35	54	54	0.45	1.01	24

BH 3



Soil layers (starting from the existing ground):

Thickness (m)	Unit Weight (kN/m3)	Soil Type	D50 (mm)	OCR
1.5	26.52	Clay	0.002	1
10	27.55	Clay	0.002	1

List of SPT blow counts:

Depth (m)	SPT Blow Counts (N)	N60	Cn	C	N1(60)
1.5	3	2	1.42	0.75	3
6	80	72	0.72	0.9	52
9	75	72	0.53	0.96	38
12	82	80	0.43	0.98	34
15	69	68	0.43	0.99	29
18	73	73	0.43	1	31
21	70	70	0.43	1	30
24	70	70	0.43	1	30
27	77	77	0.43	1	33
30	71	71	0.43	1.01	31
35	30	30	0.58	1.01	17

BH 4

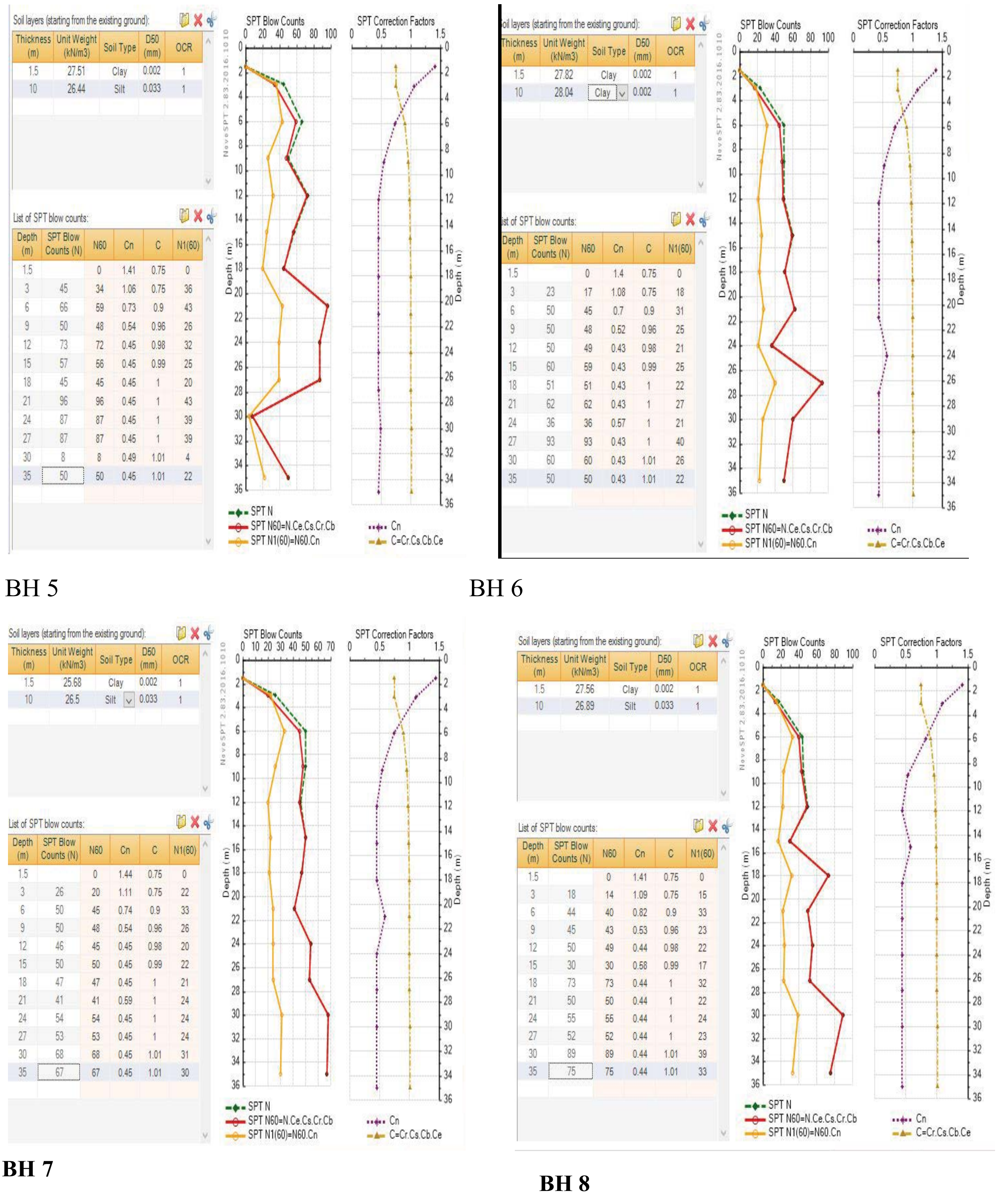


Figure 2: The SPT profiles plots from the borehole data within the study area (Boreholes 1-8).

compression and stiffening (gradual reduction in pore fluid pressure and an increase of the effective stress), and are more susceptible to subsidence. They are also affected by environmental conditions (besides others), particularly temperature and moisture, which vary irregularly throughout the year [6]. The results of the geotechnical boreholes showed that there is variation in the material on the site which was responsible for the wide range in the value of the SPT value (N). At depth of 3 m, the trend of the SPT number of blows is high, which shows a proportional rate of penetration with the nature of the lithology encountered when, correlated with geoelectric parameters.

Laboratory analyses results (Table 2) on soil samples indicate the percentage of fines range from 24.0% - 36.0% at depth of 1.5 m, while it ranges between 20.0%-44.0% at 10.0 m. Since at both depth they have an average of 30% and 34% respectively which falls within the range of a maximum of 35.0% by Federal Ministry of Works and Housing (FMWH) [47] for a foundation material, hence the soil samples for the study is rated as fair to good sub-grade foundation material. This result indicates a low amount of clay materials in the soil at these depths, as well the smaller particles can fill in the spaces between the large particles thereby giving a denser and stronger mass of interlocking particles with high shear strength and low compressibility [37].

The liquid limit of the subsoil within the area ranges from 22.0%-45.0% and 27.7%-38.5% at 1.5 m and 10.0 m respectively, while the plastic limits range from 17.5% to 25.0% and 16.0 - 27.0% at 1.5 m and 10.0 m respectively. The plastic index varies from 4.0%-18.0% at 1.5 m and 7.0% -19.5% at 10.0 m and falls within limits recommended by FMWH [47].

The materials analyzed show that the maximum value of the liquid limit is 38.5% less than 50%. Adesodun and Kolade [48] concluded that liquid limit value greater than 50% is interpreted as poor foundation materials. The plastic limit has a maximum value of 27.0 at 10.0 m and this is low when compared to 30.0% recommended for foundation materials, thus the site safe for the structural foundation of the industrial building. The maximum plastic index value of 19.5% recorded in the study area is less than 20.0% thus, the tested soil samples are of low consistency limits indicating low percentage of clay content in the soil hence, it shows a good engineering property since the higher the plastic index of a soil, the less the competency of the soil as a foundation material [49].

The Maximum Dry Density (MDD) of the studies soil range from 1680.0 kg/m^3 -1900.0 kg/m^3 at 1.5 m and 1600.0 kg/m^3-1850.0 kg/m^3 at 10.0 m while the Optimum Moisture Content (OMC) range from 14.0% -19.0% at 1.5 m and 13.0%-19.0% at 10.0 m.

Geophysical properties

Interpretation of the results shows a system of three geoelectric layers for all the Eight VES point on the 2 profiles (Figure 3). All the curves shows H curve pattern for the whole dataset. A summary of the

	Depth	BH							
		1	2	3	4	5	6	7	8
Amount of Fine (%)	1.5	24	28	36	22	36	32	31	36
	10	34	20	44	28	28	24	28	42
Optimum moisture content	1.5	16	18	18	13	15	19	17	14
	10	16	19	13	18	14	18	19	18
Maximum Dry Density(kg/m^3)	1.5	1730	1690	1680	1930	1720	1840	1820	1900
	10	1850	1730	1710	1600	1830	1820	1730	1820
Liquid Limit	1.5	22.5	28.5	28.5	35.5	45	25.5	24	35.5
	10	34	32	27.7	37	33	29	30.5	38.5
Plastic Limit	1.5	18.5	23	18	17.5	25	19	17.5	17.5
	10	27	20	17	16.5	16	21	19	19
Plasticity Index	1.5	4	5.5	10.5	18	25	6.5	7	18
	10	7	12	10.5	15.9	16	8	11.5	19.5
Specific Gravity	1.5	2.6	2.69	2.64	2.57	2.59	2.63	2.64	2.58
	10	2.65	2.66	2.66	2.6	2.67	2.64	2.66	2.64

Table 2: The summary of the Geotechnical analysis.

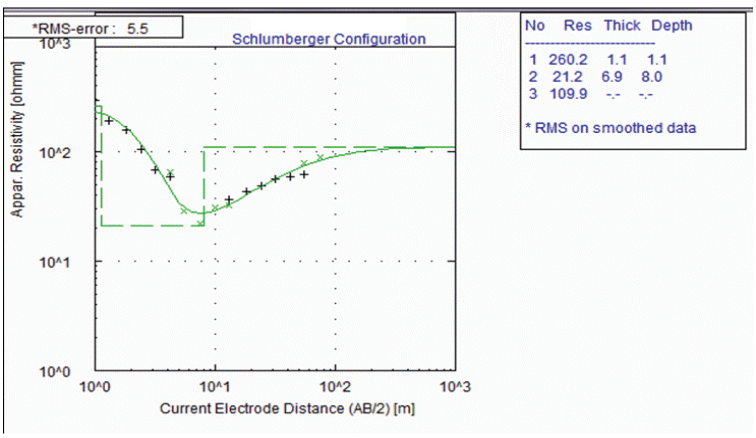


Figure 3: A typical H curve of VES 8.

Citation: Adewuyi OI, Philips OF (2018) Integrated Geophysical and Geotechnical Methods for Pre-Foundation Investigations. J Geol Geophys 7: 453. doi: 10.4172/2381-8719.1000453

VES interpretation is presented in Table 3 and are shown in (Figures 4 & 5). The resistivity of the first layer is high (48.4-404.0 Ωm) indicating the reworked top soil, the second layer ranges from 2.6 -21.2 Ωm suggesting saturated sandy clay unit with thickness ranging from 6-9.2 m. The resistivity of the third layer (71.7-159.4 Ωm) indicates a highly compacted limestone zone.

Integration of geophysical and geotechnical results

The two traverses of electrical resistivity images highlight a sub-surface of sandy materials sandwiched by pockets of clay. The presence of non-plastic materials depicts a very low clay content which is safe for foundation works/structures. The second layer constitutes the layer within which

S/N	Layers	Resistivity (Ωm)	Thickness (m)	Depth (m)	Curve Type	Reflection coefficient	Probable Lithology
VES 1	I	404	0.4	0.4	H		Topsoil
	II	13.6	9.2	9.6		0.8428	clay
	III	159.4					Clayey sand
VES 2	I	48.4	0.8	0.8	H	0.9105	Topsoil
	II	2.6	1	1.9			Clay
	III	55.5					Clay/limestone
VES 3	I	89.7	0.5	0.5	H	0.7153	Topsoil
	II	12	6	6.4			Clay
	III	72.3					Sandy/ clay
VES 4	I	212.9	0.5	0.5	H	0.7635	Topsoil
	II	16.6	8.5	9			Clay
	III	123.8					Limestone
VES 5	I	296.9	0.6	0.6	H	0.753	Topsoil
	II	14.4	6.7	7.3			Clay
	III	102.2					Limestone
VES 6	I	140.6	0.6	0.6	H	0.613	Topsoil
	II	17.2	6	6.6			Clay/Limestone
	III	71.7					Sandy clay
VES 7	I	162.8	0.7	0.7	H	0.6184	Topsoil
	II	18.6	7.5	8.2			Clay
	III	78.9					Limestone
VES 8	I	260.2	1.1	1.1	H	0.6763	Topsoil
	II	21.2	6.9	8			Clay/Limestone
	III	109.8					Sandy clay

Note: H curve type (ρ1>ρ2<ρ3).

Table 3: Summary of VES data interpretation

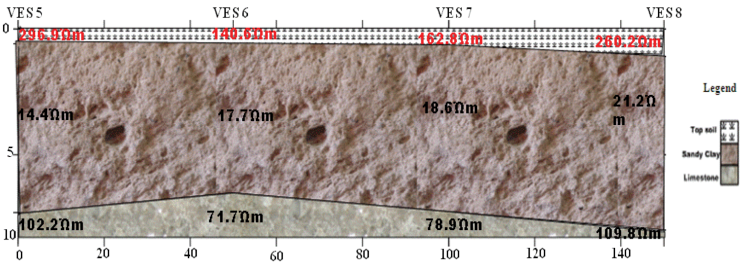


Figure 4: Geo-electric sections of the traverse 1 indicating the apparent resistivity values and their respective depth.

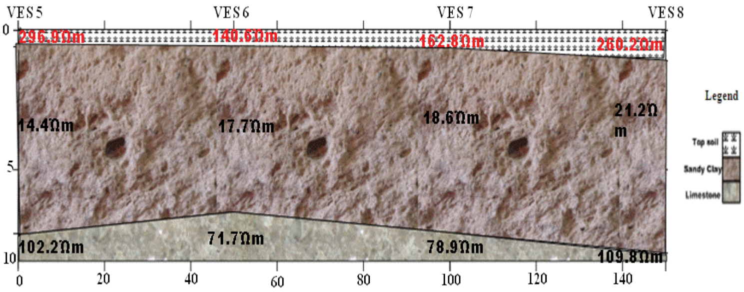


Figure 5: Geo-electric sections of the traverse 2 indicating the apparent resistivity values and their respective depth.

normal civil Engineering Foundation is founded. The layer is composed of clayey sand materials. Foundation competence of the topsoil can be qualitatively evaluated from layer resistivity and geotechnical parameter. Akintorinwa and Adeusi [25], suggested that the higher the layer resistivity value, the higher the competence of the delineated soil units, followed by clayed sand and sandy clay being the least competence.

Correlations of electrical resistivity with geotechnical data

Results of the different methods employed were correlated using least-square regression method. The best approximation equation with the highest correlation coefficient was selected from the linear, logarithmic, polynomial, exponential and power curve fittings (Table 4). The polynomial curve was the best curves that fit experimental data. The result shows a good regression co-efficient R^2=0.768 while the plot of Resistivity against plasticity index shows a mild regression of R^2=0.571. This result indicates that soil with low plasticity would have higher resistivity value and vice vasa [10,34,50-55]. Samples with high clay content more than 20% will have a corresponding upper limit of medium plasticity, therefore resistivity value will be low (Figures 6 & 7).

Conclusion

A geophysical (VES) and geotechnical integrated study have been carried out in Ibese, south western Nigeria for an industrial structure foundation. The electrical resistivity imaging of the study area revealed a maximum of three geoelectric sections which are made up of reworked topsoil, sandy clayey and Limestone.

Curve fittings	Linear	Exponential	Logarithmic	Polynomial	Power
Plastic Limits *VS* Resistivity	PL=0.046ρ + 14.96	PL=15.97$e^{0.001}$ ρ	PL=3.398 ln(ρ)+4.080	PL=0.002 $ρ^2$-0.475x+40.08	PL=10.59 $ρ^{0.131}$
	R^2=0.200	R^2=0.147	R^2=0.110	R^2=0.768	R^2=0.072
Plasticity Index *VS* Resistivity	PI=0.007 ρ + 11.85	PI=12.49e^{-5E-0} ρ	PI=1.928 ln (ρ)+3.836	PI=-0.003 $ρ^2$+0.641x-18.70	PI=9.419 $ρ^{0.051}$
	R^2=0.003	R^2=0.002	R^2=0.024	R^2=0.571	R^2=0.002

Key: PL=Plastic Limits, PI=Plasticity Index, ρ=Resistivity value.

Table: 4: The results of the different interpolation of the correlations.

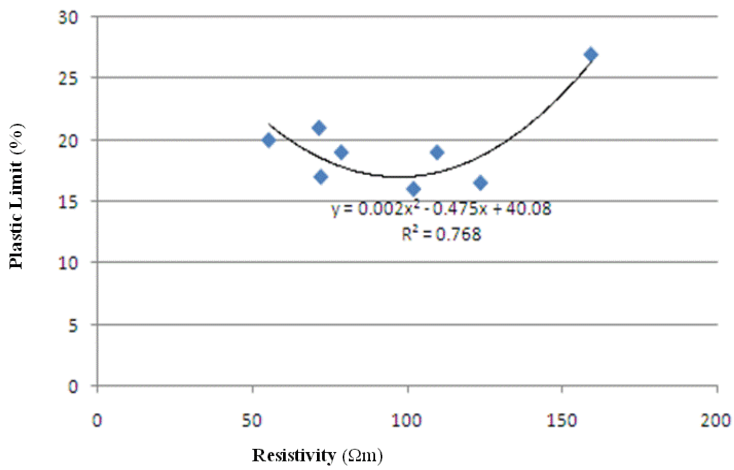


Figure 6: Graphical representation of the polynomial curve fitting correlation between Plastic Limit and Resistivity.

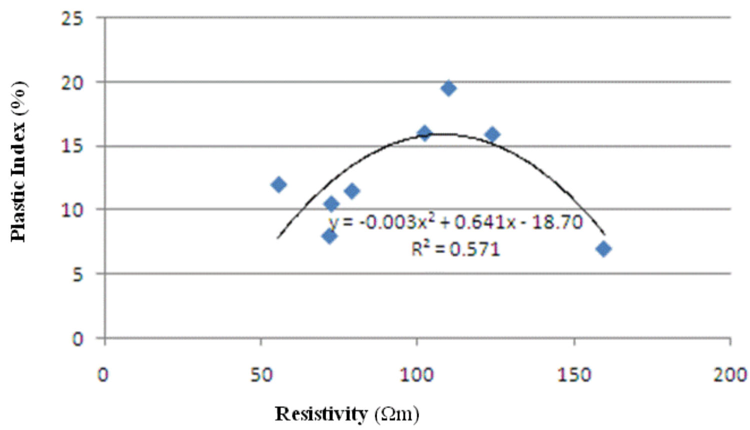


Figure 7: Graphical representation of the polynomial curve fitting correlation between plasticity Index and Resistivity.

The SPT result indicates a medium dense to very dense material which is well in agreement with the result of other laboratory results. The geotechnical results show that the soils are generally of low clay content as revealed by the percentage of fines which is generally less than 35% except in three samples. Generally, the geotechnical analyses of the soil samples show they qualify as foundation materials. The soil samples have low moisture content and relatively low clay material as revealed by the plastic index of the soils within the area and less than 20% except for a sample and interpreted as low consistency limits. It was also stated in FMWH (2000) recommendation that the higher the geotechnical parameters of a soil, the lesser the competence of the soil as a foundation material hence, the recommended value for liquid limit, plastic limit, and plastic index are 50%, 30%, and 20% respectively. In the study area, the values recorded are low and falls within recommended value except in some few points and thus the higher the competence of the soil as a good foundation material.

An integrated geophysical and geotechnical investigations offer very useful approach for characterizing subsoil and thus can provide information in early preparation before foundation of any engineering structures. Unfortunately, as it is well known, the geophysical method cannot be used as substitute for geotechnical method due to the fact that it does not provide any information about the strength parameter of the soil but its application is useful in reducing the time and cost in drilling several boreholes and carrying out laboratory tests. Based on aforementioned fact, the subsoil within the study area is suitable for the construction of industrial structures and is competent but caution should be taken based on the waterlogged nature of the area and the nature of the industry. Its advice that dewatering should be carried out and the foundation should be allowed to rest on piles between 3 m and 5 m.

References

1. Roy S, Bhalla SK (2017) Role of geotechnical properties of soil on civil engineering structures. Sci Acad Pub 7: 103-109.
2. Olayanju GM, Mogaji KA, Lim HS, Ojo TS (2017) Foundation integrity assessment using integrated geophysical and geotechnical techniques: Case study in crystalline basement complex, southwestern Nigeria. J Geophys Eng 14: 675- 690.
3. Adeoti L, Ojo AO, Adegbola RB, Fasakin OO (2016) Geoelectric assessment as an aid to geotechnical investigation at a proposed residential development site in Ilubirin, Lagos, Southwestern Nigeria. Arab J Geosci 9: 338.
4. Oghenero AE, Akpokodje EG, Tse AC (2014) Geotechnical properties of subsurface soils in Warri, Western Niger Delta, Nigeria. J Earth Sci Geotech Eng 4: 89–102.
5. Youdeowei PO, Nwankwoala HO (2013) Suitability of soils as bearing media at a freshwater swamp terrain in the Niger Delta. J Geol Min Res 5: 58–64.
6. Soupois PM, Georgakopoulos P, Papadopoulos N, Saltos V, Andreadakis A, et al. (2007) Use of engineering geophysics to investigate a site for a building foundation. J Geophys Eng 4: 94–103.
7. Oyedele KF, Olorode DO (2011) Site investigations of subsurface conditions using electrical resistivity method and cone penetration test at Medina Estate, Gbagada, Lagos, Nigeria. World App Sci J 11: 1097-1104.
8. Cosenza P, Marmet E, Rejiba F, Cui YJ, Tabbahgh A, et al. (2006) Correlations between geotechnical and electrical data: A case study at Garchy in France. J Appl Geophys 60: 165−178.
9. Akintorinwa OJ, Oluwole ST (2018) Empirical relationship between electrical resistivity and geotechnical parameters: A case study of Federal University of Technology campus, Akure SW, Nigeria. NRIAG J Astronomy Geophys 7: 123–133.
10. Akinlabi IA, Adeyemi GO (2014) Determination of empirical relations between geolectrical data and geotechnical parameters in foundation studies for a proposed earth dam. Pac J Sci Technol 15: 278–287.
11. Arora KR (2008) Soil mechanics and foundation engineering (Geotechnical Engineering). Standard Publishers Distributors, Delhi.
12. Oyediran A, Durojaiye HF (2011) Variability in the geotechnical properties of some residual clay soils from south western Nigeria. Int J Sci Eng Res 2: 1-6.
13. Laskar A, Pal SK (2012) Geotechnical characteristics of two different soils and their mixture and relationships between parameters. Elect J Geotech Eng 17: 2821-2832.
14. Oke SA, Amadi AN (2008) An assessment of the geotechnical properties of the sub-soil of parts of Federal University of Technology, Minna, Gidan Kwano Campus, for foundation design and construction. J Sci Educ Technol 1: 87–102.
15. Nwankwoala HO, Warmate T (2014) Geotechnical assessment of foundation conditions of a site in Ubima, Ikwerre Local Government Area, Rivers State, Nigeria. Int J Eng Res Dev 9: 50–63.
16. Pozdnyakov A, Pozdnyakova L (2002) Electrical fields and soil properties. 17th WCSS, Thailand, pp.14-21.
17. Anderson BT, Ruane AC, Roads JO, Kanamitsu M, Salvucci G, et al. (2008) A new metric for estimating local moisture cycling and its influence upon seasonal precipitation rates. J Hydrometeorol 9: 576-588.
18. Rungroj A, Mark EE (2015) Application of 2D electrical resistivity tomography to engineering projects: Three case studies. Songklanakarin J Sci Technol 37: 675-681.
19. Reynolds JM (2011) An introduction to applied and environmental geophysics, 2nd Edn. Wiley, pp.710.
20. Fajana AO, Olaseeni OG, Bamidele OE, Olabode OP (2016) Geophysical and geotechnical investigation for post foundation studies, Faculty of Social Sciences and Humanities, Federal University Oye Ekiti. FUOYE J Eng Tech 1: 2579-0617.
21. Pazzi V, Di Filippo M, Di Nezza M, Carlà T, Bardi F, et al. (2018) Integrated geophysical survey in a sinkhole-prone area: microgravity, electrical resistivity tomographies, and seismic noise measurements to delimit its extension. Eng Geol 243: 282-293.
22. Kayode JS, Adelusi AO, Nawawi MNM, Bawallah M, Olowolafe TS, et al. (2016) Geo-electrical investigation of near surface conductive structures suitable for groundwater accumulation in a resistive crystalline basement environment: A case study of Isuada, southwestern Nigeria J Afr Earth Sci 119: 289-302.
23. Osinowo OO, Falufosi MO (2018) 3D electrical resisititivity imaging (ERI) for subsurface evaluation in pre-engineering construction site investigation. NRIAG J Astro Geophys.
24. Hazreek ZAM, Azhar ATS, Aziman M, Fauzan SMSA, Ikhwan JM, et al. (2017) Forensic assessment on ground instability using electrical resistivity imaging (ERI). J Phys: Conf Ser 790: 012038.
25. Akintorinwa OJ, Adesoji JI (2009) Application of geophysical and geotechnical investigations in engineering site evaluation. Int J phys sci 4: 443-454.
26. Akintorinwa OJ, Adeusi FA (2009) Integration of geophysical and geotechnical investigations for a proposed lecture room complex at the Federal University of Technology, Akure, SW, Nigeria. Ocean J App Sci 2: 241-254.
27. Adegbola RB, Oseni SO, Sovi ST (2010) Geoelectric investigation of the aquifer characteristics in Topo area of Badagry, Lagos State. Rep Opin 2: 172-180.
28. Aghamelu OP, Odoh BI, Egboka BCE (2011) A geotechnical investigation of the structural failures of building projects in parts of Awka, southeastern Nigeria. Indian J Sci Technol 3: 1119-1124.
29. Faleye ET, Omosuyi GO (2011) Geophysical and geotechnical characterization of foundation beds at Kushiyaki, Kuje Area, Abuja, Nigeria. J Emerging Trends in Eng App Sci 2: 864-870.
30. Oyedele KF, Okoh C (2011a) Subsoil investigation using integrated methods at Lagos, Nigeria. J Geol Min Res 3: 169-179.
31. Oyedele KF, Oladele S, Adedoyin O (2011b) Application of geophysical and geotechnical methods to site characterization for construction purpose in Ikoyi, Lagos. Nigeria J Earth Sci Geotech Eng 1: 87-100.
32. Ezenwaka KC, Ugboaja A, Ahaneku CV, Ede TA (2014) Geotechnical investigation for design and construction of civil infrastructures in parts of port Harcourt City of Rivers State, Southern Nigeria. The Int J Eng Sci 3: 74-82.
33. Khatri R, Shrivastava VK, Chandak R (2011) Correlation between vertical electric sounding and conventional methods of geotechnical site investigation. Int J Adv Eng Sci Tech 4: 42-53.

34. Boobalan J, Ramanujam N (2015) Integration of engineering Properties of Soils in the Weathered Profile of ophiolite Suite of Rocks of South Andaman Islands, India through Vertical Electrical Sounding. Int J Eng Sci 4: 41-55.

35. Binley A, Hubbard SS, Huisman JA, Revil A, Robinson DA, et al. (2015) The emergence of hydrogeophysics for improved understanding of subsurface processes over multiple scales. Water Resou Res 51: 3837-3866.

36. Parsekian AD, Singha K, Minsley BJ, Holbrook WS, Slater L (2015) Multiscale geophysical imaging of the critical zone. Rev Geophys 53: 1–26.

37. Adejumo SA, Oyerinde AO, Akeem MO (2015) Integrated geophysical and geotechnical subsoil evaluation for pre-foundation study of proposed site of vocational skill and entrepreneurship center at the polytechnic, Ibadan, SW, Nigeria. Int J Sci Eng Res 6: 910-917.

38. Cardarelli E, De Donno G, Oliveti I, Scatigno C (2016a) Assessing the state of conservation of a masonry building through the combined use of electrical and seismic tomography. 22nd European meeting of Environ Eng Geophys, Barcelona, Spain.

39. Cardarelli E, Donno GD, Ilaria Oliveti I, Scatigno C (2018) Three-dimensional reconstruction of a masonry building through electrical and seismic tomography validated by biological analyses. Near Surface Geophys 16: 53-65.

40. Sun CG, Han JT, Choi JI, Kim KS, Kim MM, et al. (2007) Investigation into the input earthquake motions and properties for round robin test on ground response analysis. Korean Geotech Soc Autumn National Conf, Busan, Korea, 266−292.

41. Oh S, Sun CG (2008) Combined analysis of electrical resistivity and geotechnical SPT blow counts for the safety assessment of fill dam. Environ Geol 54: 31−42.

42. Sudha K, Israil M, Mittal S, Rai J (2009) Soil characterization using electrical resistivity tomography and geotechnical investigations. J App Geop 67: 74–79.

43. Nath SK, Thingbaijam KKS (2011) Assessment of seismic site conditions: A case study from Guwahati city, Northeast India. Pure Appl Geophys 168: 1645–1668.

44. Hack RC, Sundararaman P, Diedjomahor JO, Xiao H, Gant NJ, et al. (2000) Niger delta petroleum systems, Nigeria. Am Ass Petro Geol Memoir 73: 213–231.

45. Obaje NG (2009) Geology and mineral resources of Nigeria. Lecture Notes in Earth Sciences, Springer, Berlin, Heidelberg 120.

46. Jones AA, Hockey RO (2010) The geology of part of South-western Nigeria: Explanation of 1:250,000 sheets nos. 59 and 68. Geol Survey Nigeria Bull 31: 110.

47. Federal Ministry of Work and Housing Nigeria (FMWH) (2000) Specification for roads and bridges, pp.2.

48. Adesodun JK, Kolade IO (2000) Variation in rheological properties of tropical alfisol in Southwest Nigeria. Proc of the 26th Annual Conf of the Soil Sci Soc of Nigeria, Ibadan, pp.68-72.

49. Coker JO, Makinde V, Adesodun JK, Mustapha AO (2013) Integration of geophysical and geotechnical investigation for a proposed new lecture theatre at the Federal University of Agriculture, Abeokuta, SW, Nigeria. Int J Emerging Trends in Eng Devel 5: 338-348.

50. Philippe C, Marmet E, Faycal R, Yu JC, Alain T, et al. (2006) Correlations between geotechnical and electrical data: A case study at Garchy in France. J App Geophys 60: 165–178.

51. Olorunfemi MO, Akintorinwa OJ, Iginla IB, Bayowa GO (2010) Micro-resistivity measurements, near-surface sequence delineation, and empirical relationships with engineering geotechnical parameters. Pac J Sci Technol 11: 1 537–544.

52. Siddiqui FI, Osman SBAS (2012) Integrating geo-electrical and geotechnical data for soil characterization. Int J App Phys Math 2: 104-106.

53. Fahad IS, Syed Baharom AO (2013) Simple and multiple regression models for the relationship between electrical resistivity and various soil properties for soil characterization. Environ Earth Sci 70: 259-267.

54. Abidin MHZ, Wijeyesekera DC, Saad R, Ahmad F (2013) The influence of soil moisture content and grain size characteristics on its field electrical resistivity. Elect J Geotech Eng 18/D: 699-705.

55. Rahim AA, Samran AS, Nazish N, Waqas A, Sarfraz K, et al. (2016) Correlation of electrical resistivity of soil with geotechnical engineering parameters at Wattar area district Nowshera, Khyber Pakhtunkhwa, Pakistan. J Himalayan Earth Sci 49: 124-130.