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GEOTECHNICAL AND GEOPHYSICAL INVESTIGATION OF SUBSOIL FOR CONSTRUCTION OF A WASTE WATER TREATMENT PLANT IN COASTAL ENVIRONMENT, SOUTHWESTERN NIGERIA

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ABSTRACT
A combined geophysical and geotechnical studies were conducted in a coastal environment in Lagos, Nigeria in order to delineate subsurface lithologies and evaluate their suitability as foundation for a proposed waste water treatment plant. The geophysical study carried out involved electrical resistivity tomography (ERT) resulting in 2-D resistivity imaging along 3 profiles with spread length ranging from 145 – 190 m. The ERT data obtained along the profiles were analyzed using DIPRO for window, a 2-D resistivity inversion program to provide estimates of vertical and horizontal spatial distribution of resistivity beneath the survey line. A total of eight cone penetration test and four standard penetration borehole logs in were conducted to determine the strength and characteristic nature of the foundation soils. In addition, pH and sulphate concentration of a water sample from one of the SPT boreholes were determined to predict if there is possible infiltration of leachates into the groundwater. The results of the integrated investigation revealed the occurrence of thick peat, and clay ($\approx$22.00 m) which prevented the further infiltration of leachates plumes as revealed by the ERT images and sandy units at depths greater than 23 m. The occurrence of thick peat/clay horizons makes the use of shallow foundation infeasible to mobilize the proposed structure. The chemical analyses show pH to be slightly acidic (6.88) and sulphate concentration of 31 mg/l which are both within World Health Organization standard, confirms that there is no infiltration of pollutants/leachates into the groundwater, therefore the water in the area will not be inimical to Portland cement concrete at deeper depths.
Both geophysical and geotechnical methods reveal that the subsoil contains clayey material which serves as good containment and that pile foundation be used to mobilise the proposed structure to the deeper sand layer.

1.0 INTRODUCTION
Meeting the water need of the world ever-increasing population has posed enormous challenges since the last century. According to WHO, (2006) water pollution is the leading cause of deaths and diseases, and that it accounts for the deaths of more than 14,000 people daily.In United Nations Environmental Programme report (UNEP, 2016), up to 164 million people are at risk of infection from water borne diseases such as cholera, typhoid, infectious hepatitis, polio, cryptosporidiosis, ascariasis and diarrheal diseases. Nigeria has undergone an increase of five folds in just six decades of existence, putting the nation's current populationat over 170 million (NPC, 2006). The same scenario plays out all over the world. The attending consequence has led to the preponderance of technological innovations to augment water availability and management,

through wastewater recycling. One of the immediate solutions to this is the massive groundwater exploration for municipal water supply. Aside groundwater, other complimentary sources of water for drinking, agricultural and industrial uses are unconventional water sources such as wastewater treatment.

To meet the yearning water supply in Africa most populated city – in a fast growing Lagos metropolis, the Lagos State Wastewater Management Office commissioned a sub-soil investigation for the proposed Wastewater treatment plant to meet the challenges of lack of potable groundwater for the increasing populace. This is in view of the unsatisfactory bearing condition of subsoil at the proposed site for the project. Like in any foundation design and construction, the design of this kind of engineering structure (wastewater treatment plant) requires the characterization of subsurface soil and determination of soil strength as prerequisites for its foundation design prior to construction. Usually, foundation soil testing normally carried out includes Standard Penetration Tests (SPT), Cone Penetration Test (CPT) and collection of undisturbed and disturbed samples for grading characteristics and density determination.

Different methods such as the use of Standard Penetration Test (SPT), Cone Penetration Test (CPT), electrical resistivity and laboratory measurements have been employed by several authors such as Kamal et al. (2015) and Kirar et al. (2016) for the assessments of foundation. Adebisi and Oloruntola (2006); and Folorunso (2009) emphasized the usefulness of geophysical methods in complimenting geotechnical studies. Ayolabiet al. (2012) however showed the significance of using 2-D electrical resistivity tomography (ERT), which allows delineation of lateral and vertical variation of a subsurface stratum to compliment a geotechnical method that gives information of just a point (vertical) in foundation studies. In this work, this noninvasive and cost effective geophysical investigation method (ERT) has been used to compliment geotechnical surveys. Over the years, the importance of geophysical techniques to compliment engineering foundation tests has been greatly acknowledged (Cosenza et al., 2006; Folorunso et al., 2012), inspired from the work of Archie (1942) on the relationship between porosity and bulk resistivity. These techniques have been found useful to predict petrophysical and engineering properties of unconsolidated soils since the influence of these properties of unconsolidated subsurface soils on their electrical responses or measurements has been deduced (Seabrook and Boadu, 2002, Cosenza etal., 2006, Boadu and Owusu-Nimo, 2010). ERT, for example, gives a continuous scan of the subsurface soil rather than the point test of engineering soil tests (Sudhaetal., 2009; Ayolabiet al., 2010; Folorunsoet al., 2012). It therefore gives more and deeper information of the subsurface than most engineering tests. This has been found very useful and informative in areas underlain by peat or swampy terrain at great depth (Ayolabiet al., 2010; Folorunsoet al., 2012).

1.1 LOCATION AND GEOLOGY OF THE STUDY AREA

The study area is located in Lagos, Nigeria, (Fig. 1) close to an existing sewage/wastewater disposal facility. The terrain is reasonably flat and low lying. It is water logged on the surface. The geology is made of Quaternary deposits of the Dahomey Basin. The basin, viewed as a marginal Sac (Klemme 1975; Kingston etal.

1983), was developed during the commencement of the rifting, associated with the opening of the Gulf of Guinea, in the Early Cretaceous to the Late Jurassic (Burke et al., 1971; Whiteman, 1982). It comprises Abeokuta group as the oldest rock (Jones and Hockey, 1964). The group is made up of Ise Formation thought to be a conglomeratic and gritty base overlain by coarse to medium grained sandstone with interbeded kaolinite; Afowo formation – a coarse to medium grained sandstone with interbeded shale, siltstone and claystone; and a Cretaceous sediment made of fine to medium grained sandstone at the base, overlaid by shale, siltstone with interbeded limestone, marl and lignite called Araromi Formation (Omatsola and Adegoke, 1981; Enu, 1990; Obaje, 2009). On top of Abeokuta group is the shaly limestone unit, of Paleocene age, reported to be highly fossiliforous (Jones and Hockey, 1964; Adekoge, 1977). The Eocene age Akinbo Formation composed of shale and clay sequence (Ogbe, 1972) is the next litho-unit. This is overlain by the pale greenish grey laminated phosphate and glauconitic shale Oshoshun Formation of Eocene age, followed by massive yellowish and poorly consolidated cross-bedded sandstone called Ilaro Formation. The youngest lithostratigraphic unit is the poorly sorted sands with lenses of clays of Oligocene to Recent called Benin Formation, also known as the coastal plain sands (Jones and Hockey, 1964). The foundation soils in this area are recent deposits composed mainly of peat, soft clay, and sand.

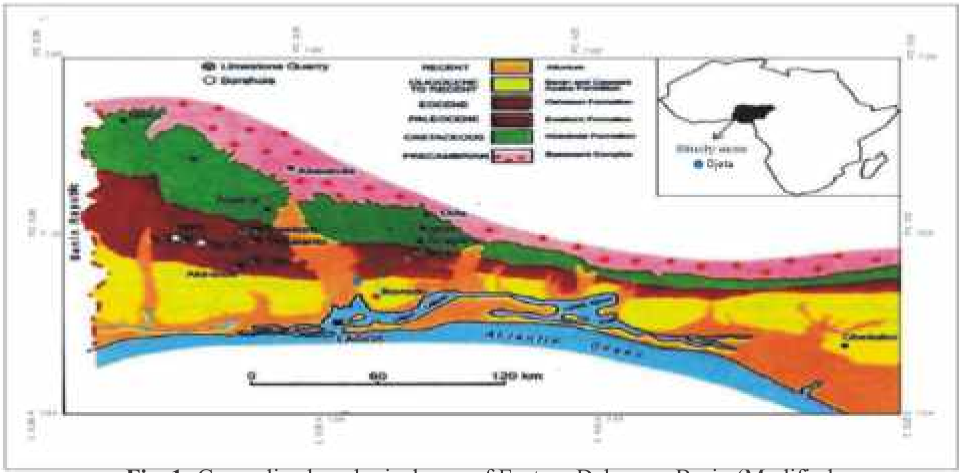

Fig. 1: Generalized geological map of Eastern Dahomey Basin (Modified from Omatsola and Adegoke, 1981)

2.0 METHODOLOGY

Geophysical and geotechnical surveys with chemical analysis of water were conducted at the study area (Fig. 2). The geophysical test involved the use of the 2-D electrical resistivity

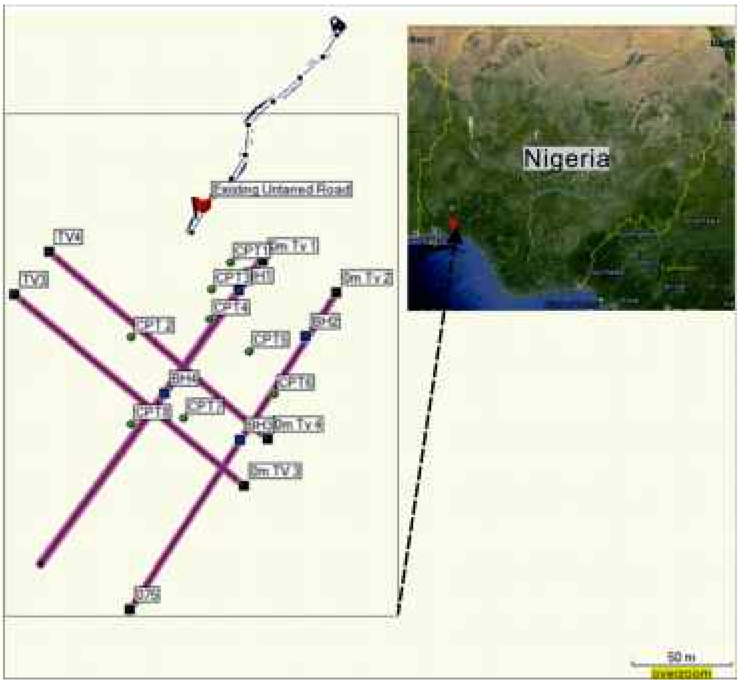

Fig. 2: Location map of the study area showing traverse lines and test points

survey aimed at delineating the nature of the sub-surface layers at various depths across the study area. The geotechnical test involves the use of dynamic cone penetration test (DCPT) and standard penetration test (SPT) within the subsurface. The Chemical analysis was conducted on a water sample from one of the boreholes within the study area.

2.1 2D ELECTRICAL RESISTIVITY TOMOGRAPHY (ERT) SURVEY

For the geophysical work, 2D resistivity imaging was conducted along 3 profiles distributed to cover the site depending on accessibility and available space as shown in Figure 2. The Geophysical survey was carried out using Ohmega Resistivity meter. Wenner electrode array was employed during the investigation. The minimum spacing between the adjacent electrodes represented as 'a' used during the study was a = 5 m for Profile 1 while a = 10 m was used for the remaining profiles to achieve deeper depth of penetration. Five levels of measurements (that is, a = 5 m, 10 m, 15 m, 20 m, 25 m for Profile 1 and a = 10 m, 20 m, 30 m, 40 m & 50 m for other profiles) were taking along each of the profiles during the study. The length of the profiles traversed varied from 145 – 190 m depending on accessibility.

The ERT data obtained along the profiles were analyzed using a 2-D inversion program called DIPRO for window to provide estimates of vertical and horizontal spatial distribution of resistivity below the survey lines. The program produces electric section of 2-D subsurface model by inverting field data iteratively, compared with theoretically calculated apparent resistivity pseudosection (Loke, 2000). Derived resistivity section is obtained using the finite-difference (Dey and Morrison,, 1979) or finite-element (Silvester and Ferrari, 1990) numerical analysis method to calculate the effective resistivity values. Minimum iteration level was chosen to update the subsurface resistivity distribution iteratively until the relative change in percentage RMS error was less than 5%.

2.2 THE GEOTECHNICAL SURVEYS

2.2.1 CONE PENETROMETER TEST (CPT)

The cone penetrometer test provides a rapid evaluation of safe bearing pressure of soils in-situ. 8 numbers of Dutch Cone probes were done at the study area (Fig. 2) to refusal depth using a 2.5 tons capacity penetrometer. The tests were terminated at refusal depths, where the machine anchor legs lifted i.e. terminal resistance point of penetration.The test involves forcing a hardened steel cone continuously into the ground and measuring its resistance to penetration. The standard cone has an apex angle of 600 and a base area of 1000 mm2. The standard cone which is manually operated is forced into the ground by outer rods and driving rods to measure the qc (cone resistance in Kg/cm2). The cone is required to advance at regular intervals of 25 cm and the corresponding pressure required to advance is transmitted to a gauge, where the pressure value is read and recorded. The operation is repeated until the required depth is reached or the total resistance to penetration of the rods and cone reaches the capacity of the machine. Successive cone reading were plotted against depth to form a resistance profile.

The tests were terminated at depths ranging between 14-22 m, due to lifting of support anchors of the testing machine. The soil profile is shown on the attached penetrometer test logs.The approximate test locations are as shown on the site map in Figure 2.

2.2.2 STANDARD PENETRATION TESTS

(SPT)

The test is made in boreholes by means of standard 50.8mmoutside diameter split spoon sampler (Raymond sampler). It is a very useful means of determining the approximate in-situ density of cohesionless soils. The sampler is driven to penetration of 450 mm by repeated blows of a 63.5 kg hammer falling through a height of 760mm. The no of blows that drive the last 300 mm is recorded as standard penetration number (N-value)

Soil samples were collected at different intervals and at every change of strata. Samples from the split spoon sampler in respect of SPT were collected in airtight bags as disturbed samples. Generally the nature and thickness of the subsoil material encountered dictated the sampling procedure. The borehole logs in which the SPT were carried out served as constraint in the interpretation of the ERT and CPT results.

2.2.3 CHEMICAL ANALYSES OF WATER

A water sample was taken with a sampling bottle from one of the SPT boreholes at depth. The container was properly rinsed with the water in the borehole. pH was taken on the field using pH meter while the water sample taken in the airtight bottle was taken to the laboratory to test for sulphate (SO4) concentration. These two parameters were particularly tested so as to investigate whether there is leachate infiltration and the effect this will have on Portland cement.

3.0 RESULTS AND DISCUSSION

Results of the 2D resistivity imaging are presented in Figs 3-5. The 2D resistivity sections generally show three geoelectric layers, viz: peat, clay and sand. These layers were delineated based on their resistivity values.

The ERT along profile 2 (Fig. 3) shows that the subsoil is comprised by peat and clay, constituting with depths range of 5 – 23 m and corresponding resistivity range of 10 – 65 Ohm-m. These layers cannot support the placement of the water treatment plant as a result of the inherently weak bearing capacity of the peat and the swelling and shrinking nature of clay. While the third layer (clayey sand) occurring at depths 23 – 27 m and resistivity of 69 – 100 Ohm-m may be favourable. It is however recommended that structure for the water-treatment plant be piled to the fourth layer, characterized by sandy materials, and resistivity value greater than 100 Ohm-m, beyond 27 m due to inherent high bearing capacity sand of sand.

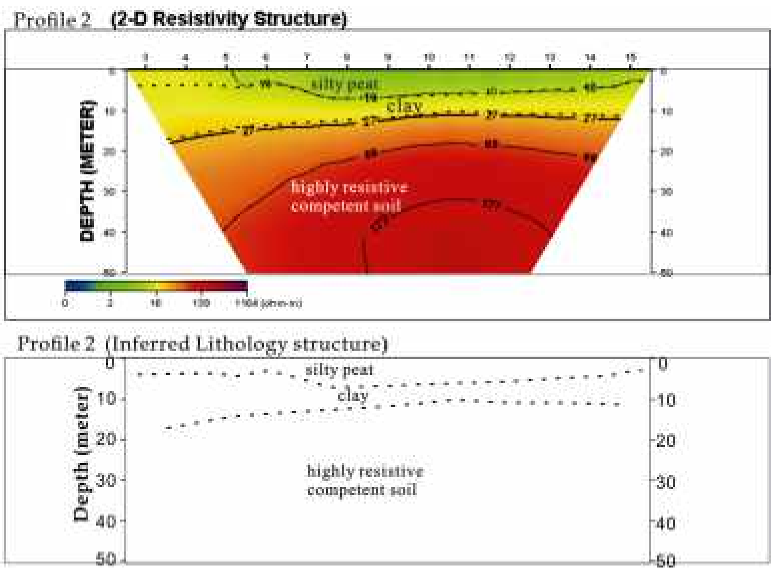

Fig. 3: 2-D resistivity image along traverse 2

The ERT on Traverse 3 (Fig. 4) shows subsurface lithologies, comprise of peat, clay/clayey sand and sand unit. As in traverse two above, it is underlain by peat and clay which are inimical to the placement of the waste water treatment plant. The peat has a very low resistivity range (1 – 12 Ohm-m) value and also points to possible infiltration of leachate within it. Clay with resistivity values ranging 60 Ohm-m extends up to a depth of about 30 m. Depth to sand layer, which can adequately support the treatment plant is about 35 m, thus the foundation for the waste water treatment plant should be a deep type (pile) up to a depth of 35 m The ERT on traverse 4 (Fig. 5) consists of very

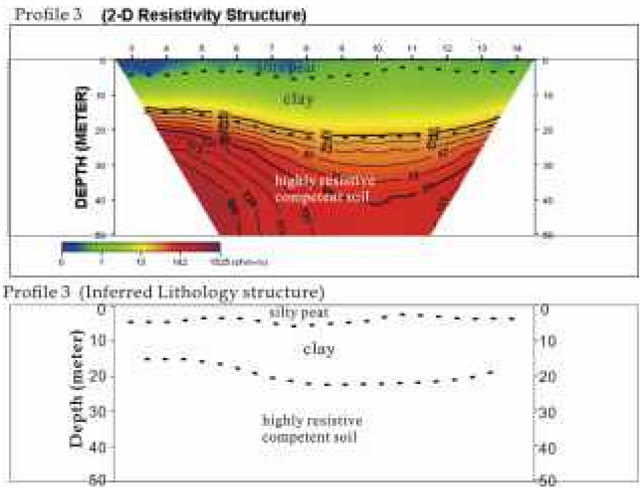

Fig. 4: 2-D resistivity image along traverse 3

low resistivity (< 2Ohm-m) approximately 20 m thick peat that is composed of brine, possibly due to leachate. This is underlain by an approximately 15 m clayey soil which forestalls the further migration of the plumes. The desirable unit (sand) of interest occurs at depth beyond 35 mand is characterized by resistivity value greater than 100 Ohm-m.

Based on the results of the ERT from the traverses, a shallow foundation should be avoided as a result of the occurrence of thick peat and clay soils at shallow depths. Deep foundation is recommended as the 2D resistivity structures reveal a continuous occurrence of materials with high resistivity inferred as

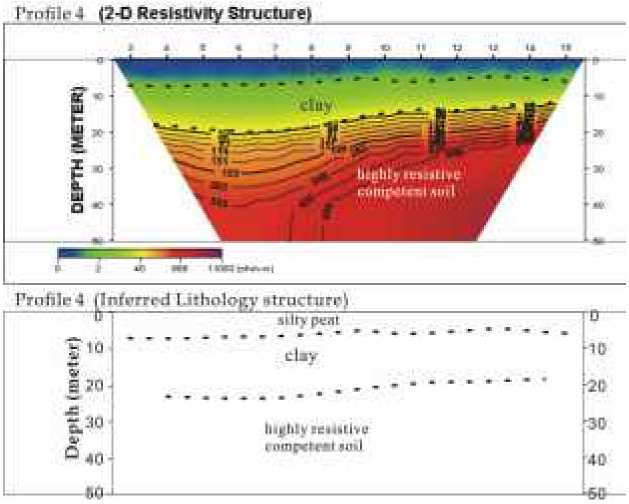

Fig. 5: 2-D resistivity image along traverse 4

sands/gravelly materials beyond a general average depth of 28 m.

The results of cone penetration test are presented in Table 1 and Fig 6. The cone resistance values from depths 0 – 22 m generally range from 0 – 40 Kg/cm2. These indicate the presence of very weak to weak soils inferred as peat and clay of low bearing capacity.The treatment plant must therefore be sited at greater depths in order to forestall the hazard that peat and clay could pose. This results of the CPT conducted are thus, to a good extent, agree with the ERT results.

Table 1: Summarized Results of Cone Resistance, Depths and Inferred Strata Description

CPT	Depth Range (m)	Cone Resistance (Kg/cm^2)	Inferred Description
CPT 1	0-2; 2-3; 3-4; 4-5.25	0-5; 5-30; 2.5-5; 18-40	peat; clay; peat; clay
CPT 2	0-12; 12-17.5	0-10; 10-25	peat, clay
CPT 3	0-2.2; 2.2-12; 12.2-22	0-30; 0-10; 12-27	clay; peat; clay
CPT 4	0-16; 16.2-20	0-10; 10-23	peat; clay
CPT 5	0-18; 18.2-19	0-10; 12-25	peat; clay
CPT 6	0-18; 18.2-20.25	0-6; 6-25	peat; clay
CPT 7	0-13.25; 13.25-14; 14.25-17.25; 17.5-18.75	0-5;5-20;3-5;5-22	peat; clay; peat; clay
CPT 8	0-15.5; 15.5-16.25	0-5; 5-25	peat; clay

The Results of the four (4) borehole logs and SPT are shown in Figs. 7, 8 and 9 and Table 2.Borehole log 1 shows a continuous thickness

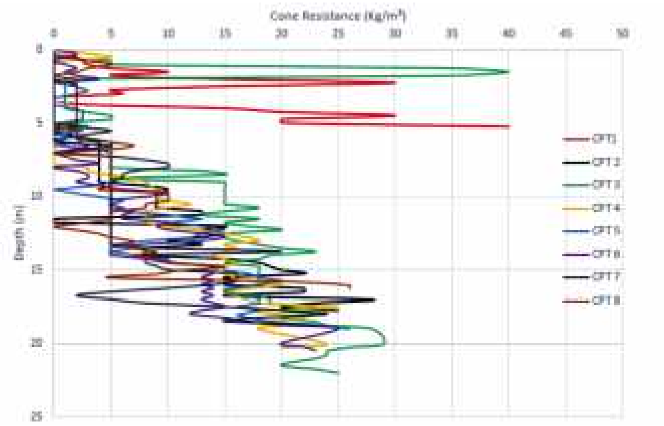

Fig. 6: CPT 1 - 8 for the study area

of dark brownish grey silty peat of 18.75 m. While borehole 2 shows the same lithologic material up to a depth of 19.50 m, which is underlain by dark grey silty to slightly sandy peat that is approximately 2.25 m thick. This layer overlies a greyish silty clayey sand unit that is 3.25 m with SPT value of 10 that is underlain by a grey siltyto medium dense gravelly sands that reaches a depth of 27 m with SPT value of 30 where the borehole terminates. Borehole 3 also reveals a dark brownish grey silty peat layer that is 18.75 m that is subsequently underlain by dark grey siltyto slightly sandy peat, greyish silty clayey sand and greyish silty medium dense gravelly sands at depths (m) 18.75, 19.50, 20.25 and 23.25 respectively. The last two layers have SPT values range of 9 – 22. Similarly, borehole log 4 shows a dark brownish grey silty peat that occurs from 0 – 18.75 m. This is underlain by a thin layer (0.75 m) of dark grey siltyto slightly sandy peat, followed by 4.75 m thick greyish silty clayey sand with SPT value of 16, then a greyish silty medium to dense gravelly sands that extend till the termination of the borehole at depth 26 m with SPT range of 24 – 28 m.

The four logs therefore show that the area is comprised of an appreciable thick layer of peat that is inimical to the proposed waste water treatment plant, which therefore will make the use of shallow foundation undesirable. The correlation of the 2-D images and the four SPT borehole logs are shown in Figs 7, 8 and 9. This correlations show that there are lateral variations in the thicknesses of the sub soils and that the sand unit occur at depths generally beyond 20 m. Based on the results from the ERT, CPT and SPT with borehole logs, deep foundation, through pilling is recommended at depths of over 22.5 m in the area.The result of the chemical analysis of a water sample in the area shows that the groundwater has a pH of 6.88 and sulphate

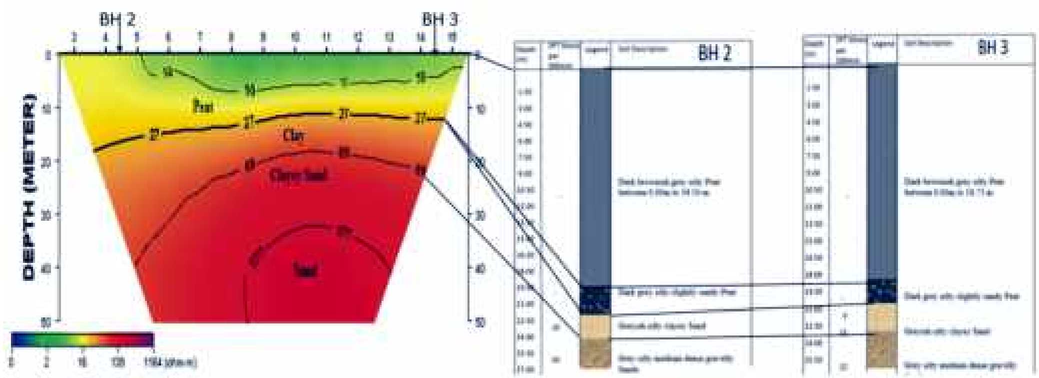

Fig 7: Correlation of 2D image (Traverse 2) with SPT Borehole logs (2 and 3) from the Study Area

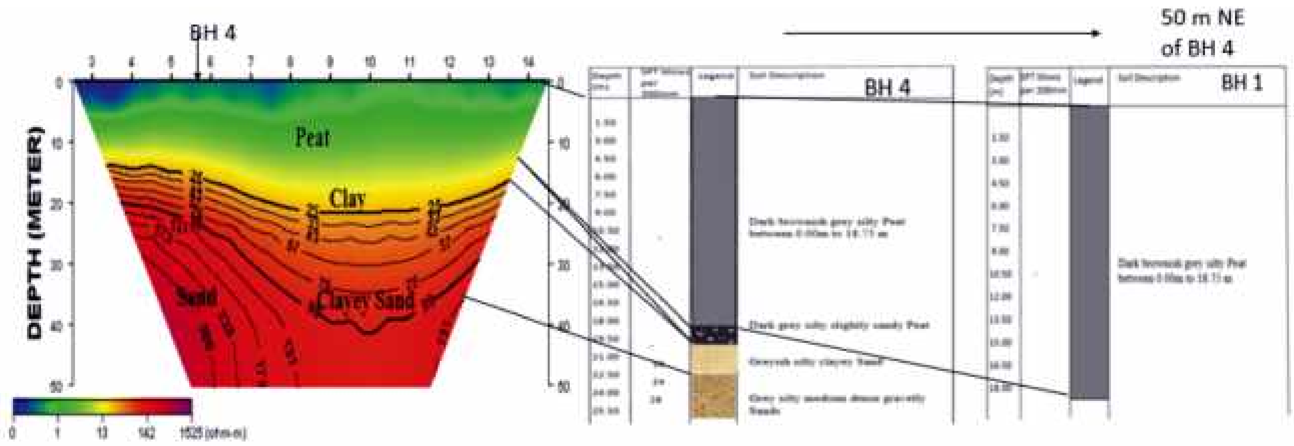

Fig 8: Correlation of 2D image (Traverse 3) with SPTBorehole logs (4 and 1) from the Study Area

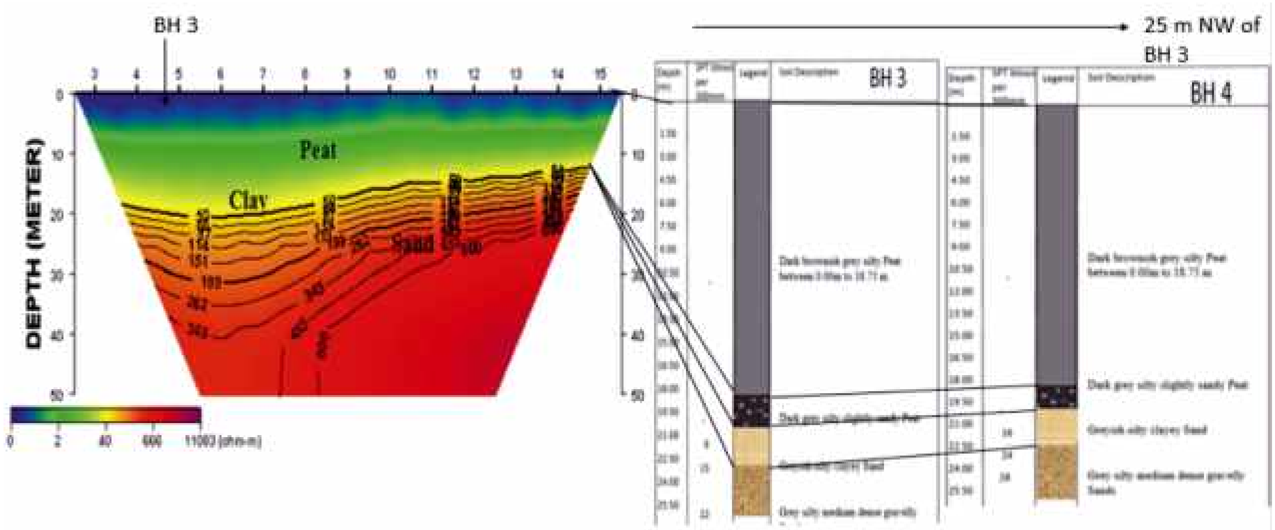

Fig 9: Correlation of 2D image (Traverse 4) with SPTBorehole logs (3 and 4) from the Study Area

Table 2: Results of the SPT Conducted in the Study Area

Depth Range (m)	Description	Range of SPT reading (No of Blow)
0.00 – 19.50 m	Dark grey silty very soft Peat	
18.00 – 21.75 m	Dark grey silty slightly sandy Peat	
19.50 – 22.25 m	Greyish clayey silty Sands	15-16
22.50 – 27m	Greyish medium dense gravelly Sands	22-30

concentration of 31 mg/l. These values are within the WHO standards (pH: 6.5 – 8.5; SO4: max. 500 mg/l) thus may not point to infiltration by pollutants or leachates. Based on these values, the groundwater at depths will therefore not be expected to pose any damage to Portland cement for buried concrete.

CONCLUSION

This study has adopted the use of 2D tomography and geotechnical methods with water chemical analysis in order evaluate the subsoil in the study area for its suitability to hold waste treatment plant. This paper has presented the characteristic nature of the subsurface layers, depth to competent layer and also predict if there is any possible infiltration of leachates into the groundwater with the aim of evaluating the suitability of the subsoil for construction of the proposed waste water treatment plant at the study area,. The geophysical and geotechnical methods revealed that the area is made up of peat, clay and sandy (competent) soils. The peat and clay constitute potential problem to the proposed plant as a result of their inherent poor bearing capacity and swelling/shrinking potentials. Because of the significantly thick nature of the peat and clay, a deep foundation through piling beyond a depth of 22.5 m is recommended. The chemical analysis carried out on the water sample in the area shows that it will not pose any hazard to buried concrete made from ordinary Portland cement as the plumes/leachates are confined to shallow depths due to the clay layer.

REFERENCES

Adebisi, N. O and Oloruntola, M. O (2006). Geophysical and geotechnical evaluation of foundation conditions of a site in Ago-Iwoye area, southwestern Nigeria. Journal of Mining and Geology, 42(1), 79 – 81

Adegoke, O.S. (1977): Stratigraphy and Paleontology of the Ewekoro Formation (Paleocene) of Southwestern Nigeria. Bulls. A Paleontol., Vol. 71, No. 295, 275pp.

Archie G.E. (1942) The Electrical Resistivity Log as an Aid in Determining Some ReservoirCharacteristics. Society of Petroleum Engineers, 146(1): 54-62

Ayolabi E.A., Folorunso A.F. and Oloruntola, M.O. 2010 Constraining Causes of Structural Failure Using Electrical Resistivity Tomography (ERT): A Case Study of Lagos, Southwestern, Nigeria," Mineral Wealth, Vol. 156, No. 4, , pp. 7-18.

Ayolabi E A., Folorunso A. F. andJegede O E. (2012). An application of 2D electrical resistivity tomography in geotechnical investigations of foundation defects: A case study. Journal of Geology and Mining Research, 3(12) 142-151

Boadu F. K. and Owusu-Nimo F. (2010). Influence of petrophysical and geotechnical engineering properties on the electrical response of unconsolidated earth materials, Geophysics, 75: 3, 21–29

Burke, K.C.B., Dessauvagie, T.F.J., Whiteman, A.J., (1971): The opening of the Gulf of Guinea and Geological History of the Benue Depression and Niger Delta. Nature Phys. Sci. 233 (38), 51-55.

Cosenza, P., E. Marmet, F. Rejiba, Y. J. Cui, A. Tabbagh, and Y. Charlery, (2006). Correlations between geotechnical and electrical data: A case study at Garchy in France: Journal ofApplied Geophysics, 60, 165–178.

DeyA., Morrison H.F. (1979). Resistivity modelling for arbitrary shaped two-dimensional Structures, Geophysical Prospecting, 27, pp. 1020-1036.

Enu, E.I. (1990): Aspect of Rock Evaluation Studies of the Maastrichtian – Eocene Sediments. Jour. Min and Geol., Vol 40(1), pp 29 – 40.

Folorunso, A.F. (2009): Integrated geological and resistivity imaging survey of Olabisi Onabanjo University Main Campus, Ago-Iwoye, Southwestern Nigeria. An unpublished M S c Dissertation, Dept of Earth Sci., OlabisiOnabanjo University, Ago-Iwoye, Nigeria, p. 136.

Folorunso, A. F., Ayolabi E. A., Ariyo, S. O., &Oyebanjo, I. O. (2012). Fault presence under a failing building complex mapped by electrical resistivity tomography. Mineral Wealth, Greece 166: 47-55

Jones, M.A. and Hockey, R.O., 1964: The Geology of Part of Southwestern Nigeria. Nig. Geol. Surv, Bull. No. 31, 101p.

Kamal, M. A., Ibrahim, M. and Abdelazim, M. I. (2015).Geotechnical properties of Sabkha Soil in the southern part of Al-Khobar city, KSA. Journal of Engineering Research and Applications, 5, 24-29.

Kingston, D.R., Dishroon, C.P.& Williams, P.A., (1983). Global Basin Classification System.AAPG. Bull., Vol. 67, pp. 2175-2193

Kirar, B., Maheshwari, B., Muley, P. (2016). Correlation between shear wave velocity (Vs) and SPT resistance (N) for Roorkee region. Int. J. Geosynthetics Ground Eng. 2 (1), 1–11.

Klemme, H.D. (1975). Geothermal Gradients, Heatflow and Hydrocarbon Recovery. In: A.G. Fischer and S. Judson (eds), Petroleum and Global Tectonics. Princeton, New Jersey, Princeton Univ. Press, pp. 251-304.

Loke,M.H. (2000): Electrical Imaging Surveys for Environmental and Engineering Studies: A Practical Guide to 2D and 3D Surveys. www.terrajp.co.jp/lokenote.pdf,2004. P.59

NPC (2006)National Population Commissions (NPC): Provisional of 2006 Nigeria Census Results.

Obaje N.G. (2009) Geology and mineral resources of Nigeria, Springer Dordrecht Heidelberg London New York.p 221p. doi:10.1007/978-3-540-92685-6

Ogbe, F.G.A. (1972): Stratigraphy of Strata Exposed in the Ewekoro Quarry, Southwestern Nigeria. In: T.F.J. Dessauvagie and Whiteman (Eds) African Geology, University Press, Nigeria, pp. 305

Omatsola, M. E. and Adegoke, O. S. (1981).Tectonic evolution and Cretaceous stratigraphy of the Dahomey Basin. Jour. Mining and Geol. 18 (1) 130 – 137.

Seabrook, B., and F. K. Boadu, (2002). Relating electrical response and petrophysical properties of sands subjected to stress changes: Journal of Environmental and Engineering Geophysics, 7, 88–99.

Silvester, P.P., Ferrari, R.L. (1990). Finite elements for electrical engineers, 2nd ed., Cambridge University Press

Sudha, K.I., Mittal, S. and Rai, J.(2009).Soil characterization using electrical resistivity tomography and geotechnical investigations. J. Appl. Geophys. 67 (1) 74–79.

UNEP (2016): A Snapshot of the World's Water Quality: Towards a global assessment. United Nations Environment Programme, Nairobi, Kenya. 162 pp

Whiteman, A.J., (1982): Nigeria: Its Petroleum Geology, Resources and Potential, Vol. 2, Grahan and Trontman, London.

World Health Organisation, (2006).Guidelines for drinking water. 3rd Edition, Geneva.