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Geoengineering Spatial Mapping for Safe and Economic Design of Building and Earthwork Structures in Northern Part of Ondo State, Nigeria

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Abstract: The objectives of the study are to assess the engineering competence of the subsoil and develop a subsoil competence map for northern parts of Ondo State, Nigeria, using integrated remote sensing, geotechnical, geophysical and geological investigations, and hydrogeological measurements. The generated subsoil competence map was obtained by integrating the results data of these parameters measured: topsoil resistivity and thickness, plasticity index, shear strength, allowable bearing pressure, soil association, lineament density, and groundwater level. Based on the design, the obtained settlement values were within the 25 mm commonly recommended. Consequently, the map classified the study area into moderate competence (60%), high competence (35%), and very high competence (5%). The corrosivity map of the topsoil shows predominant moderate to mildly corrosivity, prominently in Ose and Akoko areas and constitutes about 70 %. This type of corrosivity is suitable for buried communication equipment and electrodes. In conclusion, shallow foundations such as pad or raft foundation of reinforced concrete can be adopted for buildings. Also, the soil geotechnical properties will support adequately road structures and various earthworks. However, areas characterized by moderate competence material can be improved by less expensive mechanical compaction and proper use of admixtures (lime, cement, bituminous addition, sand/gravel grading) to increase bearing capacity, compaction, and shear strength, which will invariably reduce compressibility, settlement, and permeability.

Keywords: Soil competence, foundation, groundwater level, bearing capacity, remote sensing

Introduction

Engineering structures are designed and constructed with long life expectancy, however, the increasing rate of structural collapse such as buildings, roads, drainages, bridges (Dimuna, 2010; Fagbenle and Oluwunmi, 2010), in Nigeria is becoming worrisome (Faseki et al., 2016; Adebowale et al., 2016; Chendo and Obi, 2015; Amadi et al., 2012). In recent years, reports of the collapse of these structures had been attributed to inadequate bearing pressure, poor building materials, foundation failures, inadequate knowledge of the physical parameters governing the competency of the soil supporting engineering structures, lack of supervision, etc. Although several structures have collapsed, even though efficiently built with standard materials, well supervised and managed, and the design plan was adequately followed and properly executed, yet still failed. Therefore, it boils down to this question, "Was there any pre-foundation site investigation?" before the construction of such structures. Therefore, failures of structures do not happen suddenly, but rather systematically at the design, and construction phases. Also, many engineers usually assume the bearing capacity of many sites based on experience rather than by empirical deduction. Consequently, the importance of engineering site investigation cannot be over-emphasized in the construction industry, as the information it furnishes would in a long run assist in the safe and economic design of civil engineering structures (Olayanju et al., 2017. The primary purpose of all site investigations is to obtain the data needed for analysis and design (Oyedele et al., 2011; Ayolabi et al., 2012).

A Physical property governing the stability of structures includes but is not limited to these: unit weights, porosity, consolidation, specific gravity, consistency limits of the soil in association in water, bearing capacity, shear strength, compaction characteristics (Murthy, 1984; Meyerhof, 1951). Also, these properties depend on the nature of soil or rock in terms of mineralogical contents, texture, and geologic structures (Oyedele et al., 2011; Bayode et al., 2012; Faseki et al., 2016). Therefore, for engineering site investigation to be effective, it must employ an integrated method or multidisciplinary approach. It should involve geomorphological, geological, groundwater studies, remote sensing, geophysical

investigation, geotechnical investigation/analysis, and borehole logging. Therefore many researchers have failed in this area by not using combined methods or integrated approach, especially where geophysical methods are used; many failed to constrain the interpretation of their geophysical results with borehole logging. Also, many couldn't map or take cognizance of the groundwater table and flow direction. All these information gaps in the previous works were considered in this study by integrating all these methods to evaluate and characterized the northern part of Ondo State into different engineering subsoil competence zones, for construction purposes and building development. The findings of the study would aid the structural engineer and builders in the design of appropriate structures and earthwork that command professional feat.

Geophysical, geochemical, and geotechnical methods are widely used in engineering foundation assessment/subsoil exploration. Geotechnical investigation of the soil is discrete, invasive, and expensive; while the geophysical investigation is continuous, non-invasive, and cost-effective (Oyedele et al., 2014; Robert, 2010). The geophysical method is capable of investigating, detecting, and determining soil geotechnical properties, inhomogeneity of the subsurface, etc. Some of the commonly employed geophysical methods in engineering site investigation are the electrical method (vertical electrical sounding, very low frequency electromagnetic) seismic, magnetic, gravity, borehole logging. The advantages of geophysical methods are speed, cost-effectiveness. Cone penetration test and standard penetration test are the two most commonly used in-situ geotechnical methods (Ngah and Nwankwoala, 2013; Nwankwoala and Amadi, 2013; Oghenero et al., 2014; Youdeowei and Nwankwoala, 2013). They are the very rugged, accurate, and fast (but costly) method of characterizing the soil in terms of strength, layering, and deformation characteristics. Also, laboratory soil analysis is usually combined with a field test to determine geotechnical soil properties such as classification, chemical, and mechanical properties (Vickers, 1978; Tomlinson, 1999; Falowo and Ajiboye, 2020; Falowo, 2020; Oke and Amadi, 2008). Therefore, this study is aimed at establishing a subsoil engineering competence map for the northern part of Ondo State, Nigeria for the safe and economic design of buildings, roads, drainages, etc.

Material and Methods

Study Area

The study area is located within the northern part of Ondo State, Nigeria (Fig. 1). The selected areas include Owo, Akoko, and Use. These areas are located within longitudes 5°20´E and 6°10´E and latitudes 6°30´N and 7°40´N. The area is accessible through the Benin - Ifon highway, Abuja - Lokoja Highway, and Ado-Akure Highway. The study area has a topographical elevation varying from 80 – 750 m above the sea level. The northern part of the study area is a rugged terrain (i.e. hilly) especially in the Akoko area (Marans and Rodgers, 1975) (Fig. 2). The lowlands are widespread at the Ute and Okeluse axes of the area with a gentle slope, while the gradient of the northern areas is generally steep. Another aspect of the relief of the area is the prevalence of many erosion gullies along hill slopes (Fig. 3). The gullies are very common and rather devastating in Owo, Ifon, Ikare, Oke Agbe, and Isua.

The mean annual temperature is between 21°C and 33°C (Fig. 4) with a mean temperature of 24°C and a mean humidity of 80%. The mean temperature is highest at the end of the Harmattan (averaging 28°C), which is from the middle of January to the onset of the rains in the middle of March. The area is situated within the tropical rain forest region, with a climate characterized by dry and wet seasons. According to the Federal Meteorological Survey (Federal Meteorological Survey, 1982), the annual rainfall ranges between 1000 and 1800 mm, with a mean annual rainfall of 1500 mm (Fig. 4c). The vegetation is the rainforest type and is composed of teak, Melina/pulpwood (Fig. 1), tall crowned trees mixed with thick undergrowth, and woody savannah. The vegetation is of distinct arrangement with tall trees of about 60 m in height, with smaller herbaceous plants found below them.

The geology of the study area is of Precambrian Basement rocks of Southwestern Nigeria and includes the Migmatized gneissic complex (MGC) of Achaean to early Proterozoic age (Dada, 1999) N-S trending Schist Belts of Upper Proterozoic age (Rahman, 1988) and the Older Granitoid of Pan African age. The major rocks in the area comprise migmatite, granite gneiss, fine-grained quartzite, pegmatite and quartzo-feldspathic veins, schist, and quartz schist. These rock types dominate Owo and Akoko areas, notably along Owo – Oba Akoko, Iwaro – Akungba, Akungba – Supare, Ikare, Epinmi, Sosan, Oke Agbe, and Ido Ani.

The migmatite complex which is the most widespread basement rock in the area is mainly medium-grained gneiss. They are strongly foliated rocks frequently occurring as outcrops. On the surface of these outcrops, severely contorted, alternating bands of dark and light-colored minerals can be seen. These bands of light-colored minerals are essentially feldspar and quartz, while the dark-colored bands contain abundant biotite. A small proportion of the area especially to the northeast overlies the coarse-grained granites and gneisses, which are poor in ferromagnesian minerals. These rocks are covered by regoliths with thickness variation across the town. The sedimentary rocks/deposit is mainly of the post-Cretaceous sediments and the Cretaceous Abeokuta Formation. The major surface waters in the study area are rivers Ogbese, and Ose (Fig. 5b). Others are the small tributaries joining the major rivers (Fig. 5b). The volume of water in the streams depends on the seasons. During the rainy season, there is a great increase in water flow volume in the major rivers while there is hard water in some of the streams during the dry season. Therefore, rainfall is the dominant factor that determines the occurrence of groundwater. The soils derived from the basement complex rocks are mostly well-drained, with a medium texture (Smith and Montgomery, 1962). The major soil associations in the study area are Iwo, Ondo, and Okemesi (Fig. 6). The soil classified as Iwo Association is the most prominent soil type. All the soil associations are well-drained.

Field Survey, Sample Collection, and Laboratory Analysis

The investigation involved exploration and sampling of soil likely to be significantly affected by structural loads. The research work entailed:

1. Literature Review: The research work involved literature review of texts, technical journals, various articles, past projects thesis, etc., as related to the uses of geotechnical, remote sensing, and geophysics as tools in engineering site investigation and groundwater studies. Existing Landsat-7 ETM+ satellite imageries were used for the production of the lineament map of the study area.

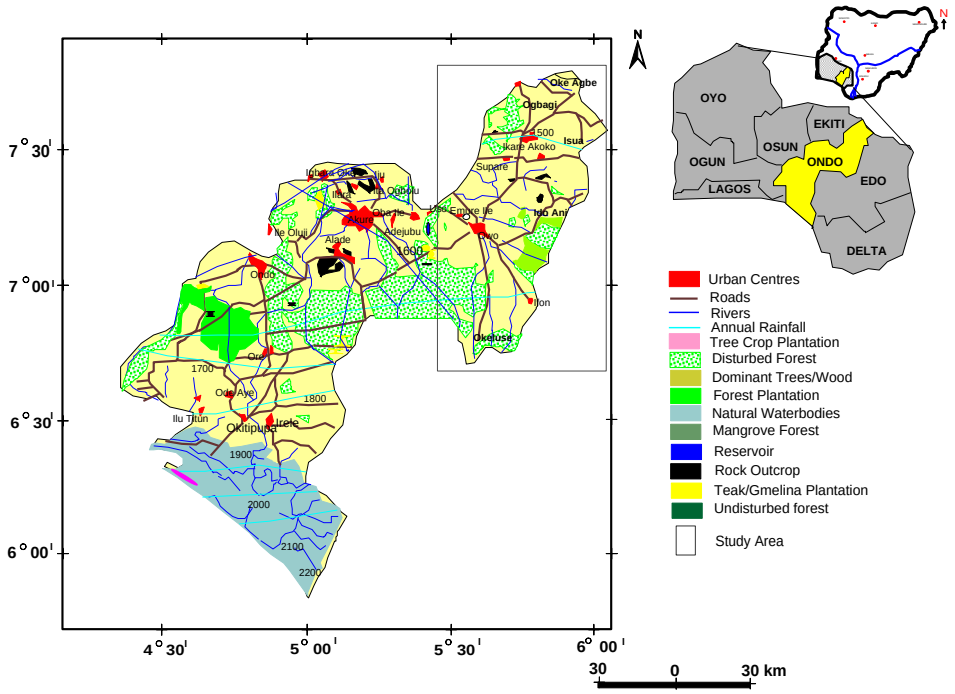
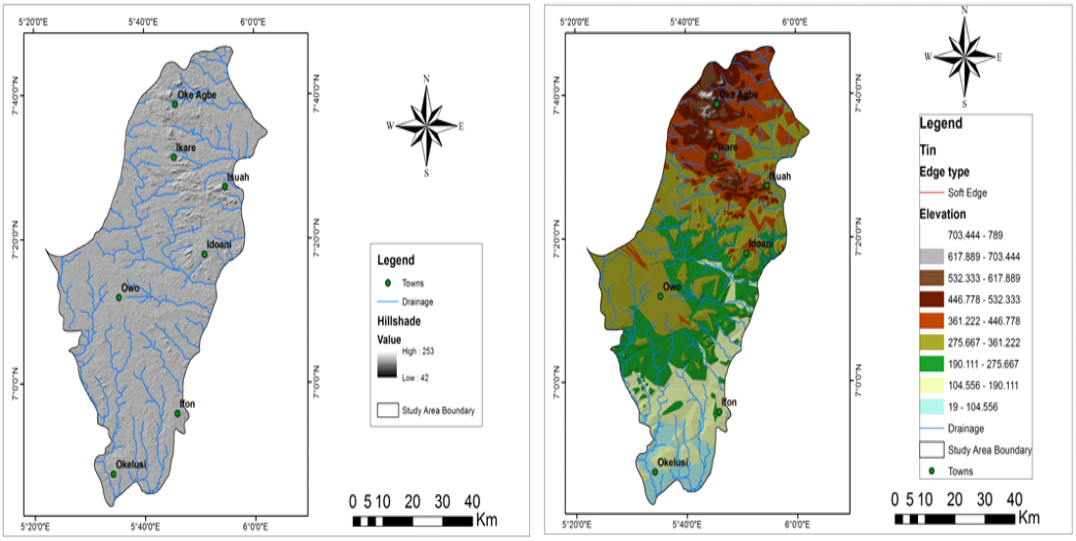


Fig. 1 Land Use Map of the Study Area showing predominant Teak/Gmelina Plantation and Disturbed Forest. Inset: Location of Ondo State on Nigeria Map (Adapted from Daramola et al., 2009)



(a) (b)

Fig. 2 Topographical Elevation of the study area (a) Hill Shaded obtained from ASTER DEM data (b) Triangular irregular Network

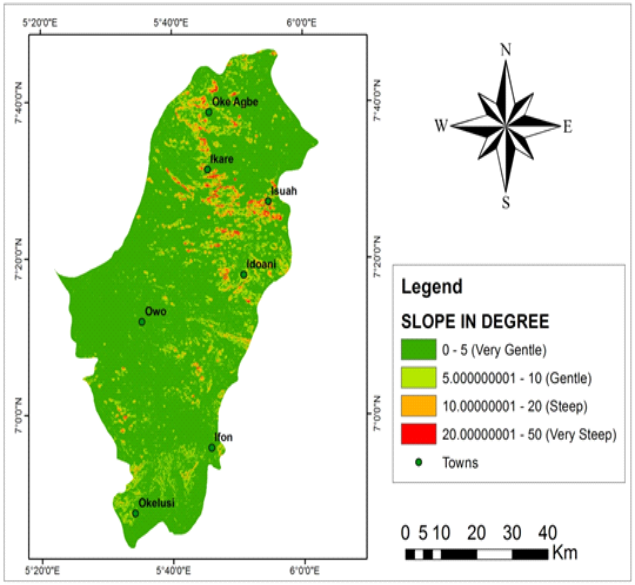


Fig. 3 Slope Map of the Study area with northern areas showing very steep gradient, while Owo and Ose are a predominantly gentle slope

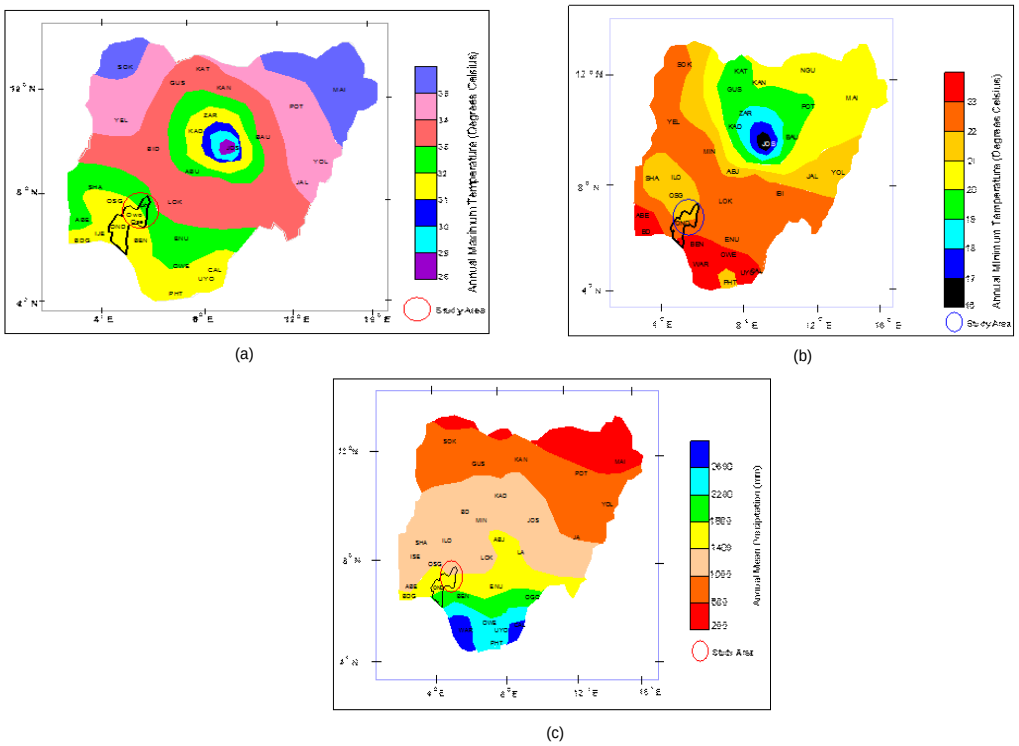


Fig. 4 (a) Annual minimum temperature across Nigeria showing a range of 20 - 23 °C in the study area (b) Annual maximum temperature ranging from 31 – 33 °C (c) Annual mean precipitation across Nigeria with a range of 1000 – 1800mm in the study area.

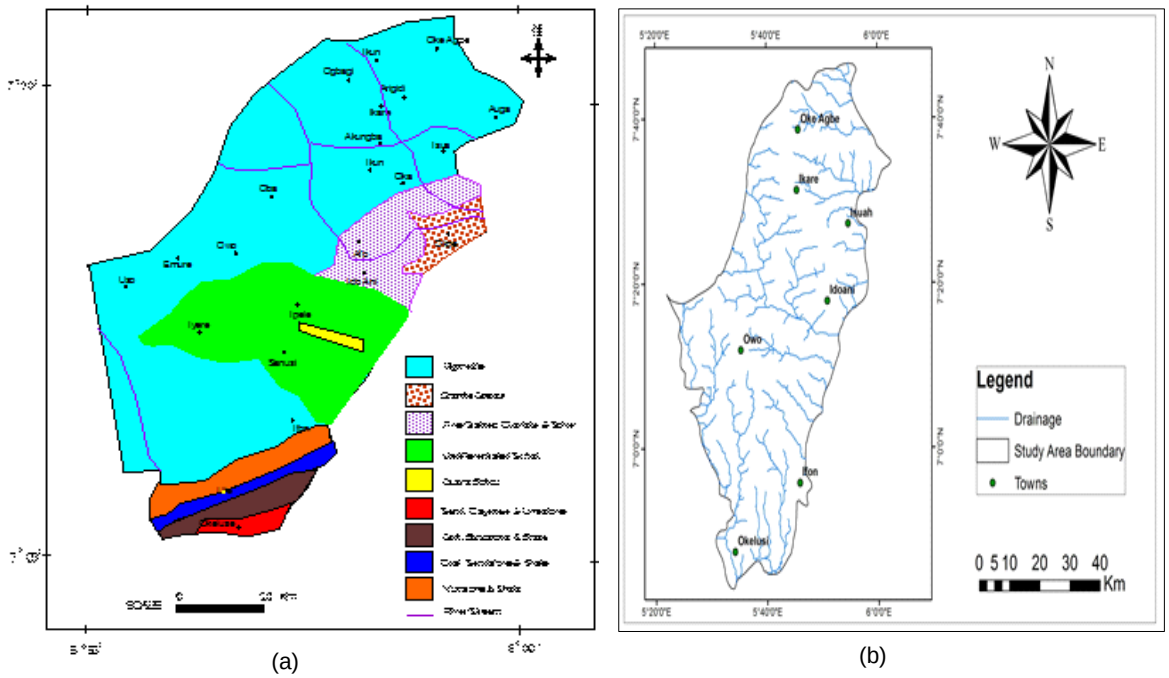


Fig. 5 Local Geology Map of the Study Area with the Basement rocks occupying 90% of the area, while the sedimentary rocks/deposits occupy a little portion of the southern area (b) Drainage Map of the Study area showing a predominantly Dendritic Drainage Patterns.

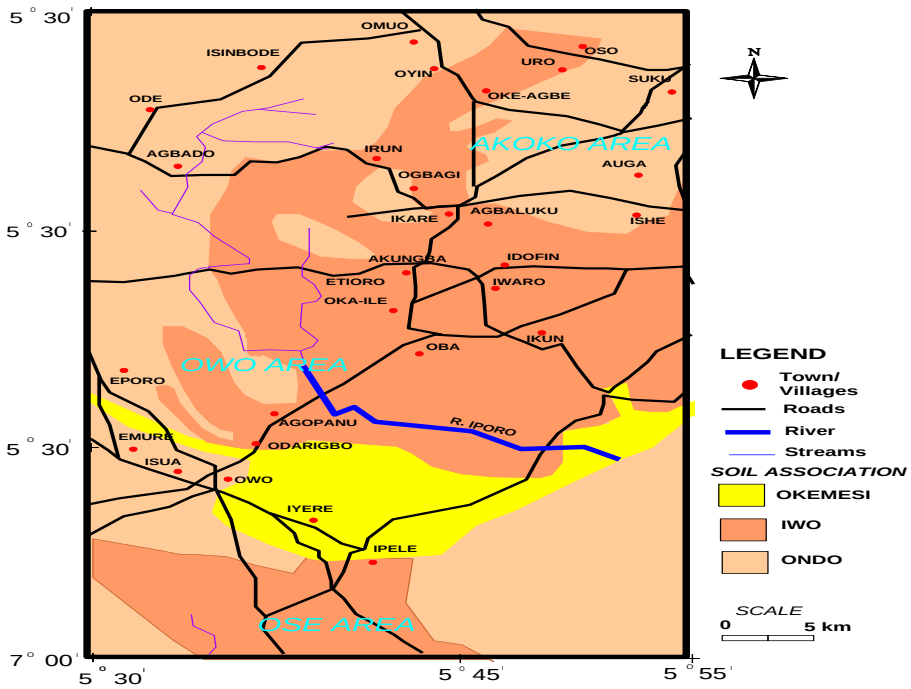


Fig. 6 Soil Map of the Study Area (Extracted from Smith and Montgomery, 1962)

2. Reconnaissance Studies and Desk Study: The purpose of the site reconnaissance is to confirm and obtain additional information from the site. This includes taking notes of the geologic and topographic setting of the area, taking photographs of the site. A personal interview was made with residents of the area with the relevant information which will assist in carrying out the research successfully. Also, sample points locations for geotechnical investigation were marked and pegged respectively. The desk study included reviewing/updating and reconciling the information obtained during the reconnaissance study and those obtained during the review of journals and various articles. Subsequently, the following information was reviewed:

(a) Geological Maps/Report: The geological map/report together with an understanding mode of origin of the rocks and the associated depositional process enabled a preliminary assessment of ground condition.

(b) Topographical Map: The topographical map was used to examine the terrain, access, and site condition. The topographic map was confirmed through site reconnaissance.

(c) Site Histories and Details of Adjacent Development: Also important information such as land use before the current development and underground services (like buried pipes and utilities) were acquired before the planning and conduct of the field test.

3. Geophysical Investigation: The geophysical investigation involving electrical resistivity (Vertical Electrical Sounding (VES) and Dipole-Dipole profiling); Very Low-Frequency Electromagnetic (VLF-EM) were carried out along thirty-six traverses (Fig. 7). The geographic coordinates of data stations were taken using GARMIN'S GPS 12 - Channel model. One hundred and three (103) sounding stations were occupied with current electrode spacing varied from 1 to 225m.

4. Geotechnical Investigation: Twenty-four soil samples were taken according to the geology/rock units in the area (at a depth less than 3m) from borough pits (Fig. 7). These samples were subjected to grain size analysis, specific gravity determination; natural moisture content test, consistency limit test, compaction test, cone penetrometer test, undrained triaxial test, shear strength, and bearing capacity were determined.

5. Hydro-geological Measurement: This includes the determination of the hydraulic head of wells/borehole and measurement of static water levels from three hundred and two (302) water wells using a water level meter recorder (Fig. 7).

The geophysical data were interpreted qualitatively and quantitatively, as related to the objectives of the study. Profiles, maps, geoelectric section, graphs, chart were produced from the interpretation of both geophysical, geotechnical, and hydrogeological data.

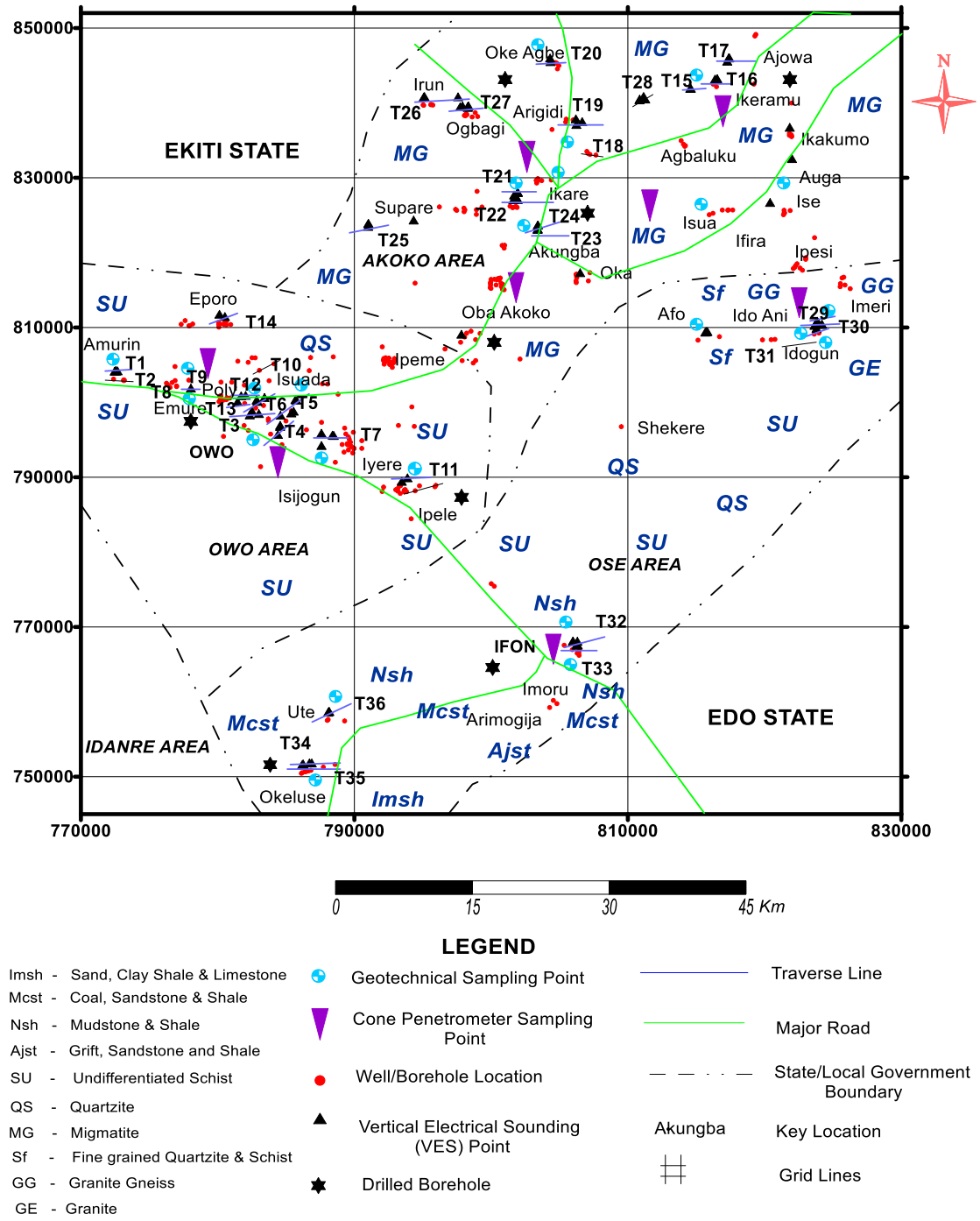


Fig. 7 Data Acquisition Map of Study Area showing the Vertical Electrical Sounding Stations, Borehole Points, and Geotechnical Sampling Points

Results and Discussion

Lineament Analysis

Some of the lineaments mapped are joints and faults. Other linear features are suspected to be fracture and fissure zones. As shown by the lineament map (Fig. 8) four major structural trends that are typical of the Nigerian basement complex are all represented in this area. These include the NE – SW, NW – SE, N- S, and EW trends (Fig. 8). The predominant structural trend is NE – SW. The lineament map shows a wide spatial variation as the lineaments are generally sparse in the southern areas (Ifon – Okeluse), and high in the Akoko area, especially around Oba, Isua, Ogbagi, Ikun, and Irun. The denser lineaments area typified the intensity of rock fracturing, which is a prerequisite for the development of hollow passages over an area. According to (Edet et al., 1998) the zones of relatively high lineament density are identified as zones of the high degree of rock fracturing, which are prerequisites for groundwater conduit development which might be inimical to foundation structures especially when they occur at shallow depth. The lineament intersection provides an interpretation of hidden subsurface tectonic configuration in the form of linear feature intersection/cross cutting geological structures, which are indicators of deep-seated fracture/fault medium. Figure 8a shows that the areas underlain by high density are characterized by relatively high lineament intersection. The zones of high-lineament intersection over the study must be seriously taken into consideration during the design process of structures and utilities in the study area, especially areas where the rock outcrops.

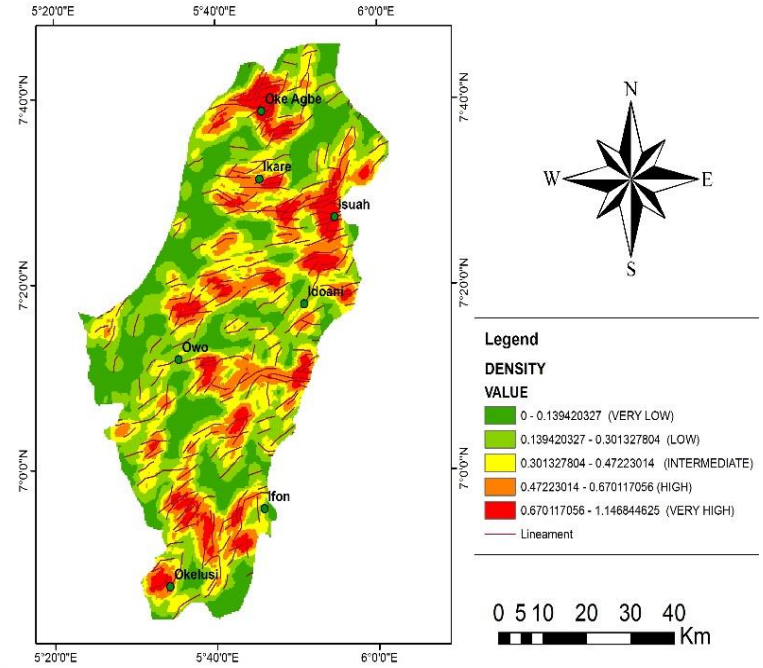
Geophysical Investigation

Table 1 gives a summary of the results of the VES curves obtained from the study area. The number of layers varies between three (3) layers and six (6) layers. Ten curve types have been identified: A, H, HA, HK, KQ, KH, QH, HKH, KHK, and KHKH (Fig. 9) The most occurring curve types identified are H, HA, and KH. Typical curve types are shown in Fig. 10. These type curves can be classified into four distinct classes about their engineering competence (Table 2) by using their interpreted resistivity and thickness values as Class 1, 2, 3, and 4 and are rated very good, good, moderate, and fair respectively. A-curve type is rated “very good” and widely found in the Akoko area; KH, KHK, KHKH, and KQ are rated “good”; HK and HKH are rated “moderate”; and H, HA, and QH are rated “fair”.

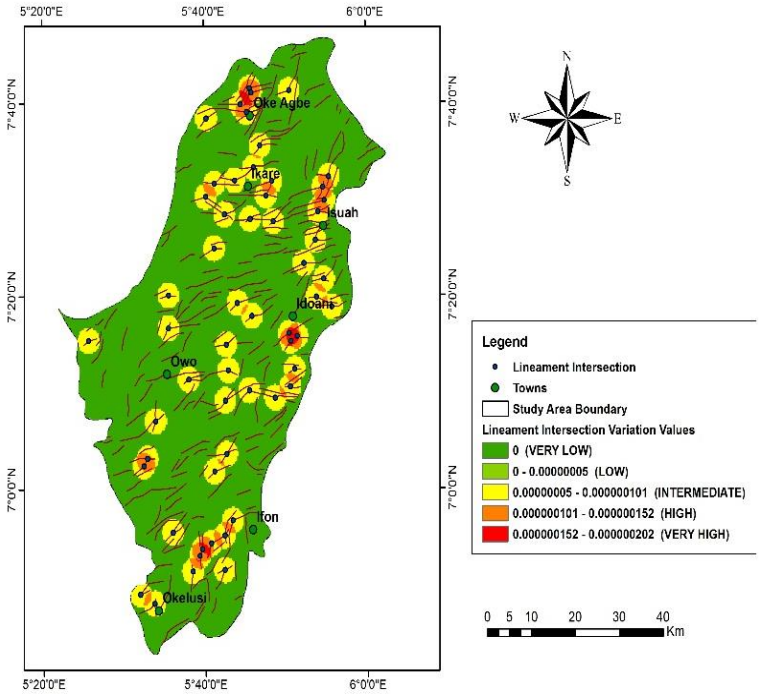
Geoelectrical Maps

The topsoil competence and corrosivity map of the uppermost 5 m and depth to basement rock over the study area are presented in Figures 11-13 respectively. The topsoil constitutes the layer within which a normal engineering foundation is founded especially in the basement complex (Olorunfemi, 2008), and can be qualitatively evaluated from layer resistivity and the geotechnical parameter. Figure 11 shows a predominant moderate competence in Okeluse, Elegbeka, Amurin, Owo, Ipele, Ido Ani, Imeri, and about constitutes about 60 % of the Akoko area. The moderate competent soil accounts for 70 % of topsoil with a resistivity between 100 Ω-m and 350 Ω-m. Areas that show incompetency include Ikun, Oba, and Aiyegunle and account for 15 % with a resistivity less than 100 Ω-m. High competent areas are observed in Isijogun, Arigidi, Ehinogbe, Agbaluku, and Ajowan. These areas are underlain by quartzite, granite, granite gneiss and gneiss, and account for about 15 %. Therefore, civil engineering foundation structure can be carried out in the study area without any failure expectation (on the basis of resistivity values obtained), while Ikun, Aiyegunle, and Oba can be graded or stabilized with more competent soil like laterite, sand, or gravel to increase their density, compaction, and bearing capacity.

The corrosivity map of the topsoil shows predominant moderate to mildly corrosivity and very prominently in Ose and Akoko areas, and constitute about 70 %. The essentially non-corrosive areas which account for 10 % are observed in Ajowa, Agbaluku, Ehinogbe, and Isijogun. However, the corrosivity of the subsoil in the study area shows that Akoko area is essentially non-corrosive except few places like Oba, Ikun, Ipesi, some parts of Irun. Our area and Ose are moderately/mildly corrosive. Figure 13 shows the overburden thickness/depth to basement rock across the study area. It shows that Akoko area (except Oke Agbe, Agbaluku, and part of Ikare) are generally characterized by thin overburden thickness less than 10 m and signifies shallow depth to basement rock and low depth of weathering; while Owo and Ose have thick overburden thickness ranging from 10 m to 50 m.



(a)



(b)

Fig. 8 (a) Lineament Density map (b) Lineament Interception map generated for the study

Table 1 Curve Types and their Statistical Frequency obtained from the Study Area

Location/Curve Type	HKH	H	HA	HK	KHKH	KQ	KH	A	KHK	QH	Total No. of VES Curves
Owo Area	2	15	2	4	3	1	6	2	-	-	35
Akoko Area	-	25	9	-	-	-	1	8	-	-	43
Ose Area	3	5	5	-	-	1	8	-	1	2	25
Frequency (unit)	5	45	16	4	3	2	15	10	1	2	-
Frequency (%)	4.8	43.6	15.5	3.8	2.9	1.9	14.5	9.7	0.9	1.9	-

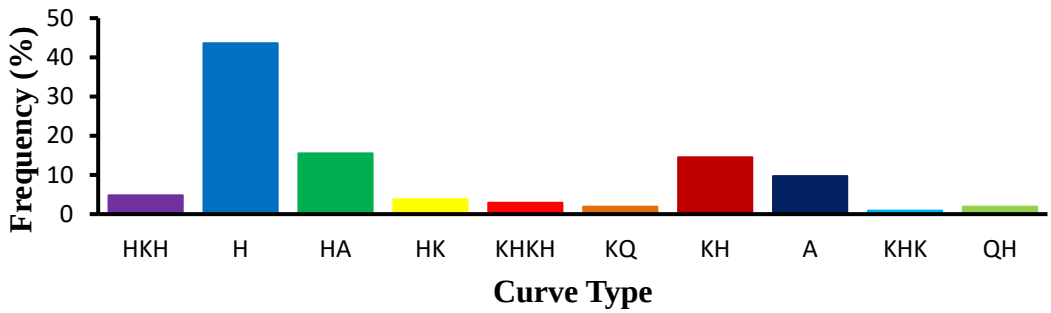


Fig. 9 Curve Types obtained in the Study Area with a predominant H-Curve

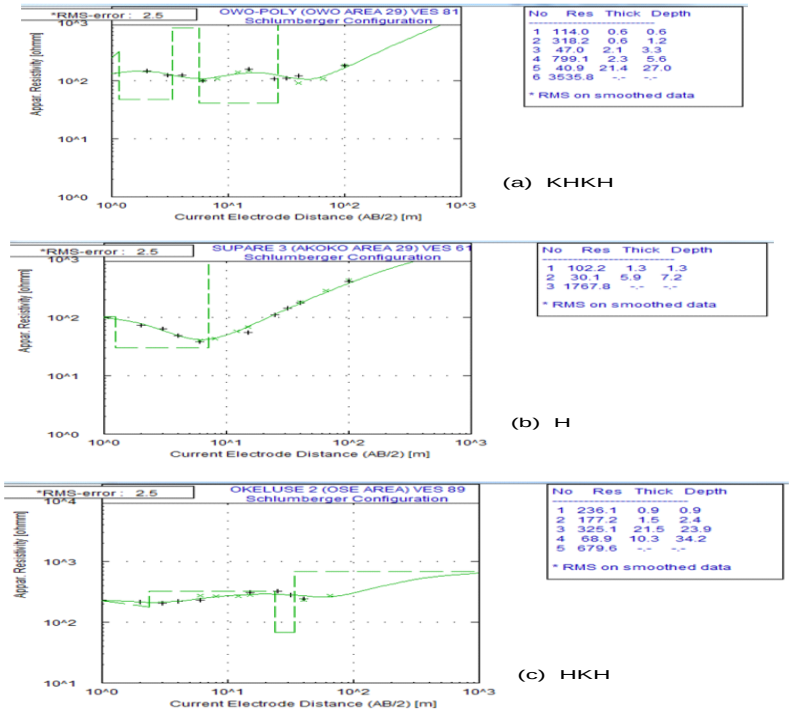


Fig. 10 Typical Curve Types obtained in the Study Area

The corrosivity map of the topsoil shows predominant moderate to mildly corrosivity and very prominently in Ose and Akoko areas, and constitute about 70 %. The essentially non-corrosive areas which account for 10 % are observed in Ajowa, Agbaluku, Ehinogbe, and Isijogun. However, the corrosivity of the subsoil in the study area shows that the Akoko area is essentially non-corrosive except few places like Oba, Ikun, Ipesi, some parts of Irun. Our area and Ose are moderately/mildly corrosive. Figure 13 shows the overburden thickness/depth to basement rock across the study area. It shows that Akoko area (except Oke Agbe, Agbaluku, and part of Ikare) are generally characterized by thin overburden thickness less than 10 m and signifies shallow depth to basement rock and low depth of weathering; while Owo and Ose have thick overburden thickness ranging from 10 m to 50 m.

Hydrogeological Measurement

A good set of reliable groundwater level measurements is the best foundation on which to build an understanding of a groundwater system. Groundwater conditions play an important part in the stability of foundations. If the water table lies very close to the base of footings, the bearing capacity and settlement characteristics of the soil would be affected. The water level in the well represents the water table or phreatic surface. Static water level refers to the level of water in a well or borehole under normal, undisturbed, no- pumping conditions. The hydraulic head obtained in the area was used to determine the groundwater flow direction as presented in Figure 14. The static water level measured in Owo varies from 1.2 m to 14.7 m with an average of 6.5 m. In the Akoko area, it ranges between 0.8 m and 15.2 with an average of 1.8 m; while in the Ose area, it is between 3.1 – 15.9 m and an average of 10 m. The hydraulic head recorded in Ose and Owo ranges between 40 m (Okeluse) – 390 m (Ido Ani) and 240 to 390 m respectively. Akoko area varies between 290 and 540 m (Irun, Arigidi, Oke Agbe). The general groundwater flow direction is south. Consequently, the SWL in the northern areas is very high indicating a likelihood of high-water levels during the rainy season (which could even lead to spring condition), which may affect basement/foundation footings, and subsequently compromise the integrity of such structures.

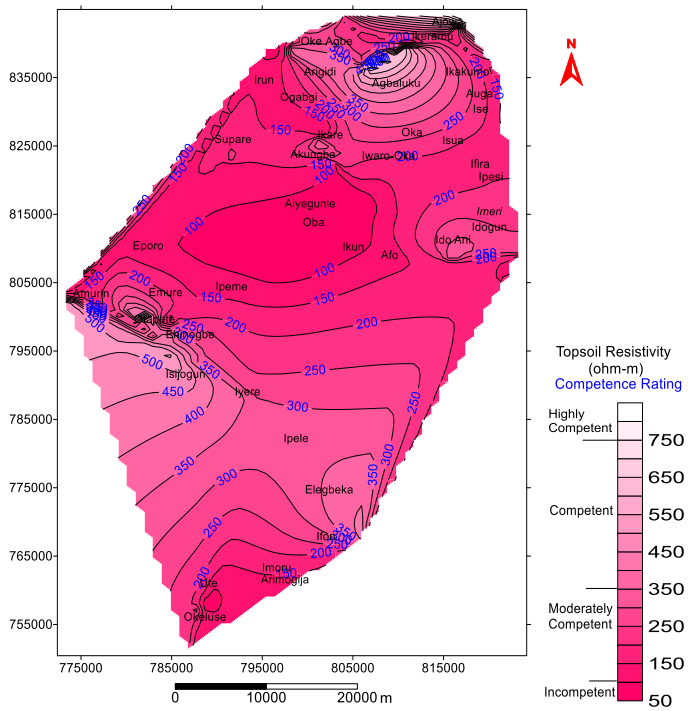


Fig. 11 Map showing Topsoil Competence with prominent moderate competence

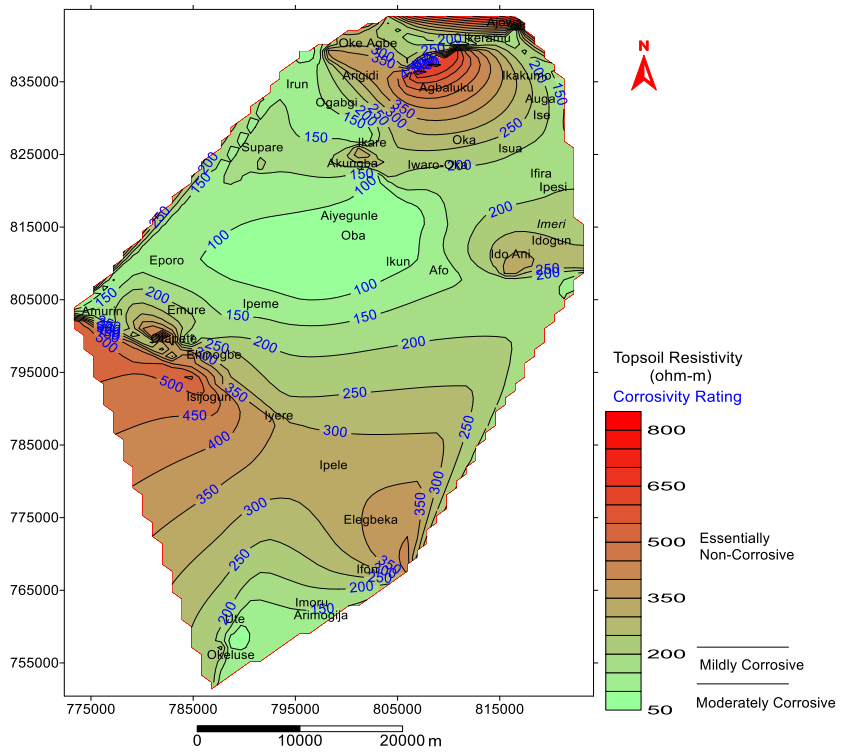


Fig. 12 Map showing Topsoil Corrosivity, with pronounced mildly/Essentially noncorrosive

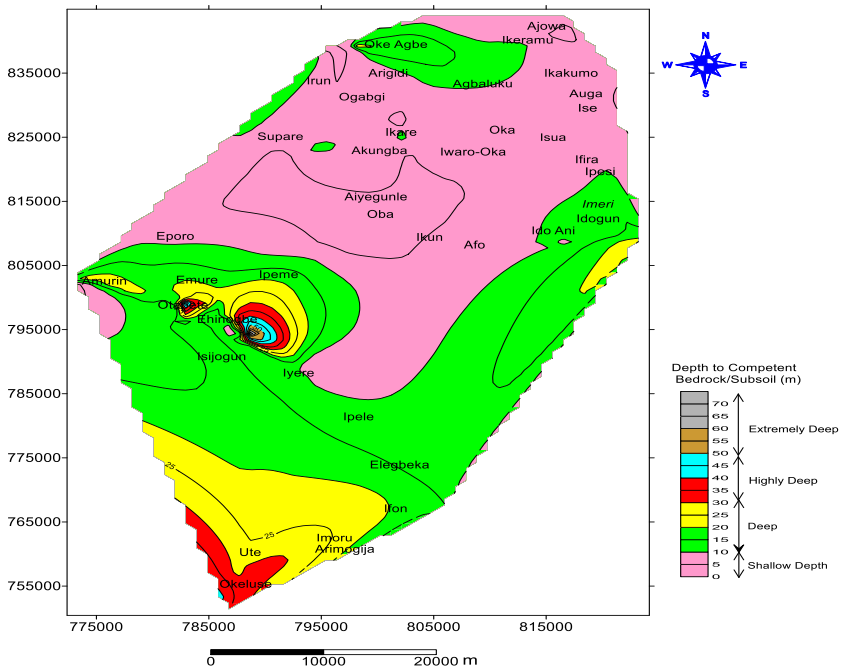


Fig. 13 Map of Depth to Basement of the Study area

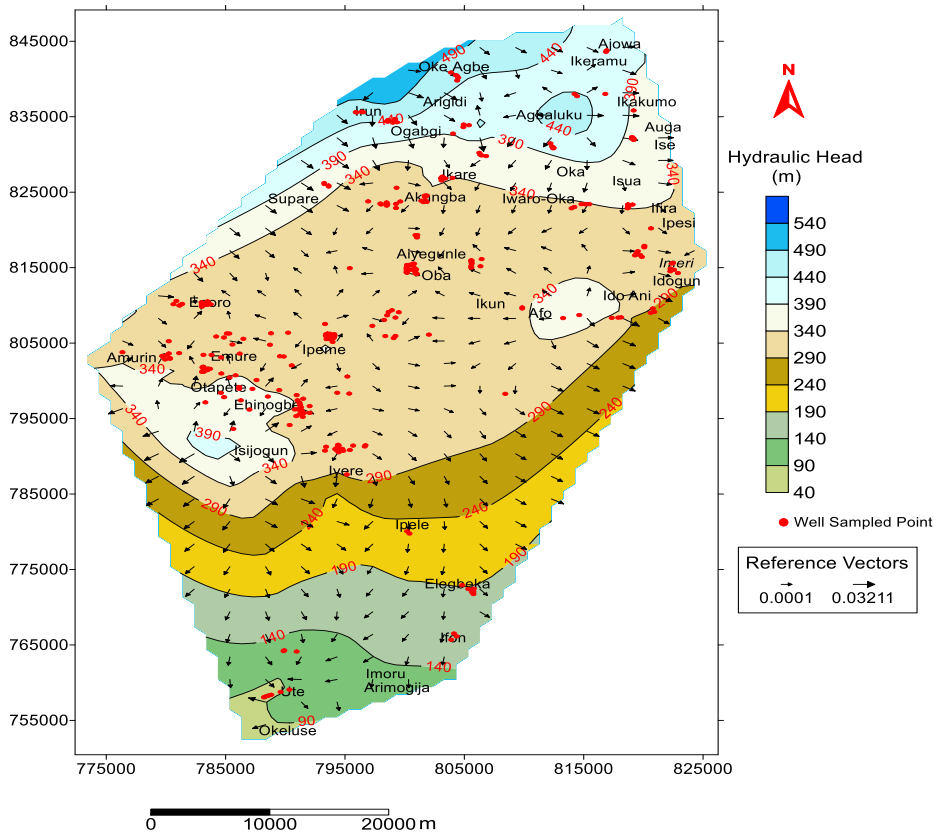


Fig. 14 An overlay of Contoured Static Water Level and 1-Grid Vector Layer obtained in the Study Area with presumably North-South Flow direction.

Geotechnical Investigation

The summary of the geotechnical results is presented in Tables 3-5. The various values of Natural Moisture Content (NMC) obtained from laboratory tests are presented in Table 3. The natural moisture content gives information on the condition of the soil. The natural moisture content of soils varied from 4.3 % to 17.4 %, with an average of 10.4 %. The samples have low moisture content in their natural state. The tested soils show % fines (percentage passing 0.002 mm) variation of 14.5 – 54.6 %, with an average of 33.3 %. The % of sand and gravel in the sampled soils vary from 42.2 % to 76 % and 1.1 % to 5.5 % respectively. Therefore the soils are dominated by sand and clay (clayey sand) except in One area where the soils are dominantly clay (with classification group of sand-clay).

Based on British Standard BS 1377 (1990) if the percentage fine is less than 35 % it is adjudged a good foundation material. Therefore, the soil samples can be generally classified as suitable foundation material since the mean % of fines are less than 35%. However, samples taken from the Ose area need some level of stabilization due to the high % of fines (clay) with high plasticity (Nwankwoala and Warmate, 2014; Falowo and Otuaga, 2020). The specific gravity correlates well with the mechanical strength of subgrade and depends on the amount of sand and also on mineral constituents and mode of formation of the soil. The specific gravity (Gs) for all the soil samples and vary between 2.64 - 2.76 with an average of 2.70, these values portray resistant soil material (Brink et al., 1992).

The liquid limit, plastic limit, and plasticity index of the soil samples vary from 22.2 % to 54.2 %, 11.0 % to 26.6 %, and 2.95 % to 29.05 %, with average values of 39.8 %, 23.2 %, and 16.2% respectively. Good foundation materials must among other significant criteria be of low plasticity such that its resistance to swelling, total expansion, and linear shrinkage should be minimal. The high plasticity index and liquid limit values are indicative of poor engineering properties. The Federal Ministry of Works and Housing (1972) recommended liquid limits of 50 % maximum, plastic limits of 30 % maximum, plasticity index of 20 % maximum for civil engineering foundation/construction material. The liquid limit of the soils is generally less than 50 %, while the plastic limits are generally lower than 30 % and the plasticity index is generally lower than 20 % except for samples AK 5 and 6 which are greater

than 20 %. Hence, most of the studied soils fall within the specification. Linear shrinkage is an important parameter in the evaluation of material soils for foundation construction. It has been suggested that a linear shrinkage (LS) value below 8 % is indicative of a soil that is good for foundation material (Brink et al., 1992; Madedor, 1983). The lower the linear shrinkage, the lesser the tendency of the soil to shrink when desiccated. The values range between 7.4 % and 13.4 % with an average value of 9.8 %, these soils can be classified as medium good material.

The importance of the compaction test is to improve the desirable load-bearing capacity properties of soil as a foundation material. The best for foundation engineering structures is one with high MDD at low OMC. The OMC varies from 10.4 % and 27.5 % with an average of 17.1 %. The MDD ranges from 1532 - 2065 Kg/m^3, with a mean value of 1820 Kg/m^3. The degree of compaction is sensitive to moisture content, thus the higher the value of MDD and the lower OMC, the more suitable the material to sustain any load imposed. All the soil samples have MDD at moderately low OMC. However, MDD values are a little bit lower in the Ose area with a range of 1532 – 1749 Kg/m^3. Cohesion is the ability of the soil to resist shearing stress. The cohesion of the studied soils varies between 51.5 kPa – 102 kPa and an average of 88.3 kPa. The values of the angle of friction are between 20.4° and 32.5°. This range of value is classified as hard soil material (Holtz and Kovacs, 1981). The shear strength varies from 151.7 kPa to 237.4 kPa and an average of 187 kPa (Table 4). These values indicate moderately cohesive material with high shear strength.

The cone penetrometer test was carried out in order to obtain geotechnical parameters required for the design of the foundation support for civil engineering structures. From Table 5, the maximum cone resistance values of 100 Kg/cm^2 to 126 Kg/cm^2 indicative of clayey sand and lateritic material were obtained between depths of 1.4 m and 3.0 m. Six major geological layers are delineated comprising clay, clay silt, silty clay, sandy clay, clay sand, and lateritic clay. Therefore, the soils show a high degree of competence at Owo at a depth range of 1.0 – 2.5 m, 1.0 m in the Akoko area, and 3.0 m in the Ose area. The allowable bearing capacity of the soils in Owo, Ose and Akoko areas varies from 17 KN/m^2 to 293 KN/m^2, 20 KN/m^2 to 309 KN/m^2, and 10 KN/m^2 to 270 KN/m^2 respectively.

Table 3 Summary of Results of Geotechnical Tests

LOCATION	SAMPLE NO.	N.M.C (%)	G.S.D % Fines	% Sand	% Gravel	S.G	Consistency Limits L.L (%)	P.L. (%)	P.I (%)	L.S (%)	Compaction OMC (%)	MDD (Kg/m^3)	AASHTO Group	Rating
OWO AREA	OW 1	6.4	38.8	61.2	-	2.67	37.4	24.1	13.35	10.1	15.3	1852	A-6	Poor
	OW 2	8.3	43.3	53.5	3.2	2.69	39.5	25.2	14.34	9.6	16.2	1816	A-6	Poor
	OW 3	4.3	22.7	76	1.3	2.66	22.2	19.3	2.95	12	11.9	1996	A-2-4	Good
	OW 4	5.4	24.2	73.7	2.1	2.68	23.2	19.8	3.40	12	11.3	2019	A-2-4	Good
	OW 5	6.5	24.1	74.7	1.2	2.65	24.0	19.7	4.35	12	10.4	2065	A-2-4	Good
	OW 6	6.4	32.8	65.9	1.3	2.64	24.0	19.9	4.15	12	11.2	2035	A-2-4	Good
	OW 7	6.5	38.7	61.3	-	2.65	31.8	25.2	6.64	11.5	18.6	1738	A-5	Fair
	OW 8	7.6	39.0	59.8	1.2	2.64	38.4	26.5	11.95	10.6	19.5	1703	A-6	Good
OSE AREA	OS 1	6.7	54.3	44.2	1.5	2.68	45.0	23.5	21.50	8.7	25.9	1586	A-7	Poor
	OS 2	11.3	54.6	42.2	3.2	2.68	52.4	24.3	28.15	7.7	27.0	1549	A-7	Poor
	OS 3	11.1	53.3	45.4	1.3	2.75	53.4	24.6	28.85	7.7	27.5	1532	A-7	Poor
	OS 4	12.4	52.8	46.1	1.1	2.76	54.2	25.2	29.05	7.7	26.3	1572	A-7	Poor
	OS 5	11.4	32.6	66.2	1.2	2.76	50.4	26.3	24.10	7.7	19.0	1741	A-2-6	Good
	OS 6	12.2	48.1	50.6	1.3	2.76	52.4	26.6	25.80	7.7	19.8	1711	A-7	Poor
	OS 7	12.3	52.8	47.2	-	2.74	53.8	26.6	27.25	7.7	18.8	1749	A-7	Poor
	OS 8	14.4	52.9	45.9	1.2	2.74	52.5	26.6	25.90	7.7	19.7	1715	A-7	Poor
AKOKO AREA	AK 1	16.4	16.5	55.6	-	2.72	37.2	22.4	14.80	10.1	14.2	1910	A-2-6	Good
	AK 2	12.2	16.1	64.7	-	2.73	30.0	22.2	7.85	12.0	12.1	1988	A-2-4	Good
	AK 3	12.7	16.5	51.4	5.5	2.72	41.2	23.2	18.00	9.6	15.0	1879	A-2-7	Good
	AK 4	9.3	14.5	70.9	2.1	2.73	27.0	23.3	3.70	13.4	11.1	2027	A-2-4	Good
	AK 5	17.4	17.4	51.4	1.3	2.73	47.2	23.4	23.80	8.7	16.0	1824	A-2-7	Good
	AK 6	16.2	20.9	49.7	2.2	2.70	48.4	23.7	24.75	8.7	16.5	1804	A-2-7	Good
	AK 7	14.4	17.2	51.3	2.5	2.70	40.8	23.4	17.45	9.6	14.8	1885	A-2-6	Good
	AK 8	8.2	15.1	68.7	3.3	2.69	27.9	11.0	6.85	11.0	11.8	1988	A-2-4	Good

Table 4 Results of the undrained triaxial Test

Location	Sample No.	(σ) Deviator stress at Different Cell Pressures (KPa) 30	60	90	Cohesion (c) Kpa	(θ °) Angle of Friction	Shear Strength (KPa) (τ)	Undrained Compressive Strength @ Max. Cell Pressure (Kpa)
OWO AREA	OW 1	395	470	545	85.1	29.1	201.9	545
	OW 2	395	468	542	86.2	28.8	196.2	542
	OW 3	440	532	625	85.3	31.2	212.5	625
	OW 4	440	528	616	88.1	30.7	230.6	616
	OW 5	440	537	633	82.9	31.7	232.4	633
	OW 6	440	545	650	78.1	32.5	237.4	650
	OW 7	337	376	415	98.2	21.5	175.0	415
	OW 8	337	372	408	102.0	20.4	176.4	408
OSE AREA	OS 1	337	383	429	91.3	23.5	173.9	429
	OS 2	337	381	426	92.7	23.1	175.0	426
	OS 3	337	378	419	96.1	22.1	171.2	419
	OS 4	337	384	431	90.4	23.7	173.8	431
	OS 5	337	382	427	92.3	23.2	175.1	427
	OS 6	395	459	523	93.2	27.3	199.0	523
	OS 7	395	455	515	96.5	26.6	198.7	515
	OS 8	337	380	422	94.7	22.5	175.5	422
AKOKO AREA	AK 1	337	380	422	94.7	22.5	173.8	422
	AK 2	296	360	425	65.3	27.3	160.8	425
	AK 3	323	381	425	82.9	24.6	168.5	425
	AK 4	269	339	419	51.5	29.1	151.7	419
	AK 5	337	384	431	90.4	23.7	175.1	431
	AK 6	337	382	427	92.3	23.2	177.6	427
	AK 7	395	459	523	93.2	27.3	200.0	523
	AK 8	395	455	515	96.5	26.6	198.2	515

Table 5 Bearing Capacity and settlements obtained for all the CPT locations at an interval of 0.2 m Depth

	CPT 1 (OWO)			CPT 2 (OWO)			CPT 3 (OSE)			CPT 4 (OSE)		
Depth (m)	q_a (KN/m^2)	q_u (KN/m^2)	S (mm)	q_a (KN/m^2)	q_u (KN/m^2)	S (mm)	q_a (KN/m^2)	q_u (KN/m^2)	S (mm)	q_a (KN/m^2)	q_u (KN/m^2)	S (mm)
0.2	17	51	12.3	41	123	5.1	21	63	10.25	22	66	9.67
0.4	21	63	10.01	82	246	2.56	20	60	10.37	31	93	6.78
0.6	54	162	3.91	127	381	1.67	26	78	8.05	43	129	4.86
0.8	63	189	3.32	174	522	1.22	32	96	6.67	42	126	5.01
1.0	87	261	2.41	270	810	0.78	43	129	4.89	76	228	2.79
1.2	102	306	2.07	273	819	0.77	70	210	2.99	10	30	21.00
1.4	112	336	1.88	293	879	0.72	88	264	2.41	11	33	19.13
1.6	124	369	1.71	-	-	-	83	249	2.55	21	63	10.13
1.8	123	369	1.72	-	-	-	98	294	2.16	33	98	6.47
2.0	131	393	1.62	-	-	-	116	348	1.82	42	126	5.01
2.2	179	537	1.18	-	-	-	123	369	1.72	61	183	3.44
2.4	281	843	0.75	-	-	-	156	468	1.35	83	249	2.54
2.6	-	-	-	-	-	-	172	516	1.23	112	336	1.88
2.8	-	-	-	-	-	-	215	645	0.98	163	489	1.29
3.0	-	-	-	-	-	-	309	927	0.68	262	786	0.80
	CPT 5 (AKOKO)			CPT 6 (AKOKO)			CPT 7 (AKOKO)			CPT 8 (AKOKO)		
Depth (m)	q_a (KN/m^2)	q_u (KN/m^2)	S (mm)	q_a (KN/m^2)	q_u (KN/m^2)	S (mm)	q_a (KN/m^2)	q_u (KN/m^2)	S (mm)	q_a (KN/m^2)	q_u (KN/m^2)	S (mm)
0.2	22	66	9.78	10	30	21.00	61	183	3.44	11	33	19.57
0.4	20	60	10.50	22	66	9.67	39	117	5.38	25	75	8.36
0.6	33	99	6.43	52	156	4.06	21	63	10.01	54	162	3.90
0.8	43	129	4.86	82	246	2.59	54	162	3.90	121	363	1.75
1.0	53	159	3.99	163	489	1.29	125	375	1.69	162	486	1.30
1.2	73	219	2.91	195	585	1.08	153	459	1.38	207	621	1.02
1.4	82	246	2.59	249	747	0.85	197	591	1.07	248	744	0.85
1.6	109	327	1.94	-	-	-	245	735	0.86	-	-	-
1.8	173	519	1.22	-	-	-	-	-	-	-	-	-
2.0	270	810	0.78	-	-	-	-	-	-	-	-	-

Table 6 Rating of Subsoil Competence using Resistivity values (Idornigie et al., 2006)

Apparent Resistivity Range (ohm-m)	Lithology	Competence Rating
< 100	Clay	Incompetent
100 – 350	Sandy clay	Moderately competent
350 – 750	Clayey sand	Competent
>750	Sand/Laterite/Crystalline Rock	Highly competent

Table 7 Soil Corrosivity Rating (modified after Agunloye, 1984)

Soil Resistivity (ohm-m)	Corrosivity Rating
>250	Essentially/Practically Non-corrosive
150 – 250	Mildly/Slightly Corrosive
50 – 150	Moderately Corrosive
UP to 50	Very Strongly Corrosive

Table 8 Multi-criteria Evaluation Parameters for the Subsoil Competence Map

S/N	Thematic Map	Attribute	Rating (%)	Weight-Age (%)
1	Topsoil Resistivity (ohm-m)	<100 100 – 350 350 – 750 >750	1 5 10 15	15
2	Topsoil Thickness (m)	<5 5 – 10 >10	3 10 15	15
3	Plasticity Index (%)	<10 10 – 20 >20	10 5 1	10
4	Shear Strength (KPa)	200 – 300 300 – 400 400 – 500	5 10 15	15
5	Allowable Bearing Capacity (KN/m^2)	<50 50 – 100 100 – 200 >200	1 5 10 15	15
6	Soil Association	Okemesi Iwo Ondo	10 7 3	10
7	Lineament Density	0 – 8 8 – 12 12 - 16	10 6 2	10
8	Groundwater Level	< 3 m 3 – 5 m >5 m	2 5 10	10

The ultimate bearing capacity varies between 51 KN/m^2 and 879 KN/m^2, 60 KN/m^2 and 927 KN/m^2, and 30 KN/m^2 and 810 KN/m^2 respectively. The settlement values obtained from the area are generally less than 20 mm. The minimum settlement values obtained from Owo, Ose, and Akoko areas ranged from 0.75 mm to 1.4 mm, 0.68 mm to 0.80 mm, and 0.78 mm to 0.86 mm corresponding to depth(s) of 1.4 m – 2.4 m, 3 m, and 1.4 m – 2.0 m respectively.

Nevertheless, for safety purposes, the Akoko area should not go beyond 1.0 m due to the high water level. The minimum allowable bearing capacity of at least 200 KN/m^2 (corresponding to 80 – 100 kg/cm^2 cone resistance values) for a raft, simple spread foundation, and/or structure was recommended by (Bell, 2007). This average value was found at depth of 1.0 m – 2.4 m (Owo), 3.0 m (Ose), and 1.4 m – 2.0 m (Akoko). These allowable bearing pressures are considered appropriate for use in the design of bases, strips, or raft foundations. Subsequently, shallow foundations such as pad or raft foundation of

reinforced concrete can be adopted in the study area (Schmertmann, 1978). Therefore, the thematic maps of the topsoil resistivity and thickness, plasticity index, soil association, allowable bearing capacity, shear strength, lineament density, and static water level are integrated to generate a sub-soil competence map for the study area by allocating different weights/ratings to each of these parameters as shown in Tables 6-8. Figure 15 shows the generated subsoil competence map of the study area. The map classifies the study area into low competence (<40 %), moderate competence (40 % - 55 %), and high competence (55 % - 65 %) and very high (>65 %). Low competence area is not represented on the map, while moderate competence accounts for 60 %. The high and very high competence areas account for 35 % to 5% respectively. The very high competence occurs as small closures in Ajowa, Ikeramu, Eporo, parts of Ikare, Arigidi, and Ido Ani. The moderate competence areas are prominent in parts of Owo, Ose, and Akoko areas. In Owo, it's observed in Ipeme, Ipele, and Amurin. Also, in Ose, it is widespread in Elegbeka, Ifon, Imoru, Arimigija, and Oculus. In addition, moderate competence is noticed in the Akoko area around Oba, Ikun, Afo, Iwao Oka, Ikakumo, Irun, Oke Agbe, Auga, and Ise. Furthermore, the high competence subsoil is observed in Owo (Eporo, Otapete, Ehinogbe, Isijogun, Iyer, and Ute); and Akoko (Agbaluku, Oka, Isua, Ifira, and Ipesi).

Conclusion

The engineering competence of the subsoil in the selected northern area of Ondo State was conducted, and the results of various parameters measured were integrated to generate an engineering competence map for the study area. The research work was able to meet up with its set objectives except that it has not been able to (fully) determine the geotechnical capability of the rock units in the area to support engineering structures such as building, road, dam, etc. The generated subsoil competence map classified the study area into low competence (<40 %), moderate competence (40 % - 55 %), and high competence (55 % - 65 %) and very high (>65 %). Moderate competence account for 60 %, the high and very high competence areas account for 35 % and 5% respectively.

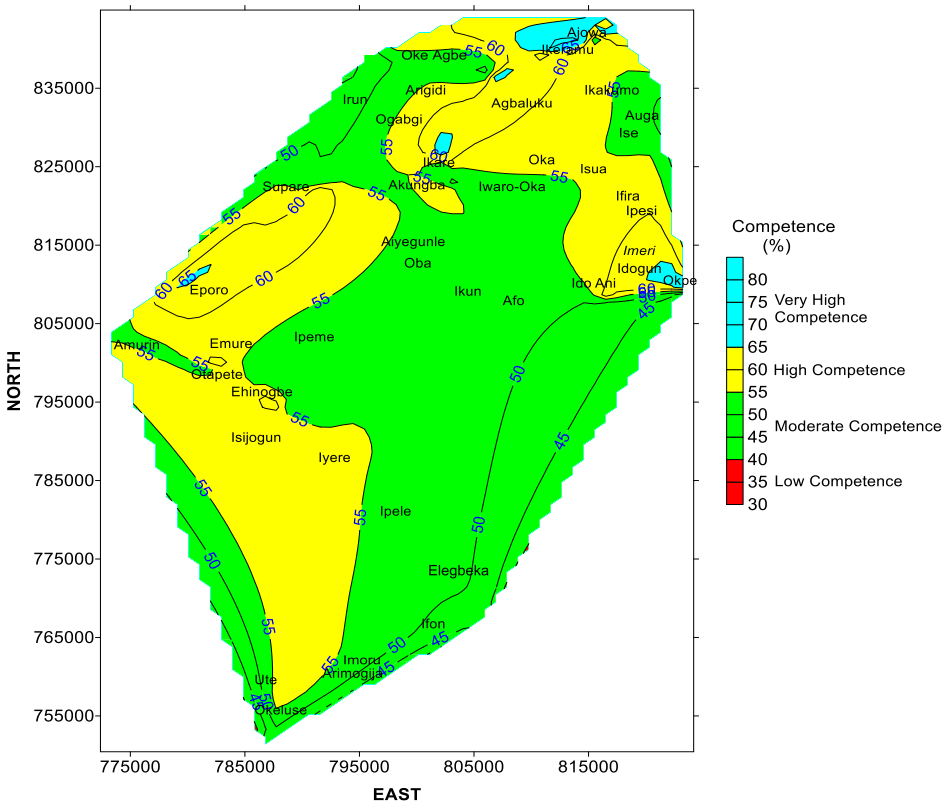


Fig. 15 Subsoil Competence Map generated for the Study Area

The corrosivity map of the topsoil shows predominant moderate to mildly corrosivity, prominently in Ose and Akoko areas and constitutes about 70 %. The essentially non-corrosive areas of the topsoil account for 10 %. The corrosivity of the weathered layer (subsoil) generally varies from mild corrosivity to essentially non-corrosivity. This type of corrosivity is suitable for buried communication equipment and electrodes, as it will protect the instrumentation when there is lighting or thunderstorm; hence any protected steel or metal structure buried within the area may not be "seriously" affected by chemical corrosion. For buildings, shallow foundations such as pad or raft foundation of reinforced concrete can be adopted. In addition, the soil geotechnical properties will support adequately road structures and various earthworks as a result of excellent soil property.

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