

**GEOPHYSICAL, MINERALOGICAL AND GEOTECHNICAL INVESTIGATIONS
OF SOILS UNDERLYING SOME BUILDINGS IN WARRI, SOUTHERN NIGERIA**

BY

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JULY, 2021.

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**A THESIS SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES,
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FOR THE AWARD OF THE DEGREE OF DOCTOR OF PHILOSOPHY (Ph.D.) IN
ENGINEERING GEOLOGY**

JULY, 2021

CERTIFICATION

This is to certify that this research work titled “**Geophysical, Mineralogical and Geotechnical Investigations of Soils Underlying Some Buildings in Warri, Southern Nigeria**” was carried out by Mr. Oghenero Enivwenaye AVWENAGHA of the Department of Geology, Faculty of Physical Sciences, University of Benin, Benin City.

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Date

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Date

DEDICATION

This work is dedicated to God Almighty for His Grace, Mercy and enablement.

ACKNOWLEDGEMENTS

I wish to express my deep sense of gratitude to my Supervisors; Late Professor T.U. S. Onyeobi Professor. C. N. Akujieze, Professor, O. C. Okeke as well as my fatherly friend Dr. Salami. They were sources of inspiration and support towards my research work. I owe them a lot especially Professor C.N. Akujieze for his constant encouragement and guidance at the challenging times of my research.

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ABSTRACT

Warri and its environs have been recently challenged with incidences/imminence of building collapse with frequency of four incidences in the past four (4) years. Hence, geophysical, geotechnical and mineralogical investigations were conducted in an area of failed building and other areas in Warri with a view to comparatively analyse the geotechnical and mineralogical properties of subsurface soils for future building and road developments in Warri.

This involved the drilling of ten (10) boreholes in the failed area and fifteen (15) holes in other areas which were all complimented with twenty five (25) Cone Penetration Tests. Samples from boreholes were subjected to geotechnical index/foundation analyses and X-ray Diffraction analyses (XRD).

Geophysical and geotechnical investigations showed that the failed area had a laterally heterogeneous two-three layer soil profile which from top to bottom consisted of sandy silt/silty sand (3m thick), clayey silt (15-17m thick) and fine-medium grained sands (2m thick). This was at variance with the other areas which had a relatively homogeneous three layer soil profile which from top to bottom consisted of loose sandy humus top soil (0.25m thick), reddish brown silty sand and fine to medium grained sands (3-8m thick). Classification characteristics using the American Association of State and Highway Transport Officials (AASHTO) showed that the superficial soils in the failed area were mainly of A-7, A-6 and A-4 characteristics with California Bearing Ratio (CBR of 3-20.5%, average: 6.25%) indicating they are competent subgrade materials but incompetent sub-base and base course materials for road construction. Similar characterization in other areas reflected soils of A-2, A-6 and A-3 characteristics with CBR (10-17.9%, average: 15.02%) indicating similar competence and deficiency to that of the failed area. Sand stabilization increased the subgrade quality of the superficial soils in both areas. Cement and composite stabilization improved all soils to sub-base and base quality materials respectively. Foundation studies showed that superficial soils in the failed area are of lower foundation quality (bearing capacity of 184-229kpa, compression indices; 0.12-0.62) than the other areas (bearing capacity of 185-575kpa, compressibility indices; 0.31-0.34). Superficial soil mineralogy showed that the failed area consisted of quartz (75.33-94.20%), kaolinite (5.79-11.99%), smectite, muscovite and microcline which is consistent with the other areas except for the absence smectite. This showed that structural failure in the challenged area was due to soil lateral variation and poor foundation quality.

CHAPTER ONE

INTRODUCTION

1.1 General Statement

Warri is one of the fastest growing metropolitan City in southern Nigeria with population of about 311,970 (National Population Commission 2006). The City is a major hub of petroleum and business activities in the Western Niger Delta which in recent years has witnessed significant population growth and extensive infrastructural development (specifically construction of various road networks, residential/commercial buildings, water factories and many other projects which are ongoing. These infrastructures are underlain by Quaternary foundation materials of the Niger Delta which are characterized by lateral and vertical heterogeneities in engineering properties (Nwankwaola and Warmate, 2014; Abam, 2016) which when ignored could adversely affect the safety and stability of infrastructures resulting in road failure and building collapse. In recent times, Warri and its environs have been challenged with incidences/imminence of building collapse with frequency of four incidences in the past 4 years. Reference cases are the collapse of the prestigious Makevaal Hotel dated September 9, 2015, demolition of a two storey building in Mercy City (Warri's largest worship arena) due to imminent collapse on June 16, 2016, collapse of St. Paul catholic church in Ugolo (outskirt of Warri) in Adagbrassa on September 2, 2018 and most recently was the collapse of an uncompleted two storey building in Marine quarter on June 15, 2019. Suggested causes of these incidences amongst others range from structural overloading, substandard material to soil failure. The differential settlement/ imminent collapse in one of the failed areas (specifically Mercy City) calls for the first time, a site-specific geotechnical research alongside a holistic investigation of the subsurface soils in Warri.

Several researchers have proven that geophysical survey is a vital tool for complementing geotechnical boreholes in detecting soil heterogeneities (Akintorinwa and Adeusi, 2009; Kumari *et al.*, 2009) while others have also established the influence of clay mineralogy on the engineering behavior of subsurface soils (Ehibor *et al.*, 2019).

This research therefore gives a comparative investigation of the geo-electrical, mineralogical and geotechnical properties of subsurface soils in Warri with reference to a failed building terrain (Mercy city) in the study area, as a guide to future roads and buildings developments.

1.2 Statement of Problem / Justification

The Niger Delta has drawn so much attention locally and globally following the discovery of oil in 1956. This has resulted in the establishment of infrastructures such as pipeline network, roads, bridges, private and public institutions which are all emplaced on the Quaternary foundation materials of the Niger Delta. Yet little efforts have been made to study the Quaternary foundation material which is typified by lateral and vertical heterogeneities in Geotechnical properties (Abam, 2016). Quaternary soils in the wet land area of the Niger Delta are challenged with high in-situ moisture content, low bearing capacity and excessive settlement resulting in poor foundation quality (Abam, 2016).

Subsoil geotechnical data have been fairly-well documented in the Eastern Niger Delta areas such as Port Harcourt, Akwa-Ibom and parts of Bayelsa with published works readily available (Akpokodje, 1989; Abam and Okogbue, 1997; Teme, 2002; Tse, 2006; Onyebolise and Akpokodje, 2008; Ugbe, 2011; Youdeowei and Nwankwoala, 2011; Tse and Akpokodje, 2010) but in the Western Niger Delta precisely Warri, little research documentations have been made on sub-soil geotechnical property and available publications are regional (Olobaniyi *et al.*, 2005; Avwenagha *et al.*, 2014a; 2014b; Oghonyon and Ekeocha, 2015). No site-specific geotechnical and mineralogical researches have been conducted in Warri.

There is also a recent history of building collapse in Warri. These recent incidences and research gap in Warri therefore prompts a site-specific/holistic geotechnical research, hence the rationale behind this study.

1.3 Aim and Objectives

The aim of this study is to investigate the geotechnical and mineralogical properties of sub-soils in Warri.

The objectives of the research are to:

- 1) Evaluate the lateral and vertical distribution of subsurface soils in an area of failed building in Warri.
- 2) Delineate and compare the stratigraphy of the area and its geotechnical/mineralogical properties to other areas in Warri.
- 3) Comparatively assess the sub-soils suitability of the failed area as well as other areas for road pavement construction.
- 4) Evaluate the mineralogical properties of subsurface soils in Warri.
- 5) Develop a bearing capacity and compression index map of Warri.

1.4 Geographical Setting and Geomorphology of the Study Area.

Warri is located in the western portion and coastal zone of the Nigerian Niger Delta (Figure 1.1) some 40 kilometers away from the shores of the Atlantic Ocean.

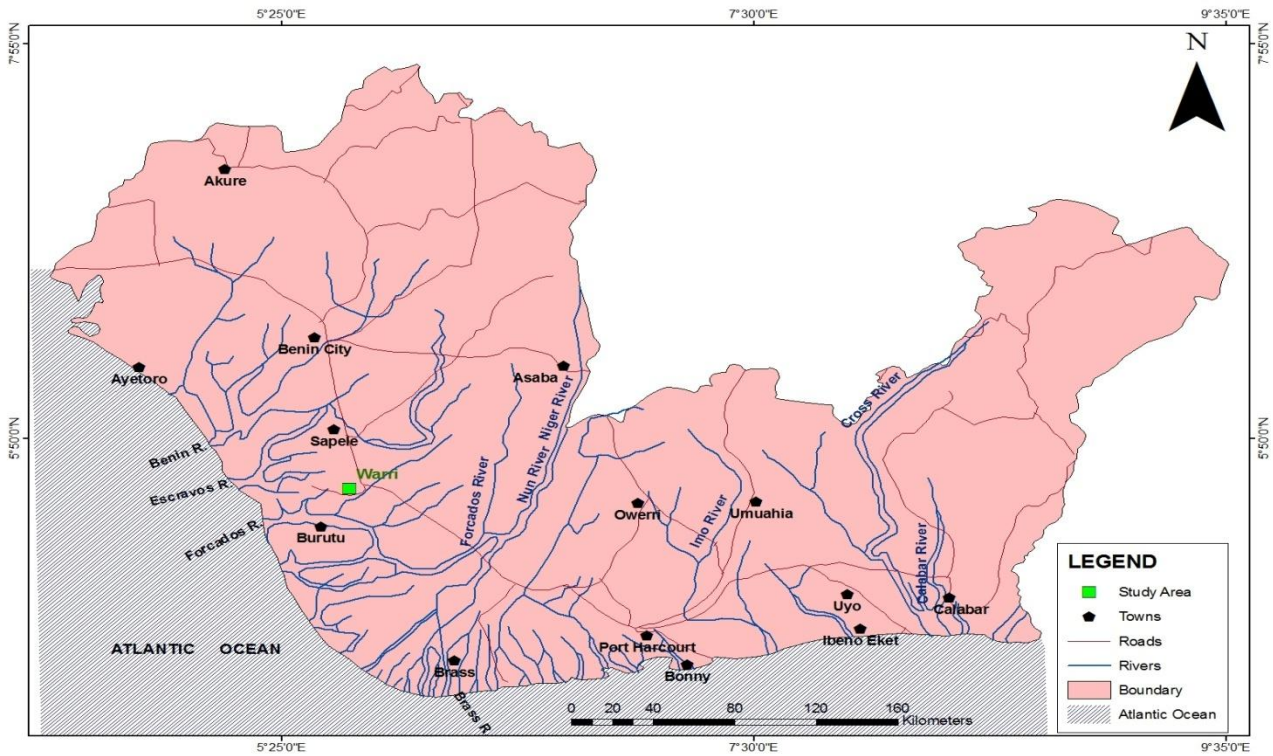


Figure 1.1: Geographical Map of the Niger Delta Niger Delta, showing the study location. (Modified after Olobaniyi and Owoyemi, 2006)

The area is a prominent centre of commercial activities in southern Nigeria which lies between longitudes $5^{\circ}25'E-5^{\circ}49'E$ and latitudes $5^{\circ}33'E-5^{\circ}37'N$. It occupies a flat low-lying terrain which is drained and moderately dissected by River Warri and its network of tributaries which empty into the sea (Figure 1.2). The flat terrain is evidenced by a dendritic drainage pattern which is also indicative of homogeneous underlying soil material.

The area of failed building (Known as Mercy City) lies between latitudes $N5^{\circ}36'-5^{\circ}24'$ and longitudes $E46^{\circ}25.5'-5^{\circ}47'$. The area which has coverage of about 3.5km^2 is not only a bee-hive of commercial activities but is now Warri's largest religious center located in the north eastern part of Warri (Figure1.2). It also occupies a flat low-lying plain (of about 13m above sea level) and is drained by a sinuous, Westerly-Easterly flowing perennial stream which is linked to River Warri (Figure1.3). The site is accessible by the Warri-Benin Express Way.

From the geomorphic point of view, the Niger Delta is subdivided into five geomorphic units which are:

- I) The active and abandoned coastal beaches.
- II) Salt/mangrove swamp
- III) Fresh water swamp
- IV) Dry flat plains
- V) Sombriero-Warri Deltaic plain with abundant fresh water swamp.

The study area (Warri) lies within the Sombriero-Warri Deltaic Plain as illustrated in Figure

1.4

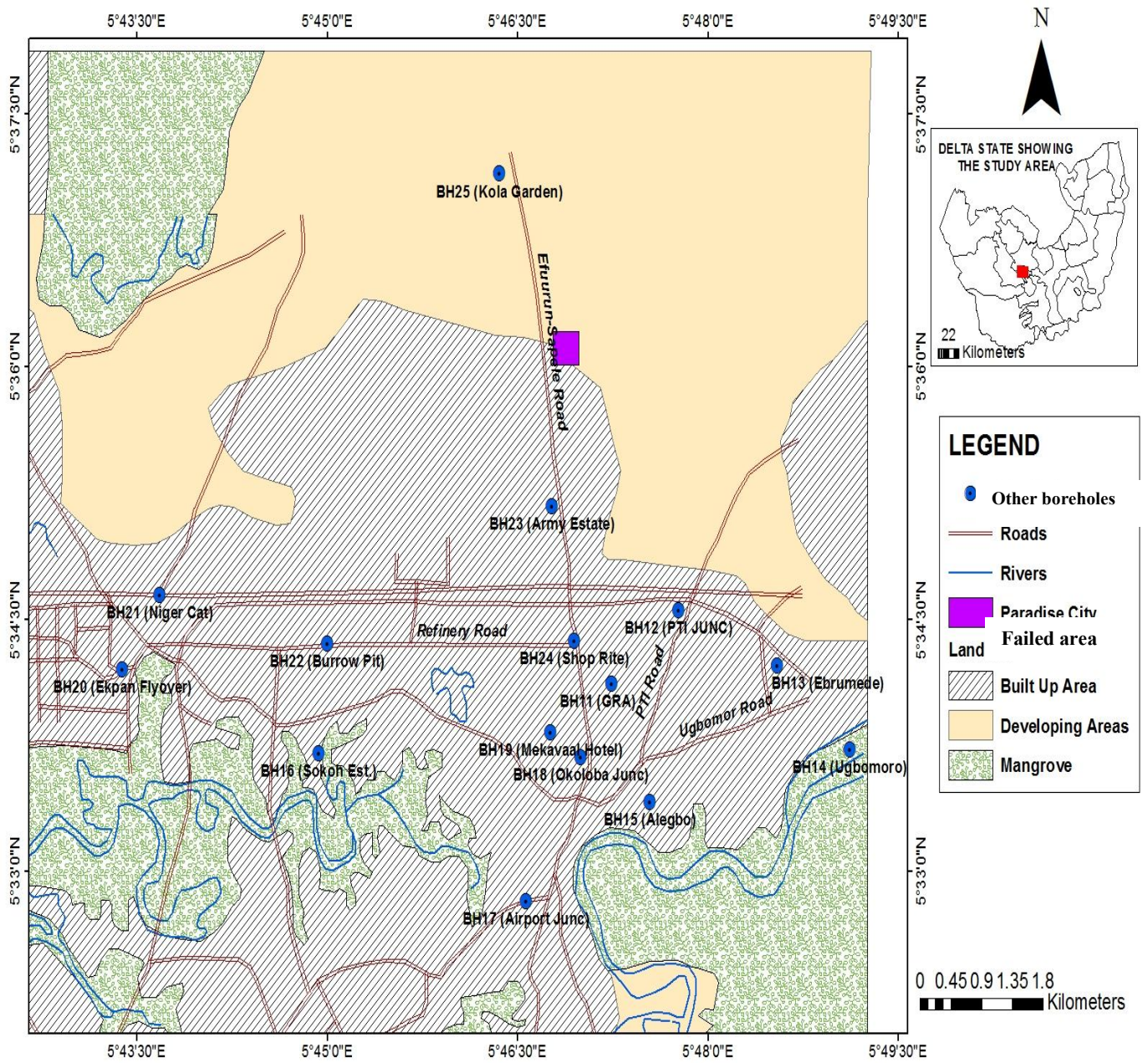


Figure 1.2: Map of Warri showing the Failed area and other borehole locations

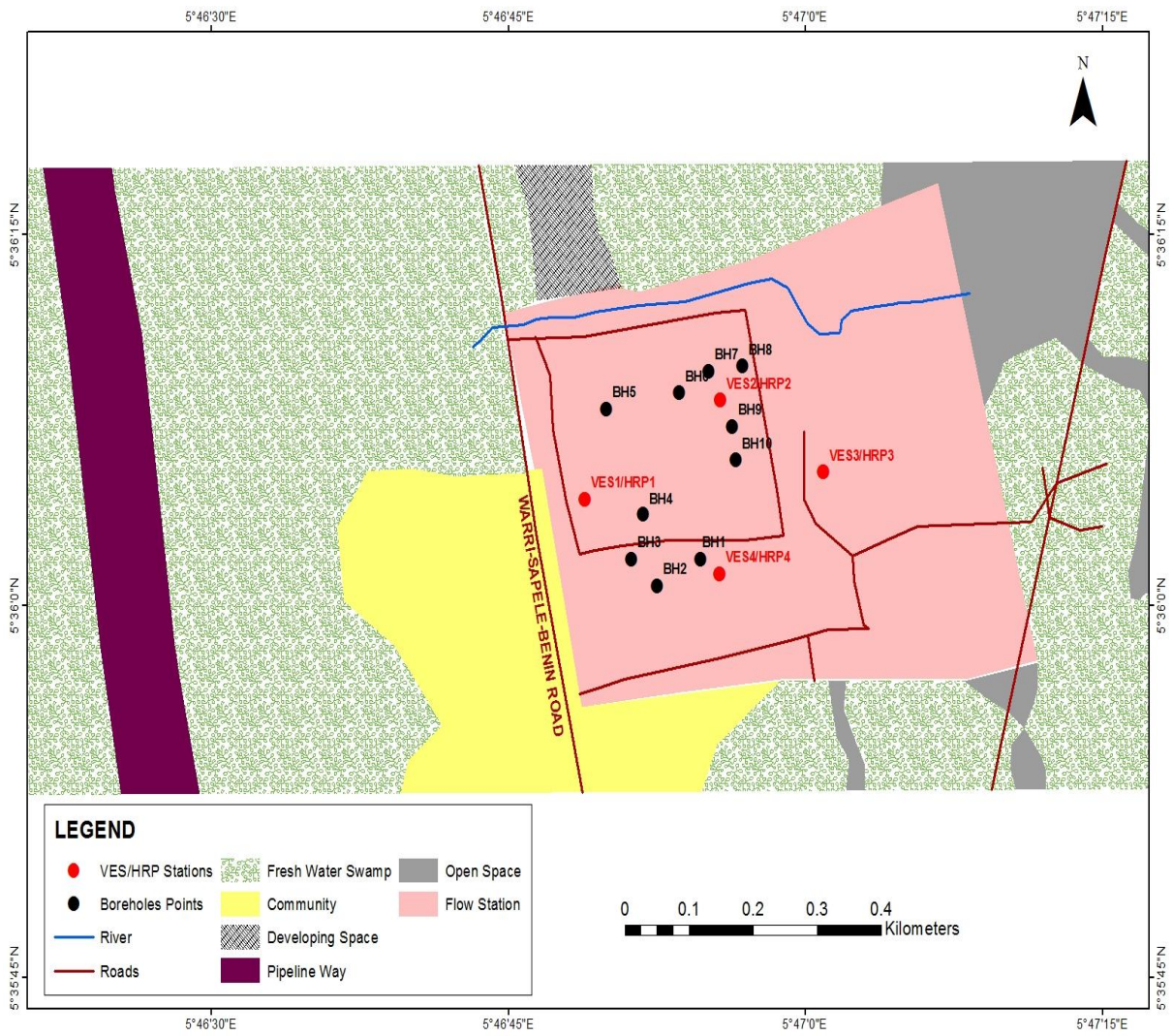


Figure 1.3: Map of the Failed Area

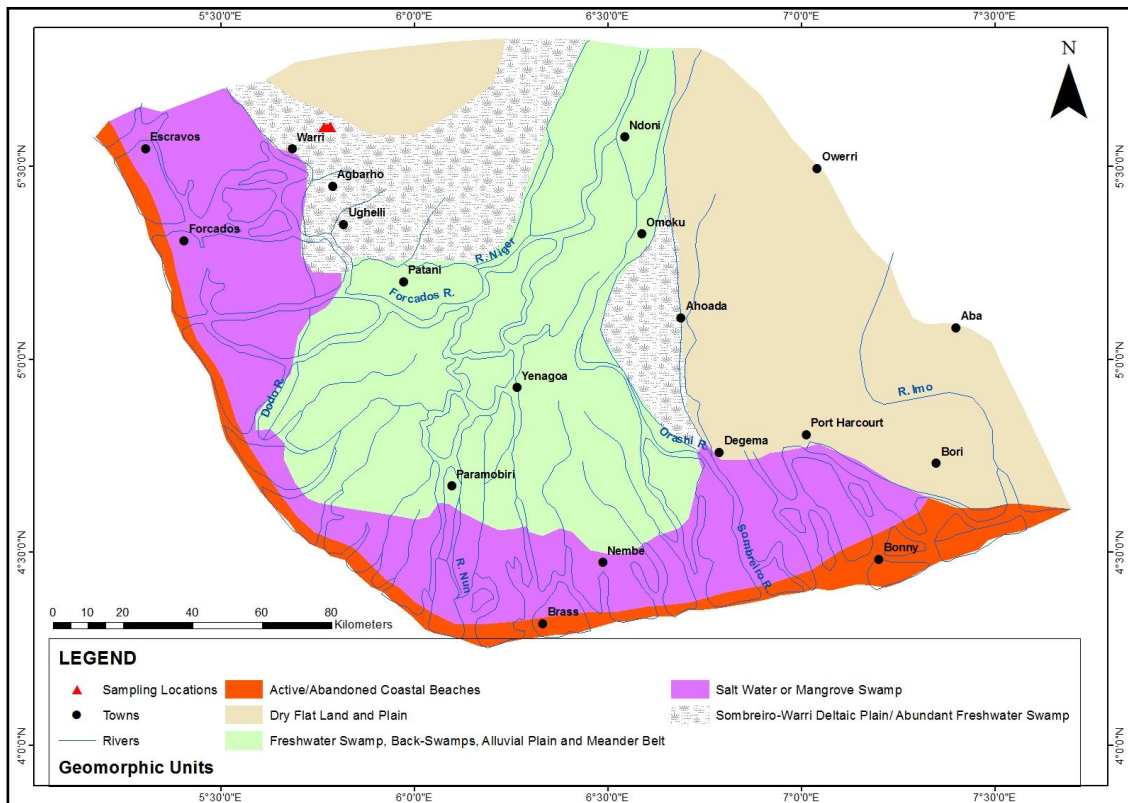


Figure 1.4: Map showing the major Geomorphic Units of the Niger Delta (modified after Akpokodje, 1987b).

CHAPTER TWO

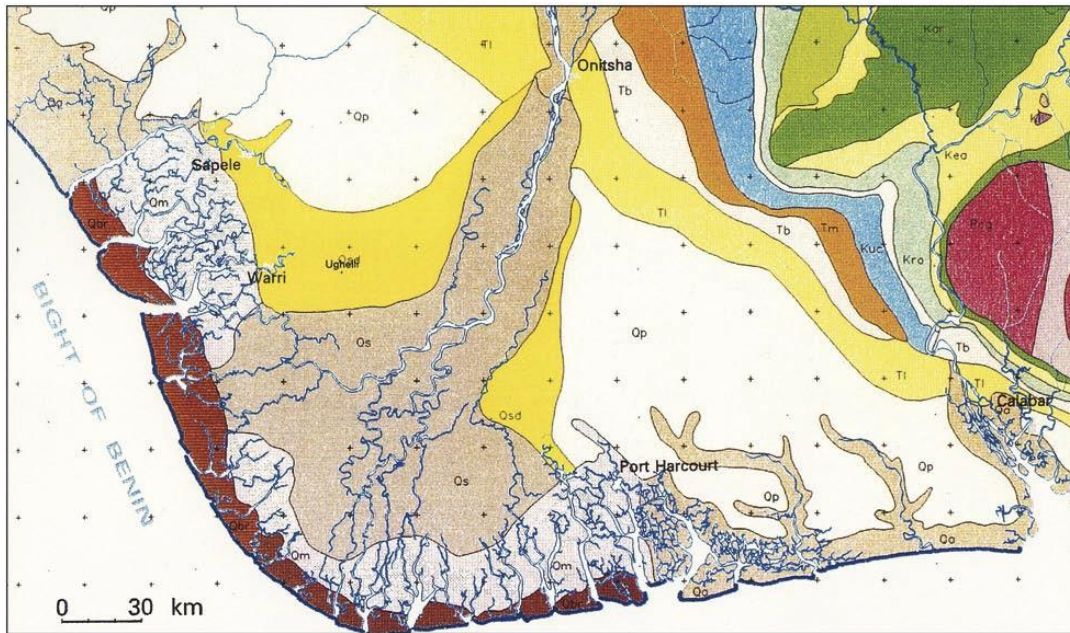
GEOLOGIC SETTING

2.1 General Geology of the Niger Delta

The general geology of the Niger Delta consists of various types of Quaternary deposits which overlie the major stratigraphic units of the Niger Delta (Table 2.1, Figure 2.1).

Table 2.1: Geologic units of the Niger Delta (Source: Reijers, 2011)

Geologic unit	Lithology	Age
Alluvium (general)	Gravel, sand, silt and clay	Quaternary- Recent
Freshwater Swamp, Meander Belt	Silty Sand, clay and gravel	
Mangrove /Back Swamps	Medium-fine sands, Clay and some silt	
Active/Abandoned and Beach Ridges	Sand, clay and some Silt.	
Sombreiro-Warri Deltaic Plain Sands	Sand, clay and some Silt	
Benin Formation (Coastal Plain sands)	Coarse to medium Sand with subordinate silt and clay lenses	Oligocene- Pleistocene
Agbada Formation	Mixture of sand, clay and silt	Eocene- Oligocene
Akata Formation	Clay	Paleocene



QUATERNARY		CRETACEOUS	
meander belt, back swamps	Qa alluvium	Falsebedded sst. and U. coal measures	Kuc Falsebedded sst., coal and shale
fresh water swamps	Qs sands, gravels and clays	lower coal measures	Klc coal, sandstone and shale
mangrove swamps	Qm sands, clays and mangrove swamps	Nkporo shale group	Kro shale and mudstone
abandoned beach ridges	Qbr sands and pebbles	Cretaceous intrusion	Ki basic and intermediate intrusions
Sombreiro deltaic plain	Qsd sands, clay and mangrove swamps	Awgu-Ndeabah shale group	Kwn shale and limestone
coastal plains sands	Qp sands and clays	Eze Aku shale group	Kea black shale and siltstone
		Odukpani formation	Kc flaggy shale and calcareous sst.
		Asu river group	Kar shale and limestone
TERTIARY		PRE-CAMBRIAN TO UPPER CAMBRIAN	
lignite formation	Ti clays, sst., lignite and shales	basement complex	Pcg older granite
Bende Ameki group	Tb clays, clayey sands and shale		
Imo clay-shale group	Tm clays and shales with lst.		

Figure 2.1: Stratigraphic Frame Work of the Niger Delta

Source: Reijers (2011)

The three main subsurface lithostratigraphic units of the Niger Delta from bottom to top are the Akata, Agbada and Benin Formations (Short and Stauble, 1967) and the entire sequence is about 8000metres thick. The Akata Formation rests unconformably on the migmatite-gneiss basement complex and forms the basal unit of the Niger Delta stratigraphic pile. This formation consist of an open marine facies unit dominated by high-pressured carbonaceous shales. The formation ranges in age from Paleocene to Eocene in age and its thickness could exceed 1000metres.

The Agbada Formation consists of a sequence of alternating deltaic sands and shales. It is Eocene to Oligocene in age and exceeds 3000meters in thickness. This Formation is the oil-reservoir of the Niger Delta Basin. It is rich in microfauna at the base decreasing upward and thus indicating an increasing rate of deposition in the Delta front. A fluvial origin is indicated by the coarsening of the grains and poor sorting. The formation underlies the entire Delta area and may be continuous with the Ogwashi- Asaba and Ameki Formation.

The Benin Formation is Oligocene to Pleistocene in age. It consists predominantly of fresh water continental friable sands and gravel that are of excellent aquifer properties with occasional intercalation of shales. This Formation contains the most productive and hence the most tapped aquifer in the Niger Delta region especially in areas north of Warri where it is shallow. The thickness of the Formation is variable but generally exceeds 2000meters. Detailed studies of the Quaternary deposits overlying the Benin Formation revealed that the sediments were deposited under the influence of fluctuating Pleistocene eustatic sea levels. These sediments vary greatly in type.

2.2 Geology and Hydrogeology of the Study area

The study area (Warri) is underlain by a Quaternary to Recent Alluvium known as the Sombreiro-Warri Deltaic Plain sands which from bottom to top consist predominantly of unconsolidated fine-medium grained sand, reddish brown clayey sand and silty top soils (Avwenagha *et al.*, 2014b). The thickness of the Quaternary Formation generally does not exceed 120m and it is predominantly unconfined (Olobaniyi and Owoyemi 2006). The hydraulic conductivity of the sand vary from 3.82×10^{-3} to 9.0×10^{-2} cm/sec which makes it a potentially productive aquifer (Offodile, 1991). The water table is close to the ground surface and varies from 0-2m. The limited water level fluctuation reflects high amount of average precipitation recorded in Warri which is about 3000mm/year (Adejuwon, 2012).

2.3 Local Geology of the Failed area.

The area lies in the wetland/swampy portion of the Sombreiro-Warri Deltaic Plain sands which is reportedly challenged by low bearing capacity and detrimental settlement (Abam 2016). The terrain is veneered by dark organic peaty top soils which are indicative of a poorly drained, low energy and reducing environment. The topsoil is underlain by a thick clayey silt horizon which is occasionally underlain by fine-medium grained sands.

2.5 Literature Review

Several studies have been carried out to investigate the geophysical, mineralogical and geotechnical properties of sub-soils in the Niger Delta (Akpokodje,1987a, Akpokodje, 1989, Okogbue,1989, Abam and Okogbue, 1997, Teme, 2002, Akpokodje and Onyebuolise 2008, Ugbe, 2011, Onyeobi *et al.*, 2013, Imasuen and Onyeobi, 2013, Ademila and Adebajo, 2017). For example, Akpokodje (1987a) investigated the engineering geological characteristics and classification of major superficial soils in the Niger Delta and established that the soils are Reddish brown sandy Clay (RBSC), Brown sandy clays (BSC) and Light grey fine sands and Clays (LGFC) especially those in Port Harcourt, Bayelsa and Warri respectively.

Okogbue (1989), studied the geotechnical and environmental problems of the Niger Delta and ascertained that the Niger Delta is characterised by wide spread and irregular distribution of weak soils whose strength is further reduced by the presence of expansive clays.

Okogbue and Onyeobi (1999), assessed the response of red tropical soils to marble dust stabilization and achieved a sub-base quality material for road construction at 7% marble dust content.

Ogunsanwo (2002), researched on the impact of inundation on soils and noticed that inundation impacts negatively on the geotechnical quality of lateritic and clayey soils which happen to be the predominant shallow foundation substratum of many residential buildings in Nigeria. The negative impacts noticed were decrease in soil shear strength which translates to undesirable settlement.

Olobaniyi *et al.*, (2005), investigated the geotechnical properties of lateritic soils in Osubi-Warri and established that the soils are of A2-4 to A2-6 characteristics based on the American

Association of State and Highway Transport Official (ASHTO) classification scheme and will be suitable as sub-base and base course fill material after appropriate stabilisation.

Tse (2006), researched on the engineering geological properties of foundation soils of parts of mangrove swamp of Eastern Niger Delta and reported that the entire swamp has a five-layered soil profile which from top to bottom consists of peaty clay, upper clay, upper sand, lower clay and low sand horizon. It was also reported that the low sand horizon constituted the best foundation substratum for large structures using pile.

Obrike *et al.*, (2007), studied the mineralogical, geochemical and physical characteristics of the Okada shales and concluded that the shales could be exploited for ceramics production.

Okogbue (2007), investigated the response of clay to stabilization using wood ash and achieved a maximum California Bearing Ratio (CBR) of 67% at 10% wood ash content.

Omotosho and Eze-Uzomaka, (2008), investigated the optimal stabilization of deltaic laterite and revealed that mechanical stabilization of the laterite produced sub-grade quality material while sand and composite stabilization produced a sub-base and base-course quality material respectively.

Onyebuolise and Akpokodje (2008), studied the engineering geological properties of sub-soils of Yenagoa, Bayelsa State and noticed the study area has a three-layered sub-soil profile which from top to bottom consist of peaty clayey-silt, sand and gravelly sand. The gravelly sand horizon was reported to be the best foundation substratum for medium and large civil engineering structures.

Osadebe (2011), conducted a mineralogical and geochemical evaluation of the usability of Imo-clay-shale Palaeocene deposit of Okada in Edo State as drilling mud. The researcher

established that deposits are competent substitute to imported drilling mud but require appropriate beneficiation to remedy some its deficiencies such as loss of ignition.

Ugbe (2011), assessed the basic geotechnical properties of lateritic soils of western Niger Delta and reported the soils were of A-2, A-6 and A-7 with A-2 being the dominant soil type.

Youdeowei and Nwankwoala (2011), investigated the sub-soil characteristics of sand deposits in some parts of Bayelsa and established that the sub-soil profile of the study area revealed an overburden of fine grained, soft to stiff, silty clay overlying medium to coarse grained plain sand.

Obrike (2012), studied the compositional characteristics and industrial usability of Asu River Group shale in Mpu area, South eastern Nigeria and reported that the shale deposits could be exploited for ceramics production.

Onyeobi *et al.*, (2013), investigated the compositional, geotechnical and industrial characteristics of Iyuku, Okija and Ubiaja clay bodies in southern Nigeria and established that the clays are essentially kaolinitic and are suitable for production of refractory bricks and ceramics but would require processing/ beneficiation to be suitable raw material for paper, rubber and cosmetic industries.

Imasuen and Onyeobi (2013) studied the mineralogical and chemical compositional characteristic of selected soils in parts of Edo State and noticed they are acidic soils which consist predominantly of quartz, kaolinite, feldspar and sesquioxides of aluminium, Iron and goethite.

Avwenagha *et al.*, (2014a) investigated the geotechnical properties of sub-soils of Warri and noticed a three-layer soil profile which from bottom to top consist of fine-medium grained sands, medium stiff-stiff clayey sands and silty sand. They concluded that geotechnical

properties suggested that the middle and basal horizons can support all size of civil engineering structures provided foundation design is preceded by appropriate ground investigation.

Avwenagha *et al.*, (2014b) investigated the compaction and classification characteristics of lateritic soils of Warri and established the soils are of A2-4, A3 and A6 characteristics but will require appropriate stabilisation to be competent sub-base and base course fill material.

Oghonyon and Ekeocha (2015), studied the geotechnical index properties of sub-soils in Warri and discovered that the soils are of low-intermediate plasticity.

Abam (2016), studied the engineering geology of the Niger Delta using geophysical and geotechnical parameters and reported the topography of the area is not as flat as had been described as some undulations of geotechnical engineering significance do occur. He has also reported that the mangrove swamp is the most compressible geomorphic unit of the Niger Delta.

Tse and Ogunyemi (2016), evaluated the geotechnical and geochemical status of tropical red soils in Deltaic environment and noticed that the soils are non-lateritic materials of low to fairly average subgrade quality in road construction.

Ojo *et al.*, (2017), assessed the geotechnical properties and geochemical composition of Kaolin deposits in parts of Ifon, south-western Nigeria and concluded that the clays are impure but could be exploited for ceramics production after appropriate beneficiation.

Ehibor *et al.*, (2019a) investigated the geotechnical and mineralogical properties of clayey soils in Uyo town, Akwa-Ibom State reported that the clays are of low to intermediate plasticity with over 80% Quartz and 6.9-19.6% kaolinite as the only clay mineral.

Ehibor *et al.*, (2019b) also investigated the geotechnical properties of subsurface soils of Uyo and established a three layer soil profile which from top to bottom consist of silty clays, sandy clays and an entirely sandy horizon with competence for sustenance of medium engineering structures.

Imafidon *et al.*, (2021), studied the response of deltaic soils to sand, cement and composite stabilization programmes in view of road construction in Agbaroh area of Delta State. They recommended that composite stabilization should be preferably engaged in the area as the programme was noticed to be most technically and economically viable.

In spite of several geophysical, geotechnical and mineralogical documentations of the Niger Delta, there is no mineralogical account of the subsurface soils of Warri. Available geotechnical research works are neither prolific nor site-specific. These research deficiencies in Warri and its environs have resulted in a literature gap.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials for study

The following are the materials used for the study:

- 1) Location map.
- 2) Terrameter.
- 3) Global Positioning System (GPS).
- 4) Drilling rig.
- 5) Auger.
- 6) Cone Penetration Test Machine
- 7) Recovered Soil samples.
- 8) Split spoon sampler.
- 9) Sieve/ Hydrometer .
- 10) Oedometer
- 11) Casagrande machine
- 12) Compaction mould.
- 13) California Bearing Ratio (CBR) Machine.
- 14) Stabilizing agents (e.g Sand, cement)
- 15) Diffractometer.

3.2 Methodology

The research programme was carried out in phases as indicated in the chart below (Fig.3.1)

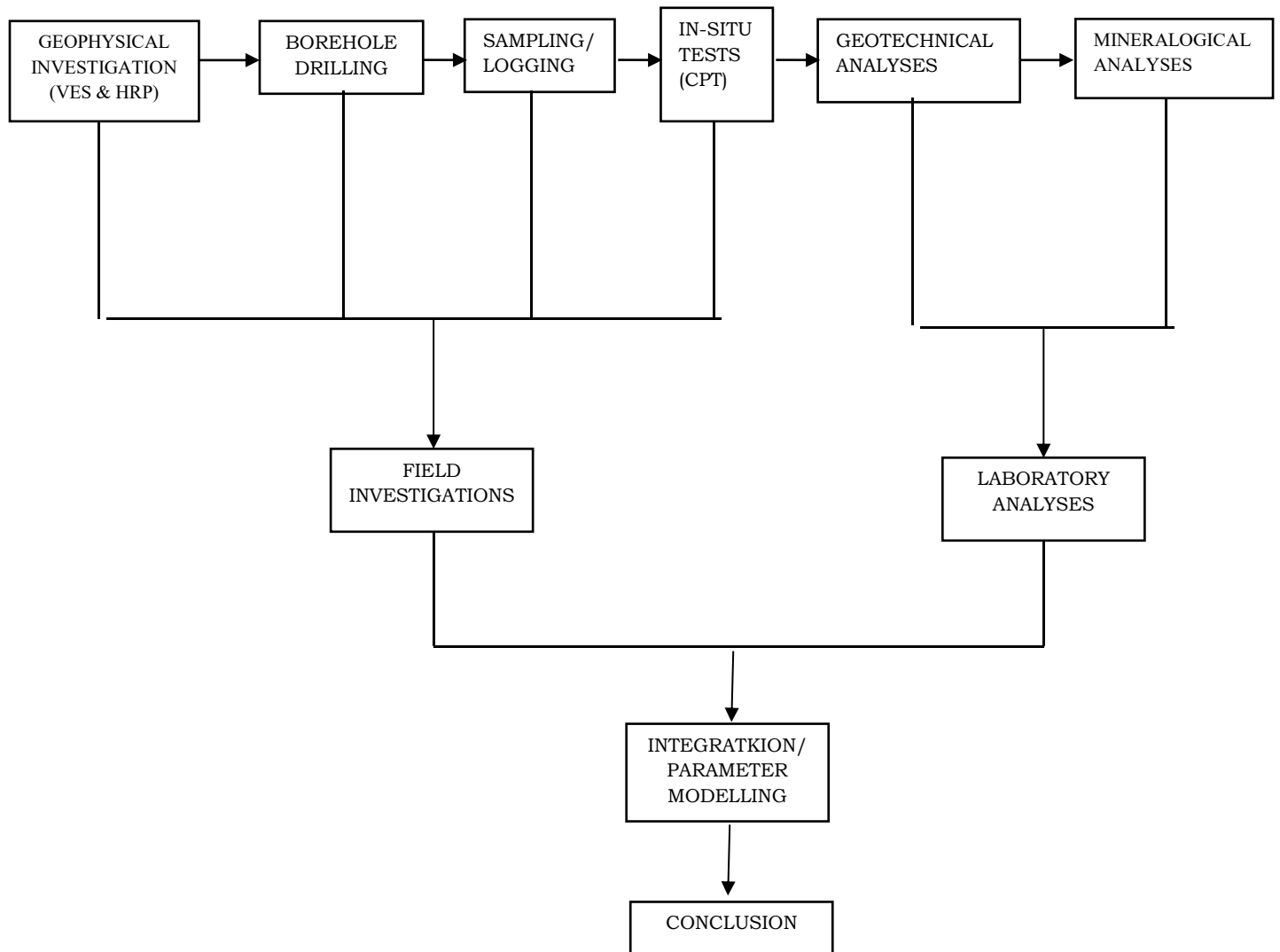


Figure 3.1: Method of Study Chart

3.3 Field Investigations

Field investigations were undertaken by engaging geophysical surveys (such as vertical electrical sounding (VES) and horizontal resistivity profiling) in combination with geotechnical surveys (such as borehole drilling and cone penetration tests). The locations of the VES, HRP, boreholes and Cone penetration tests are presented in figures 3.2 and 3.3.

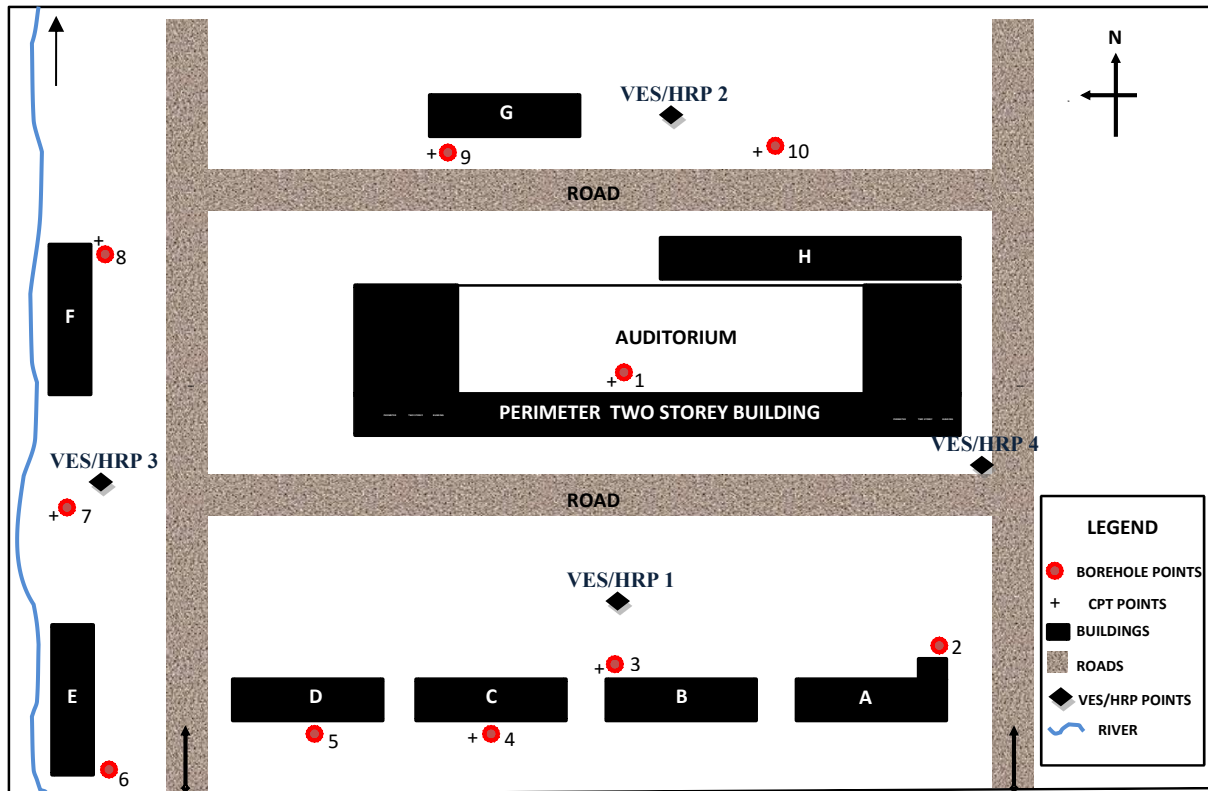


Figure 3.2: Data Acquisition Plan of the Failed area.

3.4 Vertical Electrical Sounding

Vertical electrical soundings (VES) were conducted in four locations within the failed area using ABEM-SAS 1000 Terrameter. The aim was to have an in-depth geo-electric profile that will complement the borehole stratigraphy of the area. Schlumberger configuration was employed with maximum current electrode spacing ($L/2$) of 200metres (Figure 3.2) The coordinates of each geophysical station were recorded (Table 3.0) using the hand held GARMIN 12 GPS while the apparent resistivity measurements at respective stations were fed into a computer modelling program “INTERPEX v 3.57” to produce the geo-electric layers of each location.

Table 3.1: Coordinates of VES and HRP Stations in the Failed Area

S/N	VES Location	Coordinates
1	VES1/HRP1	N05°36'01.7", E005°46'25.5"
2	VES2/HRP2	N05°36'05.4", E005°47'00.9"
3	VES3/HRP3	N05°36'08.7", E005°46'55.4"
4	VES4/HRP4	N05°33'08" ,E005°46'54.7"

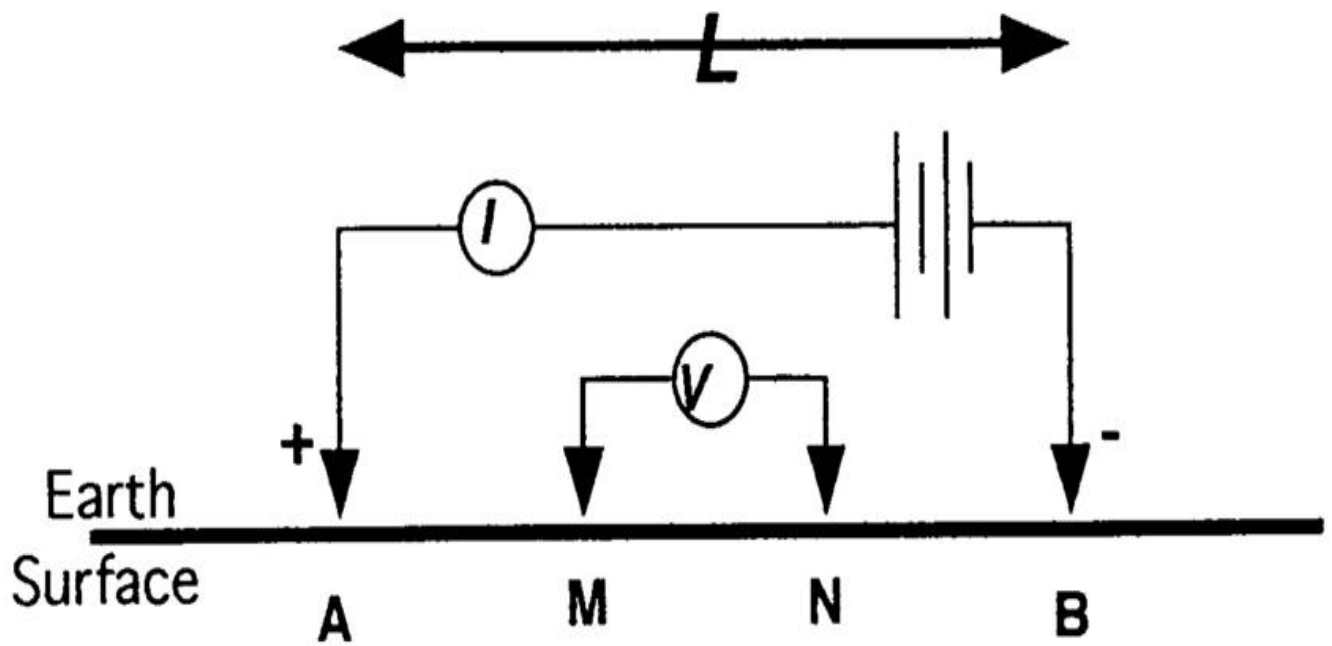


Figure 3.3: Schlumberger configuration for Geo-electric sounding

Where AB = current electrodes, MN = Potential Electrodes, L = Profile length I = Electric current, and V = Potential difference.

3.5 Horizontal Resistivity Profiling (HRP)

This profiling also known as 2-D electrical resistivity imaging was conducted in four locations in the failed area. The investigation was purposed to determine the lateral distribution of the subsoils as this would dictate the intensity (i.e the spacing) of the borehole drilling programme. This was carried out using a multi-electrode system of 50 electrodes with inter-electrode spacing of 5m along a profile line of 250m at each location. Electric Current from an Omega 1000 Terameter was injected through the current electrodes (Figure 3.4) into the subsurface then the potential difference between the potential electrodes (P1 and P2) flanked by the current electrodes (C1 and C 2) was recorded by the terameter which automatically calculates the resistance of the ground.

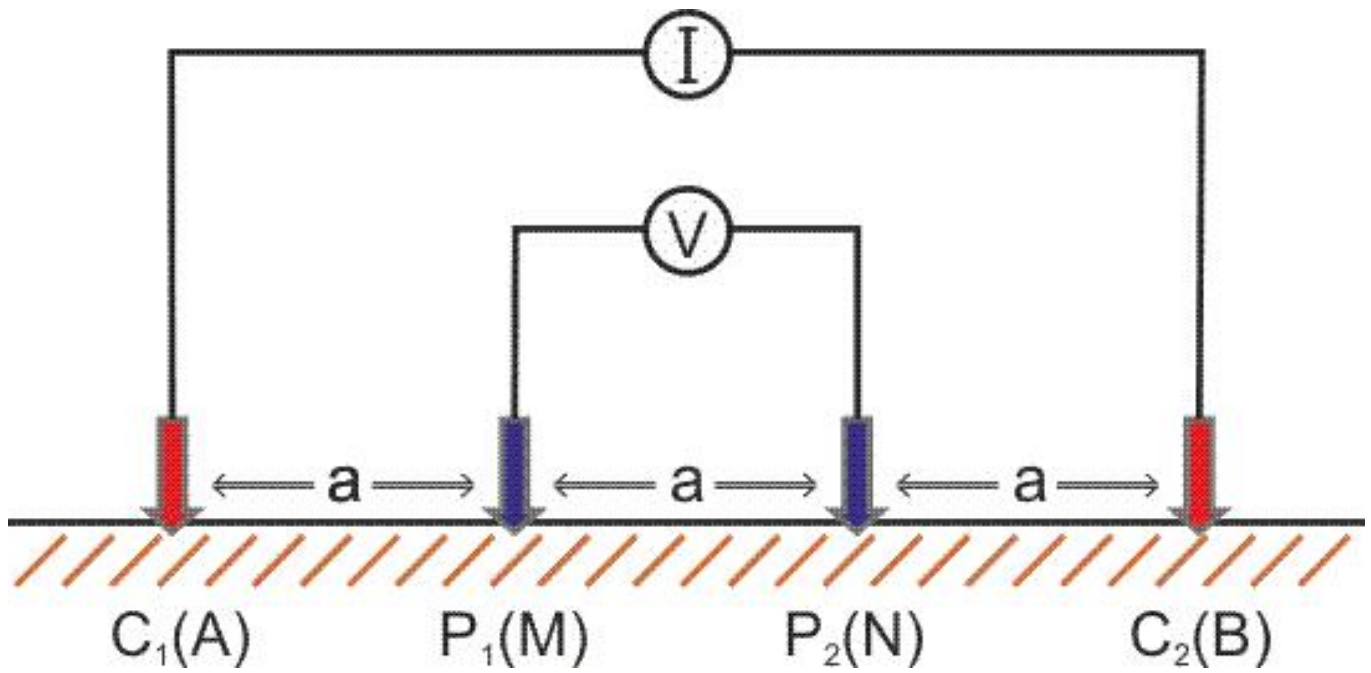


Figure 3.4: Electrode configuration of Wenner array.

Source: Bertermann *et al.*, 2016.

The resistances were later translated into apparent resistivity values using the equation below;

$$\ell_a = 2\pi a R \dots \dots \dots 1$$

where a=inter-electrode spacing.

R=ground resistance.

ℓ =Apparent resistivity.

2π =Conversion factor.

A data set of measured points along the profile line, electrode spacing and apparent resistivity values were fed into a 2-D resistivity imaging software known as RES2DINV. The software was used to generate an inverted resistivity depth image for each profile line. The precision of the inversion results was evaluated by monitoring the absolute error (ℓ_{rms}) between the measured and the modelled/ calculated apparent resistivity results using the equation below:

$$\ell_{rms} = \frac{\sum [| \log(\ell_{a \text{ measured}}) - \log(\ell_{a \text{ calculated}}) |]}{N} \quad - \quad - \quad 2$$

where $\ell_{a \text{ measured}}$ and $\ell_{a \text{ calculated}}$ are measured and apparent resistivity values at individual data points while N is the total number of data points. Hence, low ℓ_{rms} value indicate high level precision of investigation.

3.6 Borehole Drilling

Twenty five boreholes were drilled, ten of which were percussion-drilled to a depth of 20meters within the failed area (Mercy city) while the rest were auger holes drilled to depth of 8m in other locations of the study area to establish a comparative geotechnical evaluation of Warri (Table 3.2). Each borehole drilled was logged on site and samples were collected at intervals of one (1) metre for laboratory examinations.

Table 3.2: Coordinates of Borehole locations in Failed/ other areas in Warri.

S/N	Borehole Locations in Failed area	Coordinates
1	(BH1)	N05°36'008" E005°46'52.5"
2	(BH2)	N05°36'00.8" E005°46'52.5"
3	(BH3)	N05°36'03.7" E005°46'51.8
4	(BH4)	N05°36'07.2" E005°46'50.5
5	(BH5)	N05°36'08.6" E005°46'55.1"
6	(BH6)	N05°36'08.8" E005°46'56.9"
7	(BH7)	N05°36'09.0" E005°46'56.9"
8	(BH8)	N05°36'09.0" E005°47'00.2
9	(BH9)	N05°36'00.4" E005°47'00.8
10	(BH10)	N05°33'08" E005°46'54.7"
	Other borehole locations in Warri	
11	BH11 (GRA)	N05°34'01.8" E005°47'23.8"
12	BH12 (PTI Junc.)	N05°34'15.4" E005°48'03.8"
13	BH13 (Ebrumede)	N05°34'11.0" E005°48'39.0
14	BH14 (Ugbomoro)	N05°33'43.5" E005°49'07.1"
15	BH15 (Alegbo)	N05°33'24.9" E005°47'32.6"
16	BH16 (Sokoh Estate.)	N05°32'45.5" E005°46'27.5"
17	BH17 (Airport Junction.)	N05°33'16.3" E005°47'05.0"
18	BH18 (Okoloba Junction)	N05°33'40.8" E005°47'00.0"
19	BH19 (Mekavaal Hotel)	N05°34'08.9" E005°46'04.6"
20	BH20 (Ekpan Fly-Over)	N05°34'02.2" E005°44'00.6"
21	BH21 (Niger Cat)	N05°34'23.8" E005°44'55.0"
22	BH22 (Burrow Pit)	N05°34'21.4" E005°45'00.2"
23	BH23 (Army Estate)	N05°35'10.3" E005°46'46.4"
24	BH24 (ShopRite)	N05°34'22.4"E005°46'56.8"
25	BH25 (Kola Garden Hotel)	N05°36'26.9"E005°46'44.6"

3.7 Cone Penetration Test (CPT)

Cone penetration tests were conducted in twenty five locations (25) locations within the study area using a 2.5 ton CPT machine (Plates 3.1).



Plate 3.1: Cone Penetration Test in the study area.

The tests were carried out to depths of refusal which existed at 5-7 meters depending on the strength of the sub-soils of the location as well as the tolerance level of the Penetrometer

anchors. The CPT involved driving a 60° steel cone with base area of 10cm² into the ground with the view to determining the soil resistance to penetration as a basis for determining the consistency (stiffness/density) and in-situ shear strength of the soil. This was achieved by securing a winch frame to the ground by means of anchors. These anchors provided the necessary power to push the cone into the ground at the rate of 2cm/sec and the resistance to penetration registered on a pressure gauge connected to the pressure capsule was recorded. In the end, series of cone resistance and sleeve friction readings were plotted against depth. The shear strengths were calculated using the equation established by several workers (Hisham and Timothy 1998, Tomlinson 1999) as shown below.

$$C_u = q_c - \gamma d / N_k \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad 3$$

Where C_u = Undrained shear strength, q_c = Cone resistance, γ = Unit weight, d = depth and cone factor $N_k = 17.5$ which is applicable to Niger Delta Soils.

Values of undrained shear strength were used to calculate bearing capacity using the relationship below:

$$Q_c = S_u N_k + q_o \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad 4$$

Where Q_c = bearing capacity, S_u = undrained shear strength, N_k = calculated Skempton bearing capacity factor = 7.6 and q_o = Overburden pressure.

3.8 Laboratory Investigations

In agreement with standard test procedures (ISO 2720 (1986) and British Standard Institute; 1990, 1999) samples recovered from borehole drilling were subjected to the following testing programmes:

- 1) Sieve analysis.
- 2) Hydrometer analyses.
- 3) Consistency limit tests (such as liquid limit, plastic limit).
- 4) Compaction.
- 5) Stabilization analyses.
- 6) California Bearing ratio (CBR).
- 7) Consolidation test.
- 8) X-ray diffraction analysis (XRD).

3.8.1 Sieve Analysis

Two types of sieve analysis were engaged in assessing the particle size distribution of recovered soil samples which are highlighted below:

- I) Dry sieve analysis.
- II) Wet sieve analysis.

I) Dry Sieve Analysis

Here, 200g of oven dried soil sample were pulverised to separate the individual grains sizes and passed through a set of sieves arranged from top to bottom in a decreasing order of mesh/ sieve sizes as shown in the sequence; 4.75mm, 2.36mm, 0.84mm, 0.42mm, 0.149mm and 0.074mm. The sample within the set of sieves was agitated by an electric shaker for 15 minutes. The weight of the sample retained in the individual sieves were recorded and the percentage by mass of sample passing through each sieve was calculated and plotted against the respective sieve sizes to produce a Particle Size Distribution (PSD) curve from which the PSD of the sample was determined.

II) Wet Sieve Analysis.

This is a standard sieve analysis which is conducted when the fine content in a sample is more than 5% (British Standard Institute, 1990). By visual examination, some soil samples satisfied this condition hence the analysis.

200g of the soil material was dried and washed through ASTM (American Society for Testing and Materials) sieve No.200 (0.074mm) to separate the fines from the coarse fractions. The coarse fraction is dried and subjected to mechanical sieving using dry sieve analysis (which had earlier been explained).

3.8.2 Hydrometer Analysis.

The analysis is conducted when the fine content in a soil material is more than 10% (British Standard Institute, 1990). Results from wet sieve analysis showed over 40% dominance of fines in some soil samples hence the need for the analysis. The analysis was conducted by pouring 50g of an oven dried soil sample sieved through ASTM sieve No. 200 (0.074mm) into a 1 litre measuring cylinder. The cylinder was filled up to 500ml mark with distilled water and shaken thoroughly. Also, 100ml of water containing 4% of dispersing agent

(Sodium hexametaphosphate, $(\text{NaPO}_3)_6$) was further added to ensure thorough dispersion of particles, then the measuring cylinder shaken vigorously by inverting its ends for several times. The soil suspension was then left overnight in water at 30°C . The next day, water was added to the soil suspension to make the 1000ml mark then the cylinder was shaken for 10mins in three steps. Furthermore, a separate measuring cylinder containing 100ml of dispersing agent and distilled water filled to 1000ml mark was placed alongside the cylinder with soil suspension at the same temperature. The hydrometer was immersed in the soil suspension to measure the specific gravity of the particles. Readings were taken at the following time intervals: 30seconds, 1min, 2min, 4min without removing the hydrometer. The hydrometer was removed and inserted in the adjacent measuring cylinder to record the top of the meniscus R_0 and later re-inserted in the soil suspension for second set of readings taken at intervals of approximately 8min, 15mins, 30mins, 1hr, 2hr, 4hr, and 24hr. In this second phase, the hydrometer was withdrawn after each reading. Finally, calculations involving the hydrometric data and stokes law were used to determine the PSD of the fines which was illustrated in a semi-log plot.

3.8.3 Liquid Limit

The soil samples were air dried, disaggregated and passed through sieve of ASTM number “40” (0.425mm) and thoroughly mixed with small amount of distilled water until it appears as smooth uniform paste. A portion of the paste was placed into the cup of the liquid limit apparatus then squeezed down to eliminate air pockets and was spread into the cup to a depth of about 10mm thereby forming an approximately horizontal surface. The groove tool was carefully used to cut a clean straight groove down the center of the cup then the crank of apparatus was turned at a rate of approximately two drops per second and the number of drops, “N” was counted. When the number of drops exceeded 50, the number of drops on the

data sheet was recorded, then soil samples from the apparatus cup, usually from both ends of the groove were taken using a spatula. The soil was placed into a moisture can where it was immediately weighed, covered and placed in an oven for about 16 hours. The soil remaining in the apparatus cup was later placed into the porcelain dish as the apparatus cup was clean and dried for a second and third round of analysis, which was done by gradually increasing the moisture content of the paste so as to achieve groove closure at lesser blows. Finally a graph of moisture content was plotted against number of blows. The moisture content at 25th blows gave the liquid limit.

3.8.4 Plastic Limit

20g of dry soil sample was used for the liquid limit test. This was mixed with distilled water to form a uniform paste until the soil was at a consistency where it could be rolled without sticking to the hands. By rolling between the palm and glass plate, an ellipsoidal mass was formed. The mass was rolled until it formed a thread of 3mm in diameter having cracks on its surface. The thread was broken into several pieces and placed into a moisture can and sealed. The can was then oven dried for 16 hours and finally the moisture content of the set of threads was determined. The whole procedure was repeated three times to obtain three determinations. The average value of the moisture content gave the plastic limit of the soil.

3.8.5 Compaction Test

This test was conducted on 25 samples sourced from both the failed area and other areas at depths between 0-3m. The aim was to compact and improve the shear strength and engineering competence of soil samples with respect to road pavement construction. In compliance with BS1377(1990), 5kg of each sample was air-dried, then 3kg of which was mixed with 4-6% of pure water before it was transferred into a standard Proctor mould in steps of three layers. Compaction in the mould was in three layers each attracting 25blows

using a 2.5kg rammer at an impact of 300mm. Thereafter, the extension which was meant to prevent overflow of soil samples during compaction was removed so as to level off soil from the top of the mould then the mould, base plate and compacted soil were weighed for density calculation while the recovered sample from the top and base of the compacted soil were subjected to moisture content evaluation. The entire procedure was repeated for two or more times but with decreasing amount of added water (4% in subsequent test) until the mass of compacted soil began to fail. In the end, a graph of dry density was plotted against moisture content. Maximum Dry density (MDD) and Optimum Moisture Content (OMC) determine from the graph was used to prepare a specimen for California Bearing Ratio (CBR) analysis.

3.8.6 California Bearing Ratio (CBR) Test.

This is an empirical test which gives an indication of the shear strength of a soil especially in road construction (Tse 2009). It is a basis for assessing the usability of a soil material as sub-grade, sub-base, and base-course in road construction. Twenty five (25) soil samples were subjected to this test at Levant Quality Control laboratory in Koko, Delta State. Compacted soil specimens prepared using OMC and MDD values obtained from compaction analysis were soaked for 48 hours in water thereafter was placed on a purpose-made loading frame where it was penetrated by a cylindrical plunger of 50mm in diameter. The plunger was made to penetrate the sample at a rate of 1mm per minute while penetrative force at intervals of 0.25mm were recorded until a total penetration of 7.5mm was reached. The plunger was removed from the specimen while the cavity it created was filled with dry soil. The opposite end of the sample was turned over for a repeated procedure. On completion of the test, a graph of penetrative force (i.e load on plunger) was plotted against plunger penetration for both ends of the sample (i.e the top and bottom). The graph was compared with the 100% standard curve developed from California in United States of America (USA). Both curves

were compared at penetration values of 2.5mm and 5mm while penetrative forces (i.e test loads) at these points were expressed as a percentage of the standard loads at this points as shown by the equation below:

$$\text{CBR at 2.5mm} = \frac{\text{Test load(Kgf)} \times 100}{1340} \quad - \quad - \quad - \quad - \quad 5$$

$$\text{and CBR at 5.0mm} = \frac{\text{Test load(Kgf)} \times 100}{2020} \quad - \quad - \quad - \quad - \quad 6$$

The average CBR value of both ends of the specimen resulted in the actual CBR of the soil which was later compared with the Nigerian specification for road construction (FMW1997) for pavement usability assessment.

3.8.7 Soil Stabilization.

These analyses were engaged to further improve the pavement usability as well as the engineering competence of the soils in response to heavy vehicular load and adverse weather conditions. To this end, the three stabilization programmes engaged are as follows:

- I) Sand stabilisation
- II) Cement stabilisation
- III) Composite stabilisation

3.8.8 Sand Stabilisation

Coastal Plain Sands (also known as sharp sand which had less than 5% fines) were sourced from River Ologbo in Edo State. Regulated proportion of the sands in range of 30-55% weight of the soil sample (depending on the soil grade of the sample) were thoroughly mixed with 3kg of the soil samples from 25 locations of the study area and each was subjected to standard proctor compaction test in compliance with BS1377(1990). OMC and MDD values of each sample were used to prepare a 6kg compacted specimen for CBR analysis which was

conducted after being wax cured for 6days and soaked for 24hours in water as prescribed by FMW (1997).

3.8.9 Cement Stabilisation

3kg of soil specimens from all the study locations were mixed with ordinary Portland cement in conformity to B.S12 (1990). Regulated proportions of cement in the range of 7-11% by weight of the specimen were added depending on the soils A.A.S.H.T.O classification as in Table 3.3.

Table 3.3: Modified Cement Content Requirements of A.A.S.H.T.O Soil Groups.

S/N	A.A.S.H.T.O Soil Group	Range of Cement content (wt%)
1	A-1-a	4-6
2	A-1-b	4-7
3	A-2	5-8
4	A-3	6-9
5	A-4	7-11
6	A-5	8-12
7	A-6	9-13
8	A-7	10-14

Source: BS6229 (1990)

Cement mixed specimen were subjected to standard proctor compaction test from which the OMC and MDD were used to produce a 6000g cement stabilised specimen for CBR analysis after being wax cured for 6days, soaked in water for 24hours and allowed to drain for 15minutes.

3.8.10 Composite Stabilisation

This stabilisation was engaged with the view to enhancing the technical and economic viability of soil stabilization bearing in mind the costly nature of cement. In this case 3kg of 25 soil samples were thoroughly mixed with sharp sands in the range of 30-55% by weight so as to improve their AASHTO soil group. Following the upgrade, a uniform cement proportion of 7% was mixed with soil specimen in compliance with the provision of BS6229 (1990). Thereafter a 3000g specimen mixed with sand and cement was subjected to standard proctor compaction test from which the OMC and MDD were used to prepare a specimen for CBR analysis after the sample was wax cured for 6days, soaked in water for 24hrs and allowed to drain for 15minutes in agreement with BS6228(1990) and FMW 1997.

3.8.11 Consolidation Test.

This test was conducted in compliance with IS2720 (1986) with a view to determining the settlement characteristics (such as compression index, the rate and amount of settlement) cohesive sub soils in response to overburden pressure. Soil specimens were extruded from sample tubes, trimmed and inserted into a weighed consolidation ring (W1).The insertion was done such that the top and bottom surfaces of the soil sample protruded beyond the upper and lower ends of the ring to give room for further trimming so it could perfectly fit the ring size. The thickness of the soil specimen which is also the assumed height of the ring was measured as well as the weight of the soil specimen (W2). The ring-bearing specimen was then sandwiched by a bottom and upper porous stone which was further overlain by a loading cap.

separated from settled soil particles. Oriented soil particles were prepared and soaked with ethylene glycol vapour for at least 24 hours and later scanned in preparation for XRD analysis using a back loading preparation method.

XRD analyses on settled soil particles were conducted using a PANalytical Aeris diffractometer with PIXcel detector and fixed slits with Fe filtered Co-K α radiation. The phases were identified using 'X'Pert High score plus software. The relative phase amounts (weight%) were estimated using the Rietveld method.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Lateral Geo-Electric Distribution of Sub-Soils in Failed Area

Subsoil horizontal resistivity profiling (HRP) was conducted in four geophysical stations in the failed area and the findings of which were evidenced by results in figure 4.1-4.4.

4.1.1 Wenner /HRP1

The area within this profile line is characterised by relatively localised, near surface and high resistivity horizons (165-355 Ω m) which is indicative of unsaturated fine-medium grained sands which stretch from mid right to mid left of the profile line thereby covering a distance of about 240m (Figure 4.1). The High resistivity horizon is then flanked and underlain by a relatively extensive and predominantly low resistivity horizon (3-77 Ω m) indicative of soft-firm clayey silts which existed at depths of 5-13m and stretches laterally to a distance of about 400m within the limits of investigation. This low resistivity horizon is also marked by a thin (about 3m thick), extensive and relatively higher resistivity horizon (165 Ω m) indicative of saturated fine to medium grained sands existing at depth of about 5m.

The general dominance of low resistivity horizons over high resistivity horizons implies the area of investigation is fines dominated. The entire profile is characterised by wide resistivity distribution which ranges from 3.63-761 Ω m which is indicative of lateral heterogeneities in soil properties.

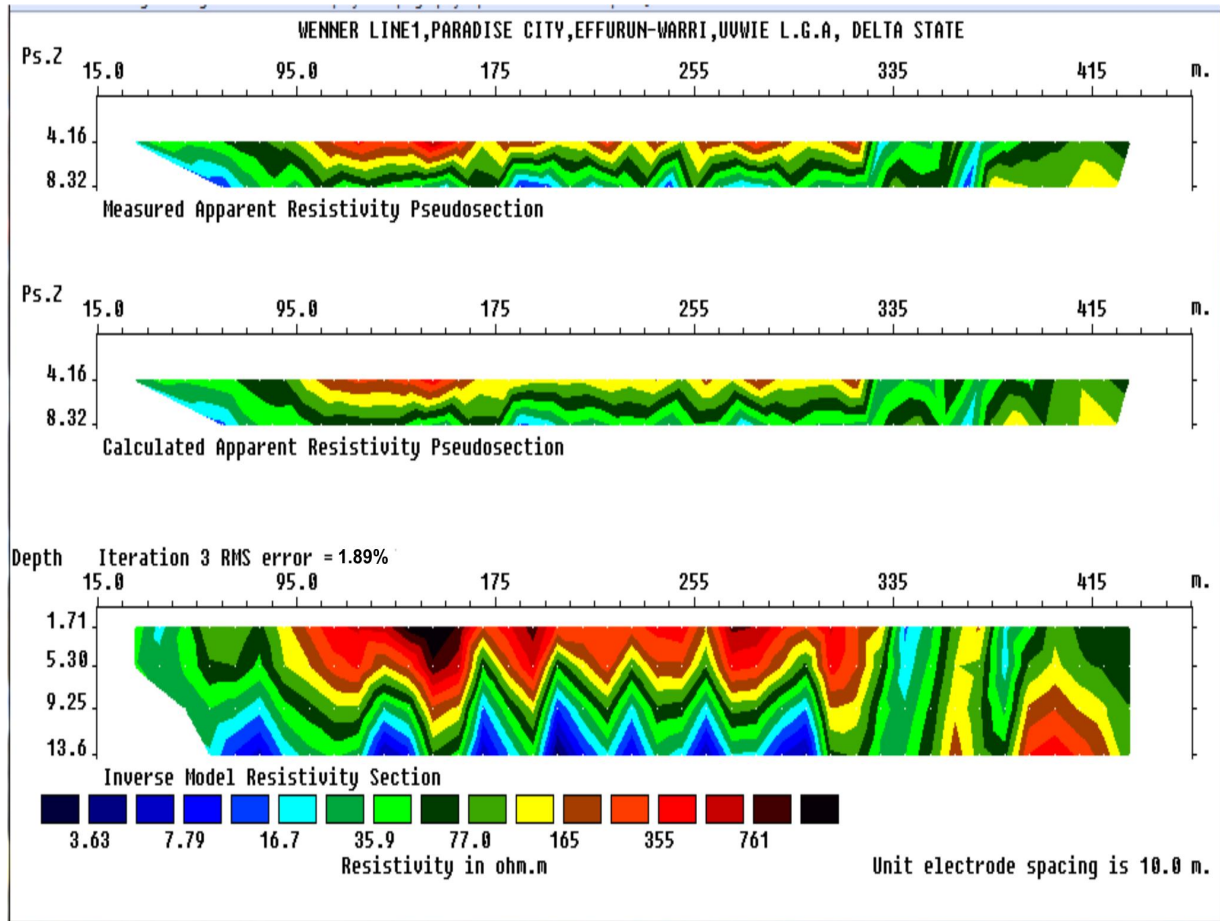


Figure 4.1: Horizontal Geo-electric Profiling of sub-soils in the Failed Area (HP1)

4.1.2 Wenner/ HRP2

The section is predominantly characterised by a low resistivity horizon (1-100 Ωm) indicative of saturated, very soft-firm sandy silt/clayey silt which runs from left of the profile line (Figure 4.2) and occupies about 60% of the surface to deep sub-surface area (0-13m) of the section. There are also localised occurrences of high resistivity zones (70-1299 Ωm) at depths of about 9.25-13.6m which stretches laterally to a distance of about (150m) within investigation limits. The zone is indicative of fine-medium grained sands. Similar localised high resistivity horizon existed on the extreme right of the profile line which ran from the surface to a depth of 13.6m. Resistivity values along this profile section ranges from 7-1299 Ωm which implies there are higher heterogeneities in sub-soil properties relative to those in HRP 1.

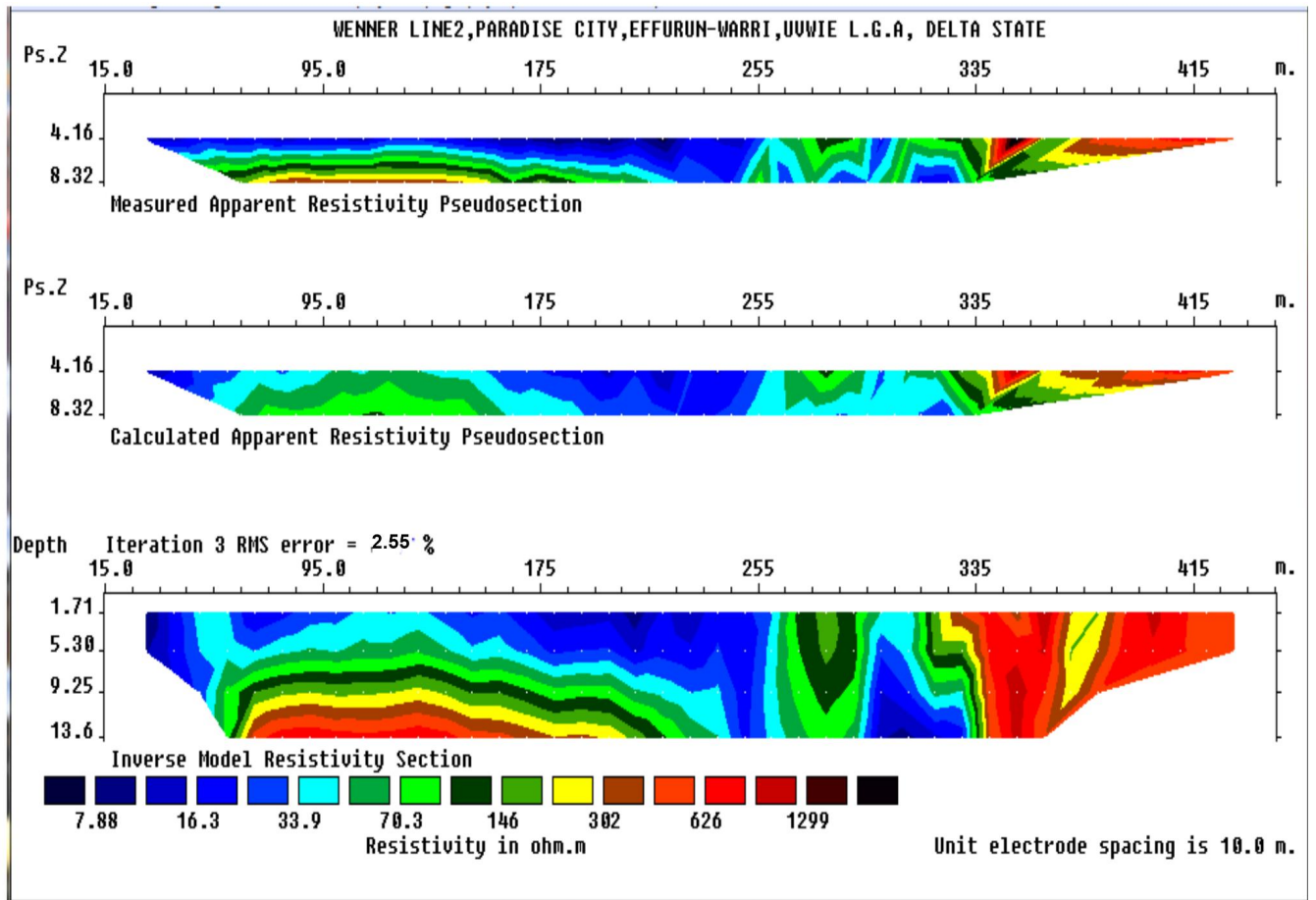


Figure 4.2: Horizontal Geo-electric Profiling of sub-soils in the Failed Area (HP 2)

4.1.3 Wenner /HRP 3

The profile section is characterised by an extensive high resistivity horizon (178-1383 Ωm) which stretches across both ends of the profile line and terminates at depths of 9-13.6m (Figure 4.3). The high resistivity implies unsaturation as well the inferred presence of unsaturated clayey silt, silty sand and fine-medium sands as indicated by VES 3 (Table 4.1). Evidence of water saturation was reflected by an extensive, low resistivity horizon (1.063-63.9) which ran across the profile section at depth of 9m and terminated at depth of 13.6m. The occurrence of extensive high resistivity horizon overlying a similarly extensive but low resistivity horizon implies relatively lateral homogeneities in lithologies in the profile line unlike other sections. However, there is also wide resistivity values (1-1383 Ωm) across this section which imply heterogeneities in soil properties such grain size and moisture content etc.

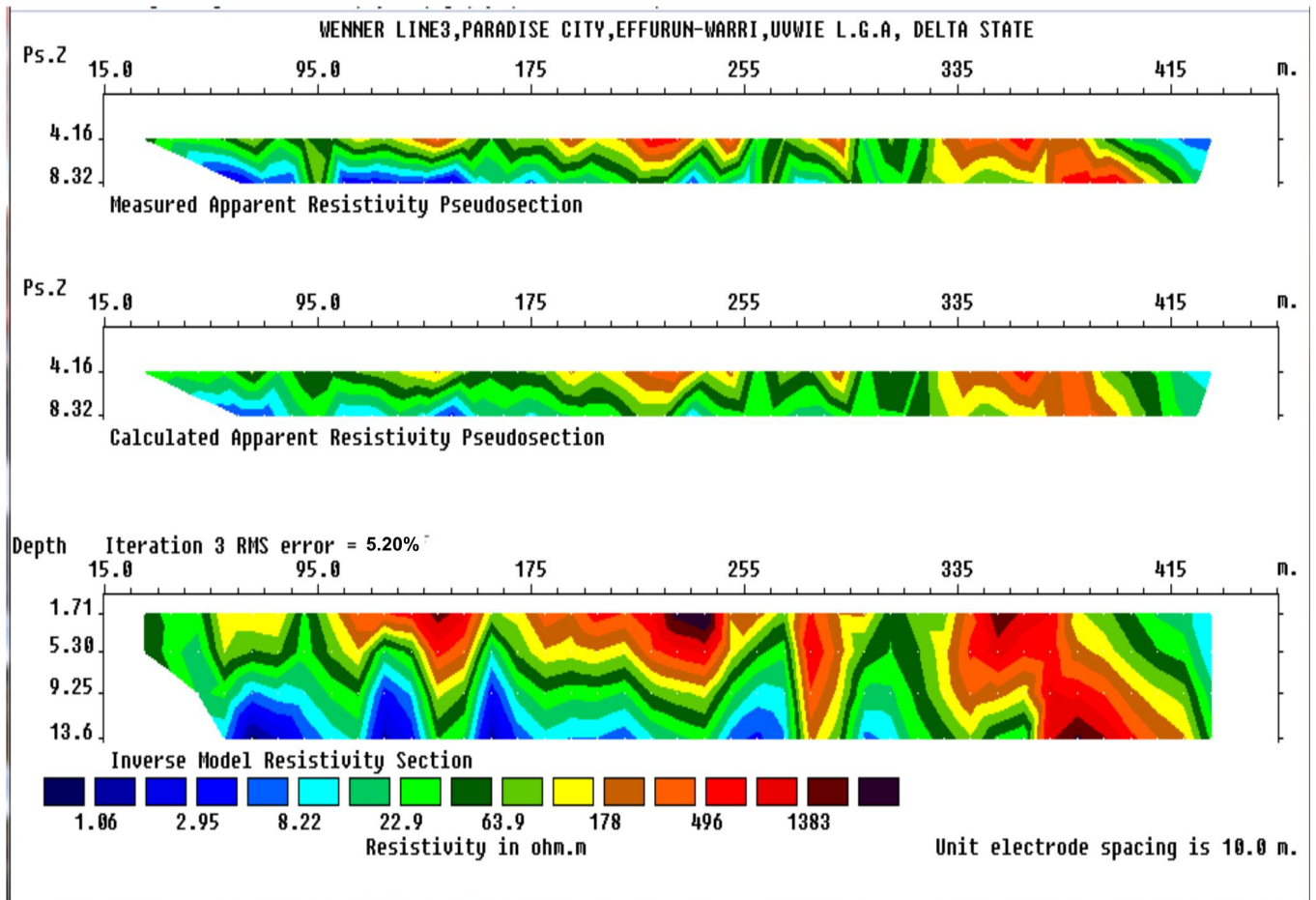


Figure 4.3: Horizontal Geo-electric Profiling of sub-soils in the Failed Area (HP 3)

4.1.4 Wenner /HRP 4

There is a wide spread low resistivity horizon (4.13-38 Ωm) which covers about 65% of the entire section. The horizon is indicative of widespread saturated sandy silt which stretches laterally to about 300m with average thickness of about 14m. This low resistivity horizon is further underlain by less extensive high resistivity zones of unsaturated fine to medium grained sands and very stiff clayey silt which agree with vertical geo-electric profile of VES 4 (Table 4.1). A wide resistivity distribution (4.13-9885 Ωm) was also recorded in this section which also implies wide variation in engineering properties of soils within this profile line.

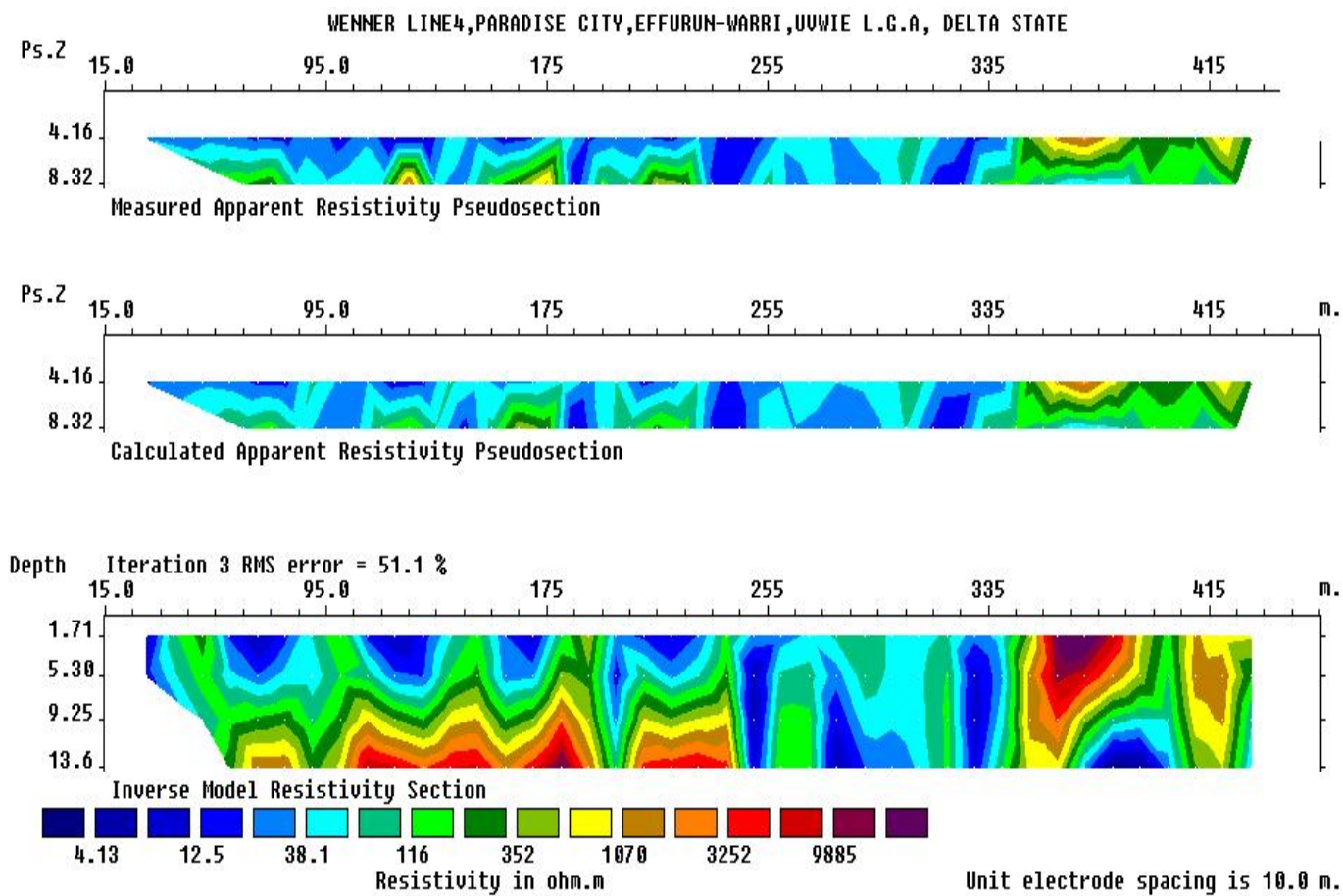


Figure 4.4: Horizontal Geo-electric Profiling of sub-soils in the Failed Area (HP 4)

4.2 Overview of Lateral Geo-Electric Distribution of Sub Soil in the Failed Area

Following the analyses of all profile lines, horizontal resistivity characterisation showed an overall dominance of low horizons across the area which are indicative of higher distribution of water saturated/fines dominated soils which is typical of a poorly drained/swampy terrain. The generally wide resistivity distribution (which ranges from 1.06-3252 Ωm) in the failed area shows heterogeneity in soil behaviour which is in contrast with the distribution (260-1445 Ωm) recorded by Avwenagha *et al.*, (2014b) in other areas in Warri. This implies there is more lateral homogeneity in soils in other locations in Warri relative to the failed area.

4.3 Vertical Geo-Electric Distribution of Sub-Soils in Failed Area

Geo-electric sounding conducted in four geophysical stations in the failed area delineated a four- five layer geo-electric profile characterised by AKH, KH and K type curves (Table 4.1). The profile from top to bottom is indicative of sandy/clayey silt (28.6-170 Ωm), silty sand (213.58-170.20 Ωm), soft- very stiff clayey silt (28-1575.3 Ωm) and fine-medium sand (528-577.53 Ωm). Apparent resistivity in the failed area ranged widely from 28.6-1575.3 Ωm which implies a significant vertical heterogeneity in soil properties (such as natural moisture content, grain size, compaction and mineralogical characteristics etc).

Table 4.1: Vertical Geo-electric Profile of sub-soils in the failed Area.

Location: Failed Area	Layer no.	Curve type	Thickness (m)	Depth (m)	Resistivity (Ω m)	Inferred Lithology
VES1	1	AKH-Type	1.7574	1.7574	39.41	Clayey silt
	2		0.6096	2.366	1470.30	Fine- medium sand
	3		3.7885	6.1551	56.03	Clayey silt
	4		6.1828	12.338	417.39	Stiff clayey silt
	5		34.94	47.28	37.55	Soft clayey silt
	6		∞	∞	1521	Fine- medium sand
VES 2	1	k-Type	0.4600	0.4600	28.627	Clayey silt
	2		1.9513	2.41	213.58	Silty sand
	3		6.8671	9.278	1575.30	Very stiff clayey silt
	4		17.46	26.74	297.32	stiff clayey silt
	5		34.794	61.535	528.12	Fine-Medium sand
	6		∞	∞	75.46	
VES 3	1	KH-Type	2.2864	2.2864	170.20	Silty sand
	2		7.8955	10.182	1085.80	Very stiff Clayey silt
	3		19.044	29.226	32.029	Soft Clayey silt
	4		19.044	48.270	1440.80	Very stiff Clayey silt
	5		∞	∞	460.26	Fine-Medium sand
VES 4	1	K-type	0.6504	0.6504	40.464	Sand silt
	2		0.6754	1.3258	74.914	Firm sandy silt
	3		3.1495	4.4753	1373.40	Very stiff clayey silt
	4		50.688	55.163	577.53	Stiff clayey silt
	5		∞	∞	106.41	Sand

Highest resistivity values in all four geophysical stations were recorded at depths between 2-19m which in comparison with the 20m borehole logs agree predominantly with very stiff clayey silt horizons (Figure 4.5).

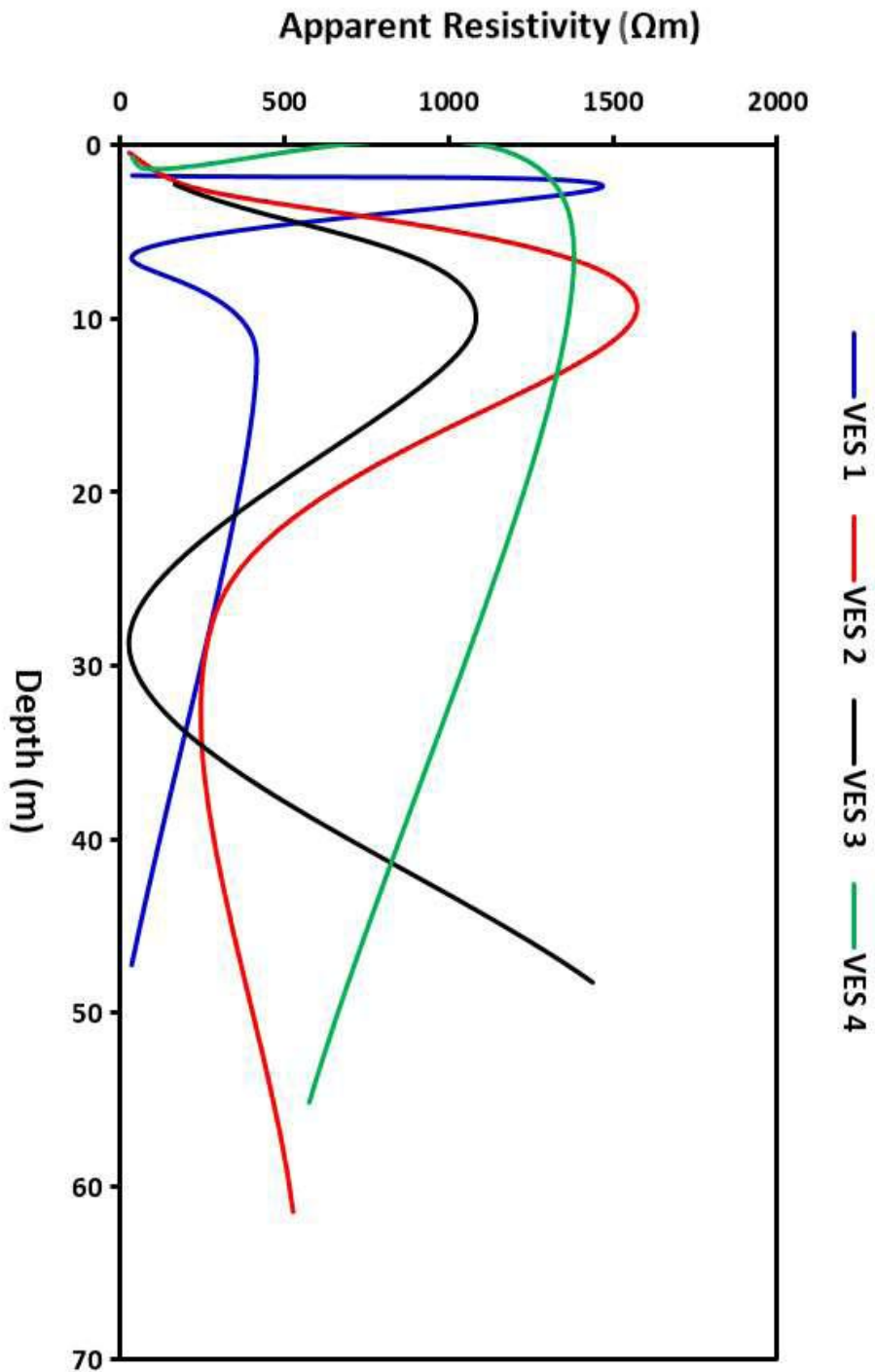


Figure 4.5: Plot of Apparent Resistivity against Depth at all VES Stations in the Failed Area

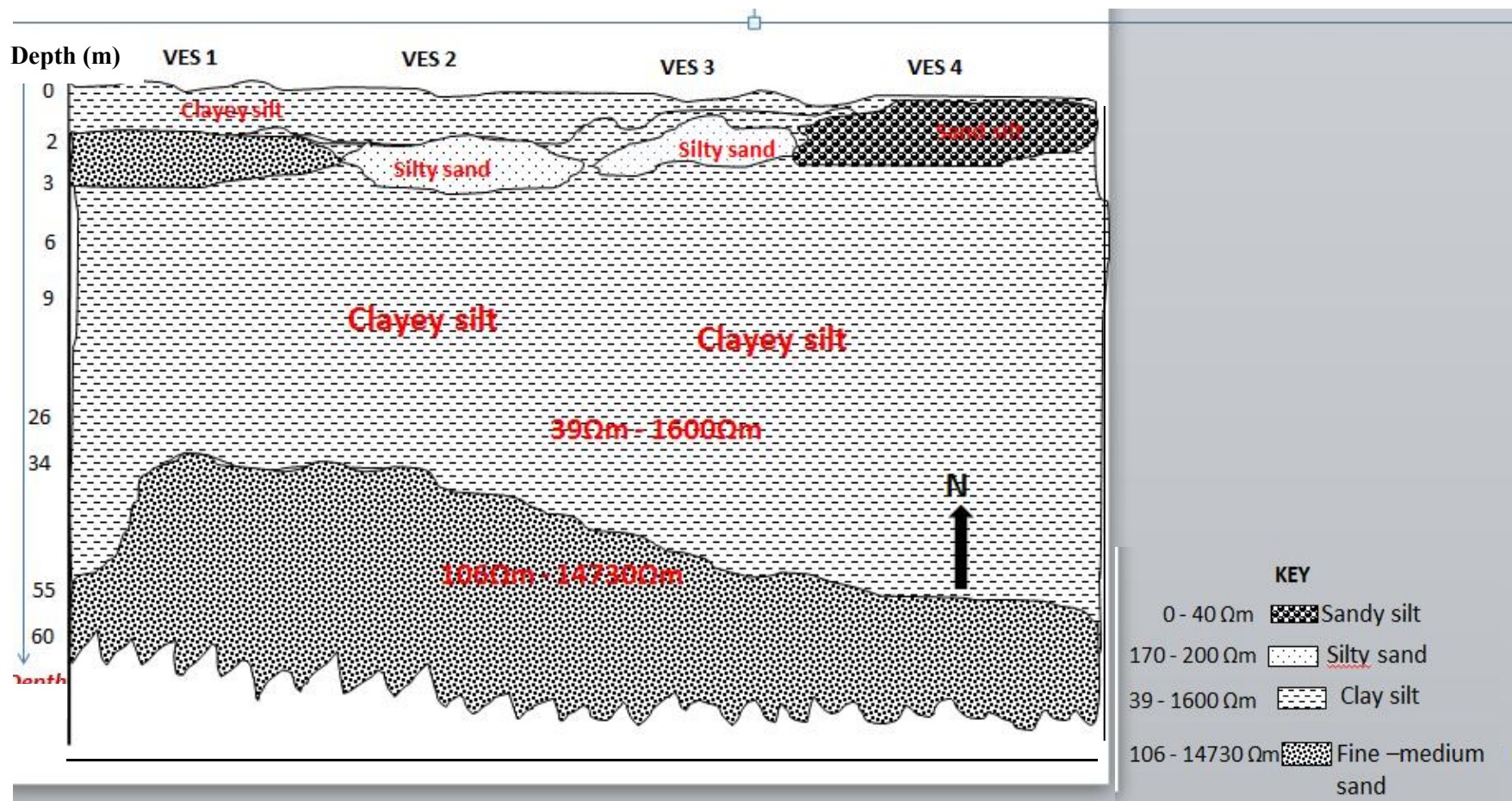


Figure 4.6: Geo-electric Cross Section of the Failed area.

Although the high resistivity values are pointers to high level compaction but the horizon is of low foundation quality on account of high fines content and high swelling potentials. Hence, high apparent resistivity does not always suggest foundation competence which partly agrees with earlier established thought of other workers such as Akintorinwa and Adesoji (2009).

4.4 Stratigraphic and Geotechnical Characterisation of the Failed Area

Synergised interpretation of results from visual/laboratory examination, geophysical investigation, borehole drilling and cone penetration testing resulted in the characterisation of failed area and other areas in Warri as reflected in Figure, 4.7 and 4.8 respectively.

Based on the aforementioned lines of evidence, It was noticed that the failed area consist predominantly of a two layer soil profile which from top to bottom consist of dark organic peaty sandy silt/silty sand underlain by a predominantly homogenous clayey silt horizon which is occasionally marked by pockets of fine- medium sands or sometimes underlain by fine-medium grained sands thereby resulting in a three layer soil profile (Figure 4.5-BH2 and BH3). The homogenous clayey silt horizon is sometimes discontinuous in some locations resulting in another type of two-layer soil profile which of sandy silt underlain by fine to medium grained sands (Figure 4.7-BH4).

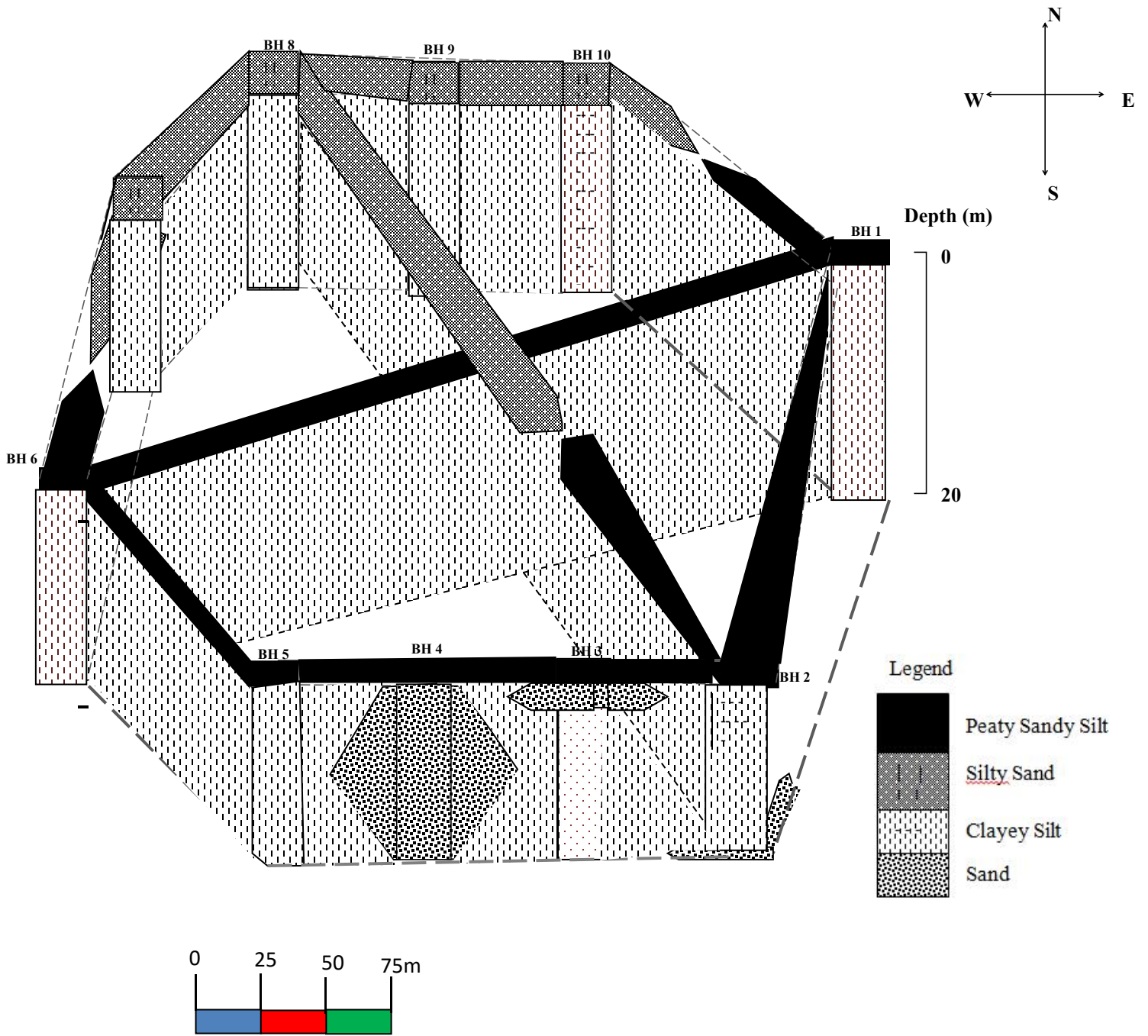


Figure 4.7: :Stratigraphic characterisation of the Failed Area in Warri.

4.4.1 Layer 1 (Sandy Silt / Silty Sand Horizon)

This is a dark, very soft- very stiff/dense, organic peaty horizon which has fine content of 3.5-96.5% and sand content of 33.5-96.5% with thickness of about 3m. The dark colouration and peaty nature depicts a poorly drained and reducing environment which typifies a swampy terrain. The layer has natural moisture content of 22-28% which implies relatively medium volume change and liquid limit of 20-72% which is indicative of a low-high compressibility horizon based on BS5930 (1999). The implied compressibility conformed with the determined/ calculated compression index (cc) which ranged from 0.2-0.65 while the average shear strength ranges from 24.5-168kpa at depths of 1-3m .The plasticity indices range from 16-47% which indicates a medium- high swelling potential as well as moderate to high plasticity according to BS,5930 (1999) and Akpokodje (2011). Specific gravity ranges from 2.56-2.58.

4.4.2 Layer 2 (Clayey Silt Horizon).

This consist of a dark grey, very stiff-Hard clayey silt with fines content of 88.5-95.3% and thicknesses of 13-17m within explored depth of 20m. The horizon is thickest mainly in the northern and eastern section of the failed area presumably due to greater impact of seasonal inundation by a nearby West-East flowing stream. The liquid limit ranges from 22-71% which implies low-high compressibility potential which partly conform to its compression index (cc) of 0.2-0.4. Natural moisture content ranges from 16-19%. CPT refusals were encountered in this horizon and the average shear strength at refusal depth of 4.8-6m ranges from 168-457.14kpa. The horizon is occasionally marked by a sandy horizon resulting in a three –layer soil profile.

4.4.3 Layer 3 (Sandy Horizon)

This is characterised by whitish medium dense to dense, poorly graded, fine to medium grained sands with sand and fines content of 86.2-93.0% and 7-13.8% respectively. The horizon was noticed at depths of 2-3m and 18-20m BH2-3 and BH4 where it was thickest (figure 4.7). The selective appearance of the horizon is an indication of lateral facies change due intermittent increase in run-off energy. The fluctuation in run-off energy could be caused by minor topographic undulations. Such minor undulations of engineering significance in the Niger Delta geomorphic unit (such as the Sombreiro-Warri Deltaic) have been recently reported by Abam (2016).

4.5 Stratigraphic and Geotechnical Characterisation of Other Areas in Warri.

With a view to establishing a stratigraphic and geotechnical bases of comparison with the failed area, fifteen auger holes were drilled in three other axes of Warri (PTI /Ugbomoro axis, Jakpa/ Refinery axis and Niger Cat/ round-about axis) bordering the failed area (Figure 4.8). Combined evidences/results from visual examination, laboratory analysis (sieve and hydrometer analyses) and cone penetration test showed that other areas consist entirely of a three layer soil profile whose horizons from top to bottom are highlighted below:

- I) Layer I (Humus Top soil).
- II) Layer II (Silty sand).
- III) Layer III (fine-medium sand).

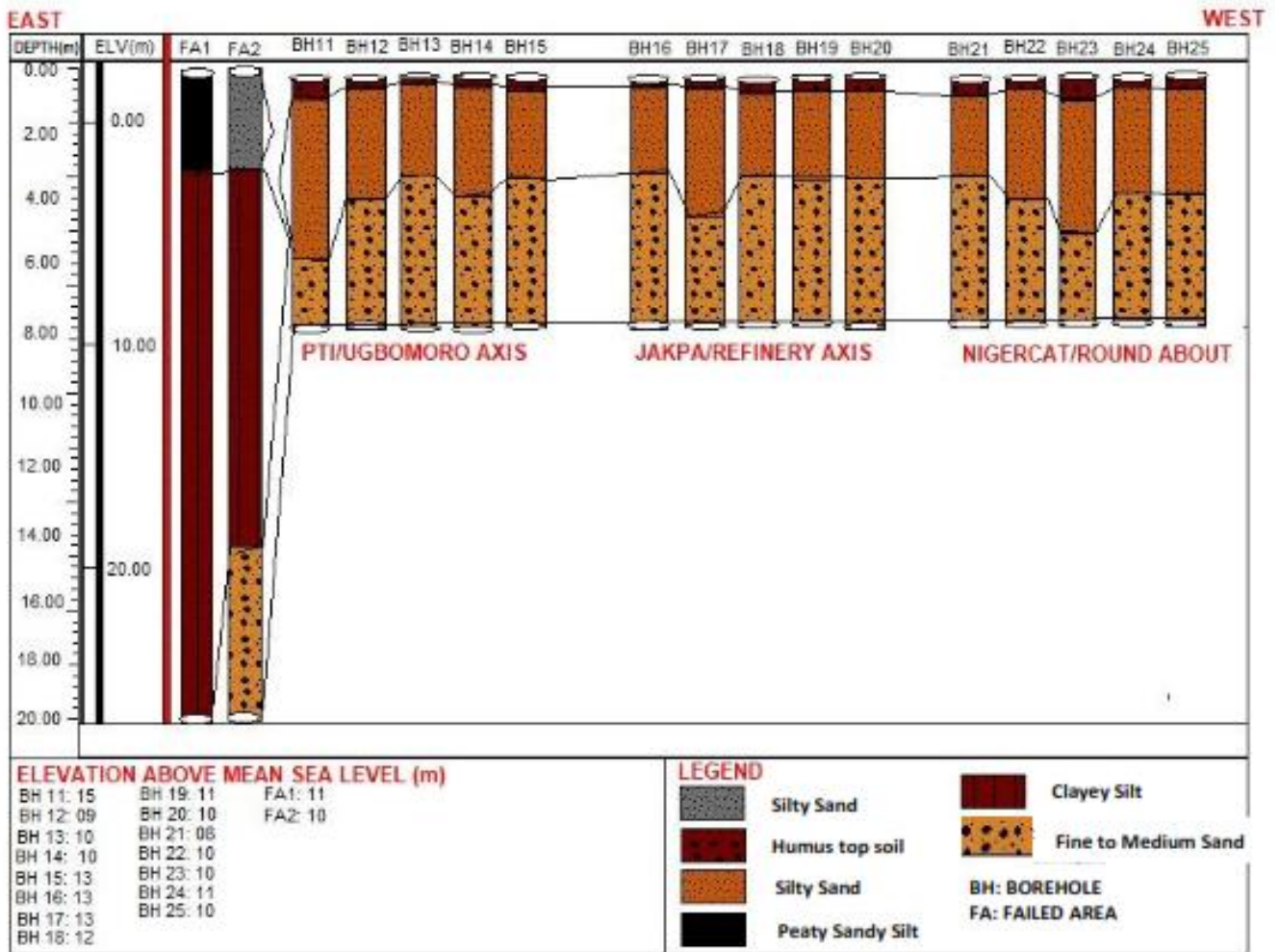


Figure 4.8: Stratigraphic characterisation of other areas in Warri

4.5.1 Layer I (Humus Top Soil)

This consists of a greyish, loose humus sandy top soil with average thickness of 0.25m. On account of insignificant thickness, the horizon has poor foundation quality. The horizon is absent in the failed area and it is replaced by dark organic peaty sandy silt/silty sand which has significant thickness but of weaker geotechnical quality on account of higher fines content and higher natural moisture content.

4.5.2 Layer II (Silty Sand)

The horizon is characterised by reddish brown soft to firm silty sands which are at variance with the brownish sandy clays and brownish clayey sands earlier reported by Akpokodje (1987) and Avwenagha *et al.*, (2014b). The horizon has thickness which ranges from 3-5m and maximum thickness was recorded in BH10 and BH22 in PTI and roundabout axis (Figure 4.6). Natural moisture content ranges from 12 to 17% which implies relatively low volume change. The fines content ranges from 12.8-39.9% while sand content ranges from 60.4-87.2%. The dominance of sand over fines implies a well drained environment unlike failed area. Liquid limit ranges from 14.5%-35.0% which implies low compressibility based on BS 5930 (1999). The implied compressibility conforms to its calculated compression index of 0.12-0.18 which is of lower value and better quality than the failed area. The shear strength ranges 21.83-73Kpa. These impressive shear strength and compressibility values give the horizon a competent foundation quality.

Unlike the other locations, Layer II in the failed area is almost entirely fines dominated which translates to poor geotechnical qualities such as higher natural moisture content, higher compression index and high swell potentials relative to horizon II in other areas. Although this Layer in the failed area has higher shear strength but it is unreliable following the significant presence of swelling smectite clays.

4.5.3 Layer III (Fine-Medium Sand)

This consist of whitish, poorly graded, dense fine to medium grained sands whose thickness within explored depth of 8m ranges from 3-5m. This is the most competent foundation horizon which has a bearing capacity of 27.64 to 78.96Mpa .The horizon conforms to that of the failed area where it is commonly deep seated, thin and discontinuous making shallow foundation design and piling difficult.

4.6 Casagrande Plasticity Chart Analysis of the Failed Area and Other Areas in Warri

The Casagrande classification of soils recovered from the study area is shown in Figure 4.9.

About 100% of soils in the failed area plotted below the “A” line of the Casagrande plasticity chart (Figure 4.9) which implies they are organic silty soils of low-high plasticity. This interpretation completely conforms to results from hydrometric and consistency analyses.

In other areas in Warri, the entire soils are of low plasticity which conforms to Oghonyon and Ekeocha (2015). About 50% of the soils plotted above the “A” line which implies the soils are 50% inorganic clayey soils and 50% organic/inorganic silty soils. The plasticity interpretation partly agrees with results of hydrometric and sieve analyses which were entirely indicative of silty sands.

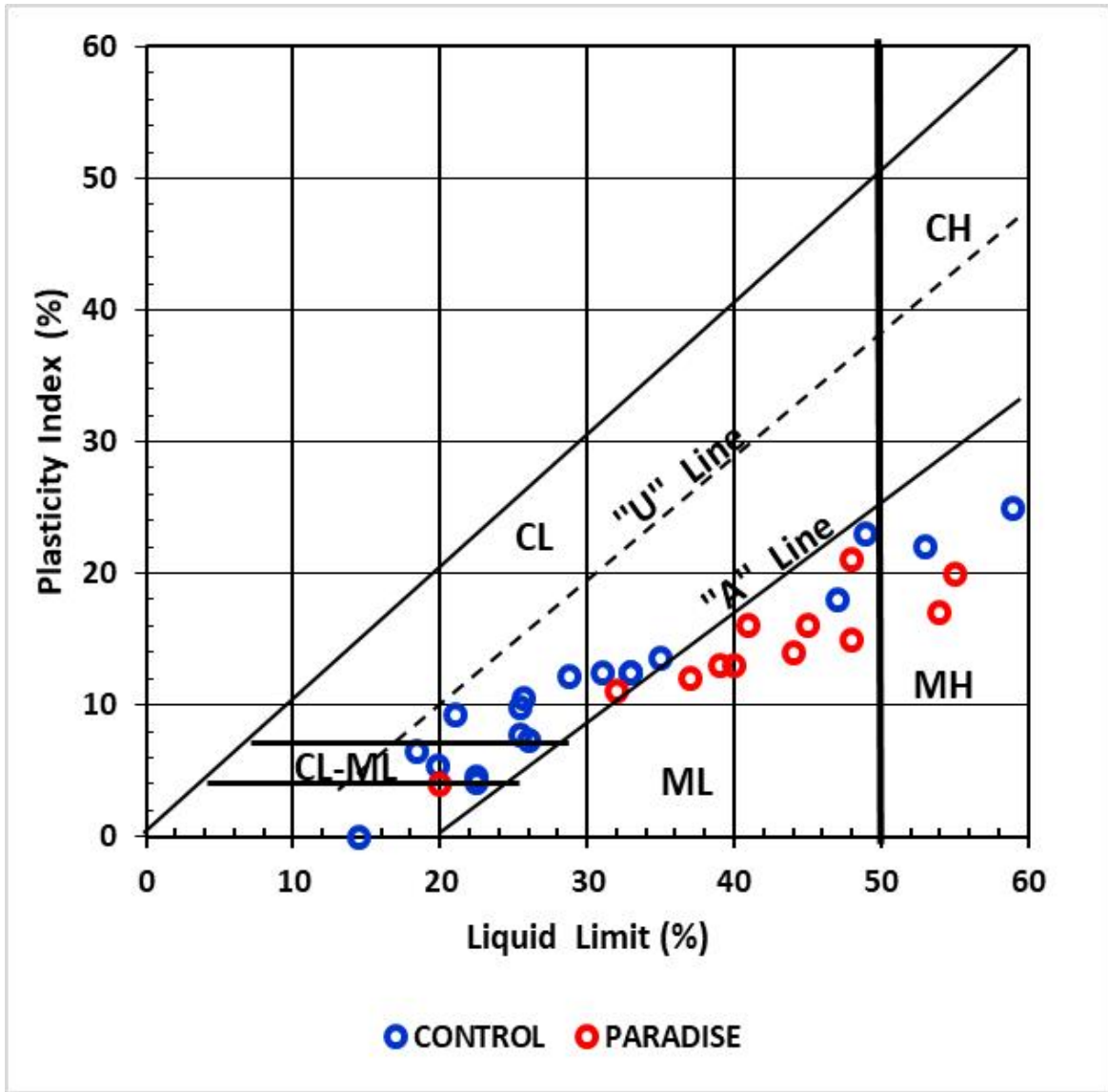


Figure 4.9: Casagrande Plasticity Classification of the Failed Area and other Locations.

(After Casagrande, 1948)

The partial conformity of the chart to the sieve analysis is due to the fact that some soils in the area are of lower liquid limit (due to low clay/organic content) which selectively lowers the soil plasticity relative to that of the chart resulting in false indication of inorganic clayey soils on the chart. Disparity between the Niger Delta soils (Precisely the dark organic peaty soil) and the plasticity chart was earlier noticed by Akpokodje (1987a) which he attributed to the higher plasticity of the organic soils relative to that of the Casagrande plasticity chart. The research also confirms that the Casagrande chart is not completely compatible with the Niger Delta soils.

4.7 Clay Activity of Soils in the Failed Area and Other Locations in Warri.

Skempton activity values of soils in the failed area range from 0.33-1.34 with average values of 0.7. Highest value was recorded in BH6 while lowest value was recorded in BH8. The range of values classifies the soil as inactive, normal and slightly active soils which agree with Ugbe (2011) while average value indicates the dominance of inactive soils. Mineralogical indications of the Skempton activity value is that the soils in the failed area consist of kaolinite, illite and slight presence of smectite (montmorillonite) where kaolinite is of predominant occurrence based on the average value of 0.7 Skempton (1953). These indices agree with XRD results except for the absence of illite in the failed area. The slight variation is due to the influence of amorphous component which increased the plasticity of some of the soils resulting in a pseudo-indication of illite by Skempton values (Figure 4.10).

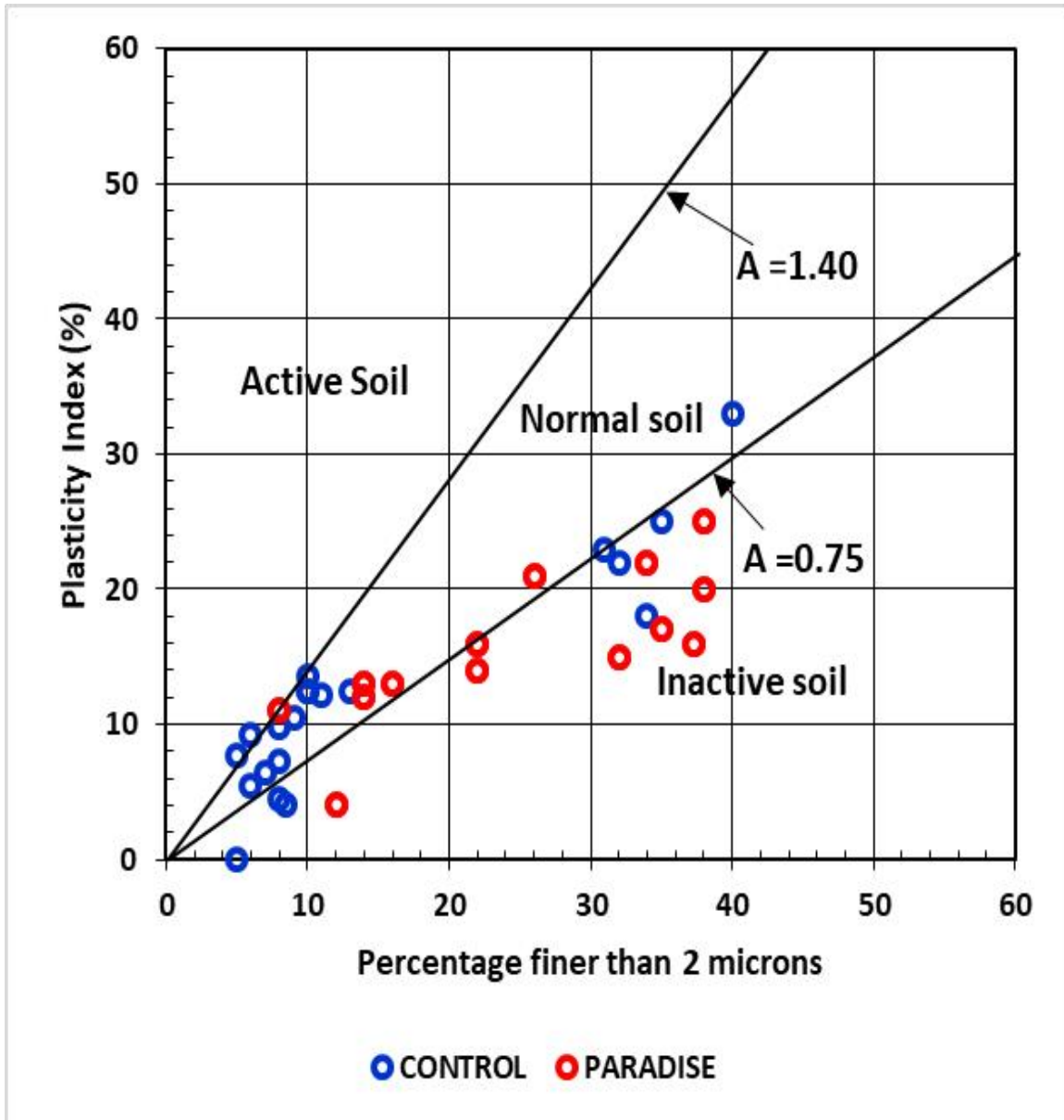


Figure 4.10: Skempton Activity Index analysis of the Failed Area and other Locations.

(After Skempton, 1953)

In other locations, activity values ranged from 0.47-1.54 with average value of 1.0. Highest value was recorded in PTI/Ugbomoro axis (precisely BH13) while least value was recorded in Jakpa/Refinery axis (BH16). These values gave the same classification as that of the failed area but average values indicated the dominance of normal clays. The indices from mineralogical perspective portrayed the presence of kaolinite, illite and smectite (montmorillonite) where Illite is of predominant occurrence. Except for the presence of Kaolinite, these indications were completely at variance with the XRD results which indicated the dominance of kaolinite. This gross variance is due to the significant influence of amorphous components on soil plasticity resulting in a false mineralogical indication from Skempton's activity chart. Going by the XRD result, the kaolinite content of the superficial soils in the failed area (2.57-9.67 %) and other areas (5.79-11.42%) is not significant to make the soils plastic yet they are plastic due to the presence of microcrystalline quartz (75.33-97.43%) and perhaps amorphous components. Hence, the plasticity of superficial soils in Warri is not controlled by clay minerals but ultimately by microcrystalline quartz and perhaps amorphous components. Amorphous influence on soil plasticity was earlier suspected by Okogbue and Onyeobi (1999).

4.8 Compaction and Classification Characteristics of Sub-Soils in the Failed Area And Other Areas In Warri.

The suitability of sub-soils for road pavement construction depends on their classification and compaction characteristics (Avwenagha *et al.*, 2014a). Sub-soil (between 0-3m) in the failed area is predominantly characterised by clayey/silty soils of A7-5 (50%) and A-6(40%) characteristics with minor occurrences (10%) of A-4 materials based on the AASHTO classification scheme (Table 4.2).

Table 4.2: Classification and Compaction Characteristics of the Soils in the failed Area and other Areas in Warri.

Location: Failed Area											
Borehole Number	Depth (m)	% Sand	% Fine	Liquid Limit	Plastic Limit	Plasticity Index	USCS	AASHTO	OMC %	MDD g/cm ³	CBR %
BH1	0-3	3.50	96.50	69.00	47.00	22.00	MH	A7-5	23	1.395	3.00
BH2	0-3	3.37	96.60	72.00	47.00	25.00	MH	A7-5	17.62	1.495	3.50
BH3	0-3	27.04	72.96	48.00	27.00	21.00	ML	A7-5	16.40	1.561	4.50
BH4	0-3	38.00	62.00	41.00	25.00	16.00	ML	A7-5	17.83	1.551	4.50
BH5	0-3	60.00	40.00	37.00	25.00	12.00	ML	A-6	18.34	1.465	6.00
BH6	0-3	37.00	63.00	44.00	30.00	14.00	ML	A7-5	19.23	1.459	4.00
BH7	0-3	65.00	35.00	32.00	21.00	11.00	CL-ML	A-6	14.42	1.634	6.00
BH8	0-3	65.50	34.50	20.00	16.00	4.00	CL-ML	A-4	9.15	1.925	20.50
BH9	0-3	60.00	40.00	39.00	26.00	13.00	ML	A-6	22.10	1.452	5.50
BH10	0-3	54.00	46.00	40.00	27.00	13.00	ML	A-6	15.74	1.510	5.00
OTHER LOCATIONS IN WARRI											
BH11 (GRA)	0-4	78.00	22.00	18.40	11.90	6.50	CL	A2-4	10.43	1.901	16.20
BH12 (PTI Junc.)	0-4	65.50	34.50	31.10	18.70	12.40	CL	A2-6	9.72	1.944	11.90
BH13 (Ebrumede)	0-4	60.40	39.60	33.00	20.60	12.40	CL	A-6	9.80	1.925	10.10
BH14 (Ugbomoro)	0-4	78.20	20.80	25.40	17.70	7.70	CL	A2-4	11.82	1.901	15.90
BH15 (Alegbo)	0-4	72.20	27.80	25.70	15.20	10.50	CL	A2-4	11.78	1.892	15.00
BH16 (Sokoh Est.)	0-4	74.30	25.70	22.50	18.40	4.10	CL	A2-4	9.10	1.927	15.50
BH17 (Airport Inc.)	0-4	79.20	20.80	25.40	15.60	9.80	CL	A2-4	9.42	1.886	17.90
BH18 (Okoloba Inc)	0-4	82.30	17.70	19.80	14.40	5.40	CL	A2-4	9.87	1.925	17.80
BH19 (Mekavaal Hotel)	0-4	75.20	24.80	26.10	18.80	7.30	CL	A2-4	8.41	1.904	17.30
BH20 (Ekpan Fly-Over)	0-4	87.20	12.80	14.50	NP	NP	CL	A-3	12.64	1.906	16.20
BH21 (Niger Cat)	0-4	76.80	23.20	22.50	18.00	4.50	CL	A2-4	12.20	1.856	15.80
BH22 (Burrow Pit)	0-4	81.50	18.50	21.00	18.50	11.80	CL	A2-4	12.13	1.881	17.30
BH23 (Army Estate)	0-4	70.20	29.80	33.00	20.60	12.40	CL	A2-6	9.61	1.944	14.10
BH24 (Shop Rite)	0-4	60.10	39.90	35.40	21.40	13.60	CL	A-6	12.30	1.826	10.60
BH25 (Kola Garden)	0-4	67.50	32.50	28.80	16.60	12.20	CL	A2-6	10.98	1.902	13.70

The Optimum Moisture Content (OMC) ranged from 9.15%-23.00% which conforms to clayey/silty soils (Arora, 2003). California Bearing Ratio (CBR) ranges from 3.00-20.50% with average value of 6.25%. A comparison of the CBR values with Nigerian standard (FMW1997) shows the soils are competent subgrade materials but incompetent sub-base and base course materials for road construction as their CBR values are less than 30% and 80% respectively.

Comparatively, 80% of the superficial soils in other areas are granular soils of A2-4, A2-6 and A-3 characteristics while 20% are silty soils of A-6 characteristics. These classification characteristics agree partly with those of Olobaniyi *et al.*, (2005) and Avwenagha *et al.*, (2014a). The soils CBR values range from 11.90-17.90% with average values of 15.02%. A comparison of these CBR values with FMW (1997) shows the soils are also competent subgrade material but incompetent sub-base and base course material. The average CBR (15.02%) shows that the sub-soils in other areas are predominantly of higher subgrade quality than that of the failed area. The difference in quality is due to the higher classification and compaction characteristics of the other locations over the failed area.

Eliminating the sub-base and base course deficiency of sub-soils in the failed area would require soil stabilization which could be done by sand, cement and composite stabilisation as engaged by other workers (Omosho and Eze-Uzomaka 2008).

4.9 Sand Stabilization Characteristics of Sub Soils in the Failed Area and Other Areas.

Strength improvement, dust control and soil water proofing are the principal focus of soil stabilization (Amu and Adetuberu 2010). With a view to improving the strength quality or engineering competence of subsurface soils of the failed area as well as other areas to become suitable sub-base and base course material, sand stabilization was engaged.

In response to sand stabilisation using 30% by weight of sand, the low-high plasticity, clayey/silty soil material which were dominantly of A7-5, A-6 and A-4 characteristics were upgraded to low plasticity clays of A2-6 and A2-4 characteristics resulting in CBR of 9.5-28.3% (Table 4.3). By Nigerian standard FMW (1997), the CBR shows the sub-soils are of better subgrade quality but still remain incompetent sub-base and base-course material. This conforms to the findings of Omotosho and Eze-Uzomaka (2008) who established that sand stabilised deltaic laterite produce only subgrade quality material.

Table 4.3. Sand Stabilization Characteristics of the Soils in the Failed Area and other Areas.

Location: FAILED											
AREA											
Borehole Number	Depth (m)	modifying sand (wt %)	% Fine	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	OMC (%)	MDD (g/cm ³)	USCS	AASHTO	CBR (%)
BH1	0-3	30.00	35.50	30.00	21.50	8.50	14.88	1.810	CL	A2-6	11.00
BH2	0-3	30.00	34.78	33.50	20.90	12.60	13.54	1.755	CL	A2-6	10.00
BH3	0-3	30.00	34.96	32.80	20.60	12.20	13.61	1.754	CL	A2-6	9.50
BH4	0-3	30.00	35.30	31.80	18.90	12.90	13.16	1.754	CL	A2-6	10.70
BH5	0-3	30.00	30.30	30.00	22.30	7.70	11.82	1.911	CL	A2-4	26.90
BH6	0-3	30.00	25.60	32.70	20.60	12.10	9.40	1.949	CL	A2-6	11.00
BH7	0-3	30.00	26.00	27.50	19.00	8.00	9.48	1.925	CL	A2-4	27.50
BH8	0-3	30.00	23.57	17.00	14.00	3.00	11.45	1.932	CL	A2-4	25.40
BH9	0-3	30.00	30.00	34.90	34.80	10.10	12.21	1.882	CL	A2-6	26.50
BH10	0-3	30.00	26.00	27.50	19.00	8.00	11.24	1.914	CL	A2-4	28.30
OTHER AREAS											
BH11 (GRA)	0-4	30.00	18.00	15.10	10.70	4.40	9.46	1.989	CL	A2-4	28.80
BH12 (PTI Junc.)	0-4	30.00	27.90	27.10	19.50	7.60	11.51	1.905	CL	A2-4	19.10
BH13 (Ebrumede)	0-4	30.00	33.10	27.10	18.80	8.30	11.80	1.889	CL	A2-4	18.70
BH14 (Ugbomoro)	0-4	30.00	17.10	23.00	17.40	5.60	11.35	1.889	CL	A2-4	18.70
BH15 (Alegbo)	0-4	30.00	22.20	21.30	14.00	7.30	11.95	1.948	CL	A2-4	24.10
BH16 (Sokoh Est.)	0-4	30.00	20.20	19.00	17.00	2.00	12.32	1.961	CL	A2-4	26.70
BH17 (Airport Jnc.)	0-4	30.00	15.10	23.00	16.80	6.20	8.52	1.962	CL	A2-4	27.50
BH18 (Okoloba Jnc)	0-4	30.00	12.50	15.20	11.90	3.30	9.20	1.979	CL	A2-4	25.70
BH19 (ekavaal Hotel)	0-4	30.00	20.60	21.50	16.70	4.80	9.07	1.988	CL	A2-4	26.20
BH20 (Ekpan Fly-Over)	0-4	30.00	11.60	14.50	-	-	10.34	1.966	CL	A-3	26.70
BH21 (Niger Cat)	0-4	30.00	16.20	15.50	12.90	2.60	10.36	1.961	CL	A2-4	26.20
BH22 (Burrow Pit)	0-4	30.00	14.20	18.70	15.70	3.00	9.53	1.990	CL	A2-4	28.60
BH23 (Army)	0-4	30.00	23.20	28.30	18.20	10.00		1.972	CL	A2-4	20.4

Estate)			0				9.20				0
BH24 (Shop Rite)	0-4	30.00	30.80	25.10	15.90	9.20	11.91	1.921	CL	A2-4	17.00
BH25 (Kola Garden)	0-4	30.00	25.30	22.30	14.30	8.00	10.60	1.952	CL	A2-6	20.40

In the other areas, the earlier low-medium plasticity granular/silty soils which were of A2-4, A2-6, A-6 and A-3 characteristics were upgraded to a predominantly homogenous A2-4 and A-3 soils resulting in an increased CBR which ranges from 17-28.80%. These CBR values by Nigerian standard indicate the soils have been upgraded to higher subgrade quality (even higher than the sand stabilised quality of the failed area) but still remains an incompetent sub-base/base-course material. It is therefore noticed that sand stabilization does not improve the usability of soils but rather upgrade their classification characteristics.

4.9.1 Cement Stabilization Characteristics of Sub-Soils in the Failed Area and Other Areas.

The impact of cement stabilization on the compaction properties of soil in the study area is shown in (Table 4.4). Following the influence of cement stabilisation, the unstabilised or naturally low-high plasticity clayey/silty soils of A7-5, A-6 and A-4 characteristics yielded an increased CBR which ranged from 71.3-117% at 11% cement content. With reference to FMW (1997), the CBR value indicates that the soils have been upgraded from their subgrade status to a sub-base status but still remain incompetent base-course materials as their CBR is less than 180% for cement stabilised soils. This finding conforms to that of Omotosho and Eze-Uzomaka (2008) who established that cement stabilisation of deltaic laterite produce sub-base quality material. Further stabilisation of the soil to produce a base quality material

would be economically unviable hence such sub-soils of the failed area should be avoided to ensure cement economy.

Comparatively, cement stabilisation of naturally low-medium plastic granular soils in other areas of Warri yielded a CBR of 128-193% using 7% cement content. The CBR values imply that the subsoil have been upgraded not only to sub-base status but also to base quality status especially in PTI junction (BH12), Okoloba Junction (BH8) and Kola garden (BH25). This result is at variance with that of Omotosho and Eze-Uzomaka(2008) who established that cement stabilization of deltaic laterite to produce base quality material using 7% cement is economically unviable.

Table 4.4: Cement Stabilization Characteristics of the Soil in the failed Area and other Areas.

Location: FAILED AREA											
Borehole Number	Depth (m)	Cement Content (wt %)	% Fine	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	OMC (%)	MDD (g/cm ³)	USCS	AASHTO	CBR (%)
BH1	0-3	11.00	35.50	69.00	47.00	22.00	12.72	1.622	MH	A7-5	71.30
BH2	0-3	11.00	34.78	72.00	47.00	25.00	13.30	1.735	MH	A7-5	73.00
BH3	0-3	11.00	34.96	48.00	27.00	21.00	13.50	1.737	ML	A7-5	75.20
BH4	0-3	11.00	35.30	41.00	25.00	16.00	12.40	1.739	ML	A7-5	76.00
BH5	0-3	10.00	30.30	37.00	25.00	12.00	10.90	1.891	ML	A-6	103.80
BH6	0-3	11.00	25.60	44.00	30.00	14.00	13.12	1.876	ML	A7-5	90.00
BH7	0-3	10.00	26.00	32.00	21.00	11.00	11.15	1.883	CL-ML	A-6	117.80
BH8	0-3	10.00	23.57	20.00	16.00	4.00	10.28	1.921	CL-ML	A-4	111.00
BH9	0-3	10.00	30.00	39.00	26.00	13.00	10.81	1.858	ML	A-6	99.80
BH10	0-3	10.00	26.00	40.00	27.00	13.00	10.73	1.873	ML	A-6	108.40
OTHER AREAS											
BH11 (GRA)	0-4	7.00	22.00	18.40	11.90	6.50	9.30	1.979	CL	A2-4	171.70
BH12 (PTI Junc.)	0-4	7.00	34.50	31.10	18.70	12.40	10.99	1.921	CL	A2-6	193.30
BH13 (Ebrumede)	0-4	10.00	39.60	33.00	20.60	12.40	11.74	1.882	CL	A-6	128.50
BH14 (Ugbomoro)	0-4	7.00	20.80	25.40	17.70	7.70	11.25	1.935	CL	A2-4	170.00
BH15 (Alegbo)	0-4	7.00	27.80	25.70	15.20	10.50	11.84	1.920	CL	A2-4	168.70
BH16 (Sokoh Est.)	0-4	7.00	25.70	22.50	18.40	4.10	11.21	1.941	CL	A2-4	163.40
BH17 (Airport Inc.)	0-4	7.00	20.80	25.40	15.60	9.80	8.46	1.939	CL	A2-4	168.00
BH18 (Okoloba Inc)	0-4	7.00	17.70	19.80	14.40	5.40	9.12	1.964	CL	A2-4	189.20
BH19 (Mekavaal Hotel)	0-4	7.00	24.80	26.10	18.80	7.30	8.95	1.965	CL	A2-4	175.60
BH20 (Ekpan Fly-Over)	0-4	7.00	12.80	14.50	-	-	10.29	1.964	CL	A-3	130.00
BH21 (Niger Cat)	0-4	7.00	23.20	22.50	18.00	4.50	10.22	1.941	CL	A2-4	150.30
BH22 (Burrow Pit)	0-4	7.00	18.50	21.00	11.80	9.20	9.48	1.983	CL	A2-4	143.30
BH23 (Army	0-4	7.00	29.80	33.00	20.60	12.40	9.12	1.917	CL	A2-6	178.90

Estate)											
BH24 (Shop Rite)	0-4	10.00	39.90	35.00	21.40	13.60	11.82	1.901	CL	A-6	133.60
BH25(Kola Garden)	0-4	7.00	32.50	28.80	16.60	12.20	10.55	1.934	CL	A2-6	185.00

4.9.2 Composite Stabilization Characteristics of Soil in the Failed Area and Other Areas.

With a view to producing base quality material as well as enhancing cement economy using cheap and readily available material like sand, composite stabilisation was engaged. Following the impact of composite stabilisation, the naturally fine dominated soils of the failed area yielded improved CBR values of 128.2-183% with average values of 152.16% using 7% cement and 30-55% sand (Table 4.5). CBR results imply that composite stabilisation predominantly improved the sub-soils of the failed area to sub-base quality except for minor occurrence of base quality material produced in BH7. This implies that predominant upgrade to base quality would demand cement above 7% which amounts to unviability in the economic sense.

Sub-soils in other areas of Warri responded more positively to composite stabilisation resulting in higher CBR values which ranged from 110-272.50% with average value of 212% using 7% cement and 30% sand. The CBR indicates the soils are now base quality compliant except for sub-base quality produced at BH20 by Ekpan Flyover. This exception is due to the cohesionless nature of soil in BH20 as cohesion would have added more strength to the soil material but rather the CBR became lower than when it was only cement stabilised. This

implies that cohesionless soils do not respond positively to composite stabilisation as addition of sand increases such soil's porosity resulting in lower MDD.

Table 4.5: Composite Stabilization Characteristics of Soils in the Failed Area and other Areas.

LOCATION: FAILED AREA											
Borehole Number	Depth (m)	Modifying Sand (%)	Cement (Wt %)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	OMC (%)	MDD (g/cm ³)	USCS	AASHTO	CBR (%)
BH1	0-3	55	7	30.00	21.50	8.50	14.67	1.771	CL	A2-6	130.7
BH2	0-3	55	7	33.50	20.90	12.60	15.50	1.780	CL	A2-6	128.2
BH3	0-3	55	7	32.80	20.60	12.20	14.12	1.791	CL	A2-6	133.9
BH4	0-3	55	7	31.80	18.90	12.90	13.84	1.765	CL	A2-6	127.3
BH5	0-3	30	7	30.00	22.30	7.70	11.10	1.937	CL	A2-4	179.0
BH6	0-3	30	7	32.70	20.60	12.10	10.24	1.878	CL	A2-6	156.9
BH7	0-3	30	7	27.50	19.00	8.00	10.95	1.972	CL	A2-4	183.0
BH8	0-3	30	7	17.00	14.00	3.00	6.20	1.992	CL	A2-4	165.0
BH9	0-3	30	7	34.90	34.80	10.10	11.30	1.892	CL	A2-6	141.5
BH10	0-3	30	7	27.50	19.00	8.00	10.60	1.948	CL	A2-4	177.0
OTHER AREAS											
BH11(GRA)	0-4	30	7	15.10	10.70	4.40	9.52	1.997	CL	A2-4	227.00
BH12 (PTI Junc.)	0-4	30	7	27.10	19.50	7.60	10.99	1.921	CL	A2-6	207.40
BH13 (Ebrumede)	0-4	30	10	27.10	18.80	8.30	11.62	1.894	CL	A-6	221.70
BH14 (Ugbomoro)	0-4	30	7	23.00	17.40	5.60	11.43	1.943	CL	A2-4	214.60
BH15 (Alegbo)	0-4	30	7	21.30	14.00	7.30	12.12	1.953	CL	A2-4	229.90
BH16 (Sokoh Est.)	0-4	30	7	19.00	17.00	2.00	11.61	1.975	CL	A2-4	198.80
BH17(Airport Inc.)	0-4	30	7	23.00	16.80	6.20	8.20	1.970	CL	A2-4	215.20
BH18 (Okoloba Inc)	0-4	30	7	15.20	11.90	3.30	8.32	1.996	CL	A2-4	215.10
BH19 (Mekavaal Hotel)	0-4	30	7	21.50	16.70	4.80	9.12	1.995	CL	A2-4	272.50
BH20 (Ekpan Fly-Over)	0-4	30	7	14.50	-	-	9.48	1.964	CL	A-3	107.00
BH21 (Niger Cat)	0-4	30	7	15.50	12.90	2.60	10.45	1.968	CL	A2-4	219.20
BH22 (Burrow Pit)	0-4	30	7	18.70	15.70	3.00	9.02	1.996	CL	A2-4	210.10

BH23(Army Estate)	0-4	30	7	28.30	18.30	10.00	9.01	1.979	CL	A2-6	207.60
BH24 (Shop Rite)	0-4	30	10	25.10	15.90	9.20	11.21	1.926	CL	A-6	204.70
BH25(Kola Garden)	0-4	30	7	22.30	14.30	8.00	10.18	1.961	CL	A2-6	229.50

4.9.3 Hydrometer and Mineralogical Characterisation of Soils in the Failed Area and Other Areas.

Hydrometer evaluation of the failed area showed that the terrain is fines dominated consisting of 34.5-96.6% fines with an average of about 58.66% (Table 4.6). About 23-57% of the fines are silt sized particles with an average of 41.20% silt while 12-40% of the fines are clayed sized particles. Specifically, the area is silt dominated which typifies a poorly drained and low energy environment.

From the mineralogical point of view, the clay sized particles are essentially characterised by 32.90-94.20% quartz (average 78.81%) and subordinate presence of kaolinite, smectite, microcline and muscovite which ranged from 6.46-37.31% (average 13.50%), 5.42-26.10% (average 5.56%), 1.52-5.32%(average 1.09%) and 2.15-4.87 (average 1.01%) respectively. The presence of smectite is an indication of a poorly drained environment where chemical weathering is inhibited (Huyghe *et al.*, 2011) and such conforms to swampy nature of the area.

The other areas in Warri are sand dominated terrains which consist of 60.4-87.2% sand with an average of 79.91%. The fines content ranges from 12.8-39.9% with an average of 26.03%. About 9.8-39.9% of the fines are silt sized particles while 3-13% are clay sized particles. This implies the other areas are characterised by silt dominated fines. The overall dominance of sand in other areas is an indication of a well drained and high energy environment unlike the

failed area. The mineralogy of the clay fraction reflect the dominant presence of 90.31-97.43% quartz (average 94.37%), with minor presence of 2.57-9.67% kaolinite (average 5.64%). The absence of smectite corroborates the well drained nature of the other areas in Warri (Akpokodje 1987). The general dominance of quartz in the clays of both the failed/other areas is an indication of residual clays (Onyeobi *et al.*, 2013) which is further evidenced by the sharp diffraction peaks (Onyeobi *et al.*, 2013) as shown in Figure 4.9. The dominant presence of clay mineral like kaolinite in both areas is an indication of tropical weathering of acidic/felsic source rock (Ajayi and Agagu 1981).

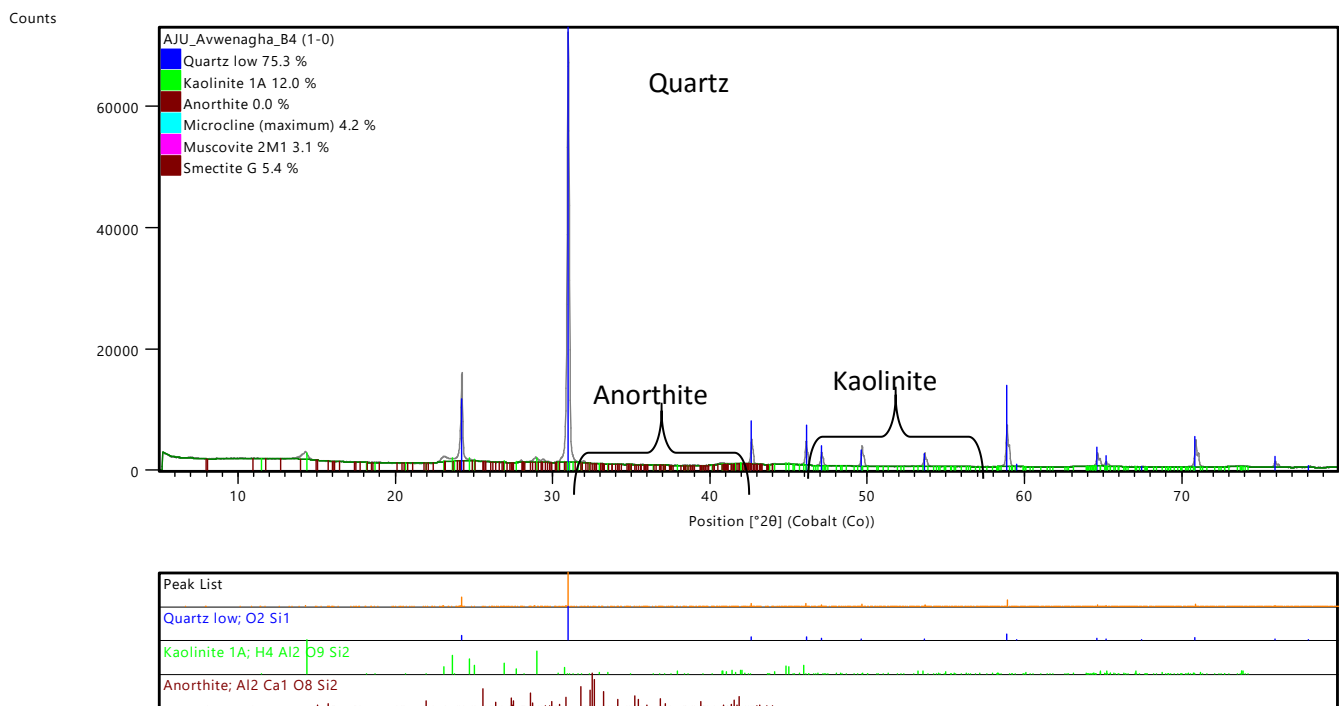


Figure 4.9: Typical X-ray Diffractogram of Soils in the Failed Area

Table 4.6: Hydrometer and Mineralogical Characterisation of the Failed Area and other Areas in Warri.

Location: Failed Area										
Borehole Number	Depth (m)	Fine Content (%)	Silt content (%)	Clay content (%)	Clay activity Index	%Micro crystalline Quartz	% Kaolinite	% Smectite	% Microcline	% Muscovite
BH1	0-3	96.50	52.5	34	0.65	88.56	11.42	-	-	-
BH2	0-3	96.6	58.6	38	0.65	93.52	6.46	-	-	-
BH3	0-3	72.96	46.9	26	0.80	92.36	7.62	-	-	-
BH4	0-3	62.0	40	22	0.73	75.33	11.99	5.42	4.15	3.08
BH5	0-3	40.0	26.0	14	0.86	91.88	8.10	-	-	-
BH6	0-3	63.0	41	22	0.64	-	-	-	-	-
BH7	0-3	35.0	27	8	1.34	94.2	5.79	-	-	-
BH8	0-3	34.5	24.5	12	0.33	-	-	-	-	-
BH9	0-3	40.0	26.0	14	0.93	92.87	7.11	-	-	-
BH10	0-3	34.6	32	14	0.81	91.41	8.58	0.01	-	-
BH9	3-20	92.5	60.5	32	0.69	35.10	30.48	24.08	5.32	4.87
BH10	3-20	91.5	56.5	35	0.71	32.90	37.31	26.10	1.52	2.15
Other Areas										
BH11 (GRA)	0-4	22.0	15.0	7.0	0.93	-	-	-	-	-
BH12 (PTI Junc.)	0-4	34.5	24.5	10	1.24	91.02	8.96	-	-	-
BH13 (Ebrumede)	0-4	39.6	26.6	13	0.95	90.31	9.67	-	-	-
BH14 (Ugbomoro)	0-4	20.8	15.8	5	1.54	-	-	-	-	-
BH15 (Alegbo)	0-4	27.8	18.8	9	1.12	-	-	-	-	-
BH16 (Sokoh Est.)	0-4	25.7	17.2	8.5	0.47	-	-	-	-	-
BH17 (Airport Jnc.)	0-4	20.8	12.8	8	1.20	-	-	-	-	-
BH18 (Okoloba Jnc)	0-4	17.7	11.7	6	0.9	94.55	5.43	-	-	-
BH19 (Mekavaal Hotel)	0-4	24.8	16.8	8	0.9	96.51	3.57	-	-	-
BH20 (Ekpan Fly-Over)	0-4	12.8	9.8	3	-	-	-	-	-	-
BH21 (Niger Cat)	0-4	23.2	15.2	8	0.56	96.37	3.62	-	-	-
BH22 (Burrow Pit)	0-4	18.5	12.5	6	1.53	-	-	-	-	-
BH23 (Army Estate)	0-4	29.8	19.8	10	1.24	-	-	-	-	-
BH24 (Shop Rite)	0-4	39.9	29.9	10	1.36	97.43	2.57	-	-	-
BH25	0-4	32.5	22.5	11	1.10	-	-	-	-	-

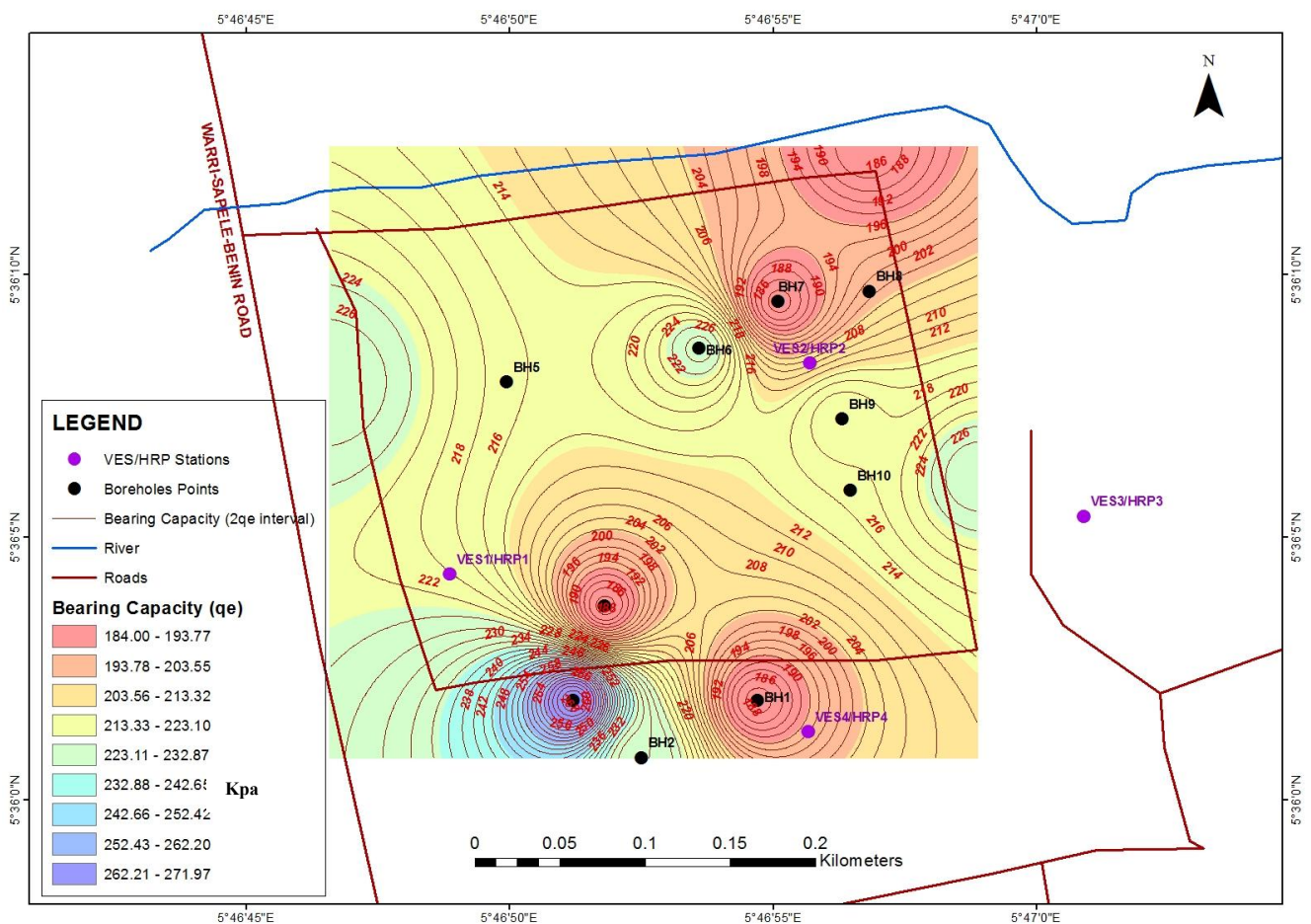
(Kola Garden)										
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4.9.4 Foundation Characteristics of the Failed Area and Other Areas.

The fundamental strength properties which determine the safety and stability of any foundation substratum are the bearing capacity and compressibility status. Bearing Capacity is the average maximum load a foundation substratum can sustain without shear failure. It is a common code of practice and fact that the depth to foundation for residential buildings in Nigeria is about 1m (Ogunsanwo, 2002). The failed area as well as other locations in Warri are dominated by residential buildings and on this premise, emphasis on soil bearing capacity and compressibility were confined to depth of 1m. In the failed area, bearing capacity at this depth ranges from 184-229Kpa with an average of 215Kpa (Figure 4.10). The failed area is dominated by low-medium bearing capacity zones (184-223kpa). The low bearing capacity zone which host (BH1, BH7, BH4 and BH8) range from 184-193kpa as indicated by the pink colouration in the Map. The zone has a history of imminent building collapse specifically within BH4 (due to differential bearing capacity and compressibility indices of superficial horizons of borehole 5 and borehole 4). Hence more building collapse could be anticipated within BH1, BH7 and BH8 if appropriate foundation improvement techniques are not engaged since they fall within the weak zone. The relatively stable/ competent areas are the medium (201-233kpa)/high bearing capacity (223-271) zones which are indicated by yellow-blue colorations. The significant variation in bearing capacity within the failed area is due to variation in soil properties (such as moisture content, grain size and mineralogy). Similar

variation in soil properties also influenced heterogeneity in soil compression index as it ranges from 0.31-0.62 which is an indication of medium-high compressibility (Figure 4.11).

In other areas, bearing capacity at depth of 1m ranges from 184-575Kpa with an average value of 368Kpa (Figure 4.12) while compression indices range from 0.12-0.34 which is indicative of low-medium compressibility (Figure 4.13). This implies the foundation substratum in other areas of Warri have better geotechnical quality than the failed area. The difference in foundation quality is due to the poor drainage condition in the failed area



compared to other areas.

Figure 4.10: Bearing Capacity Map of Soils in the failed Area.

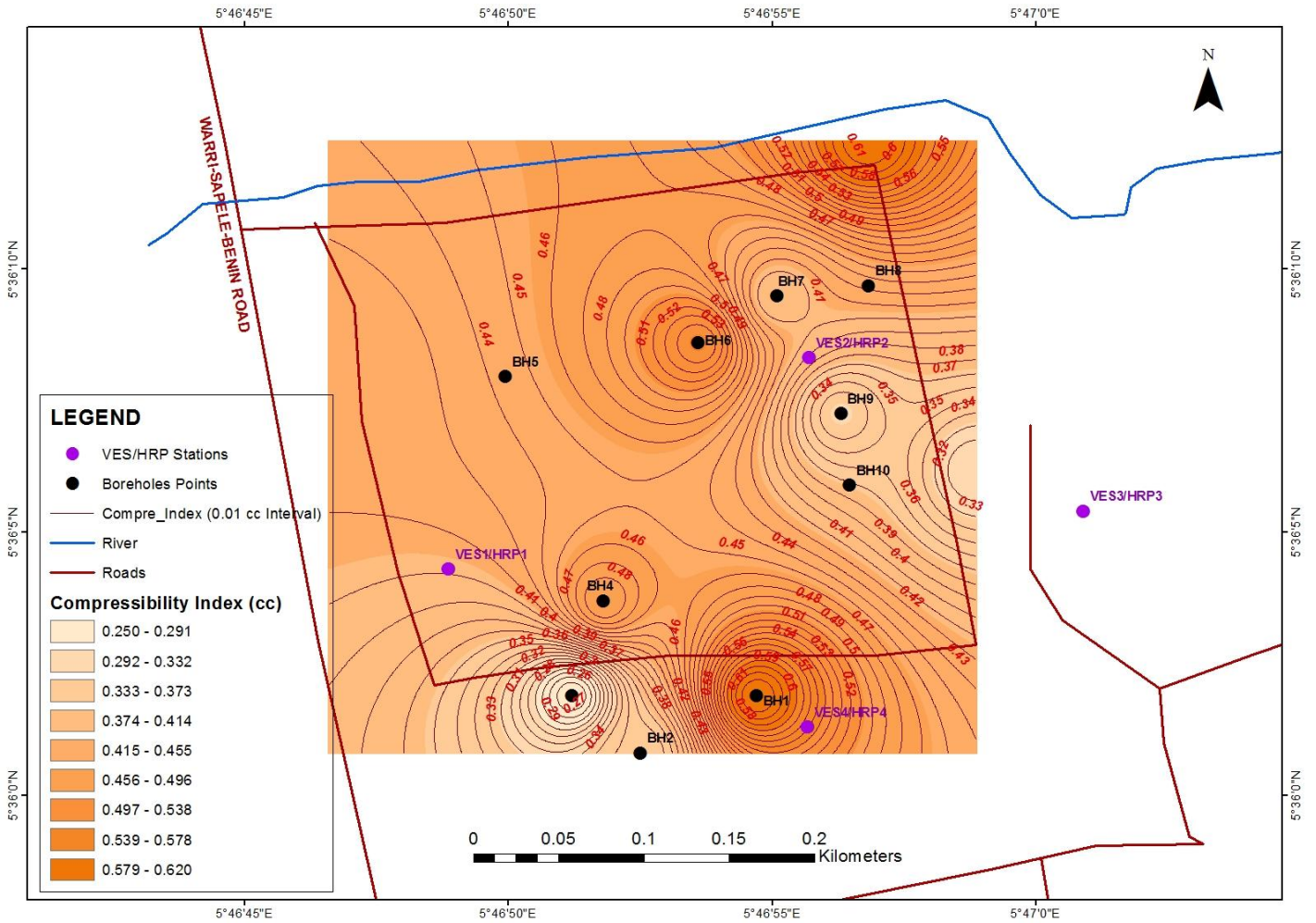


Figure 4.11: Compression Index Map of Soils in the Failed Area.

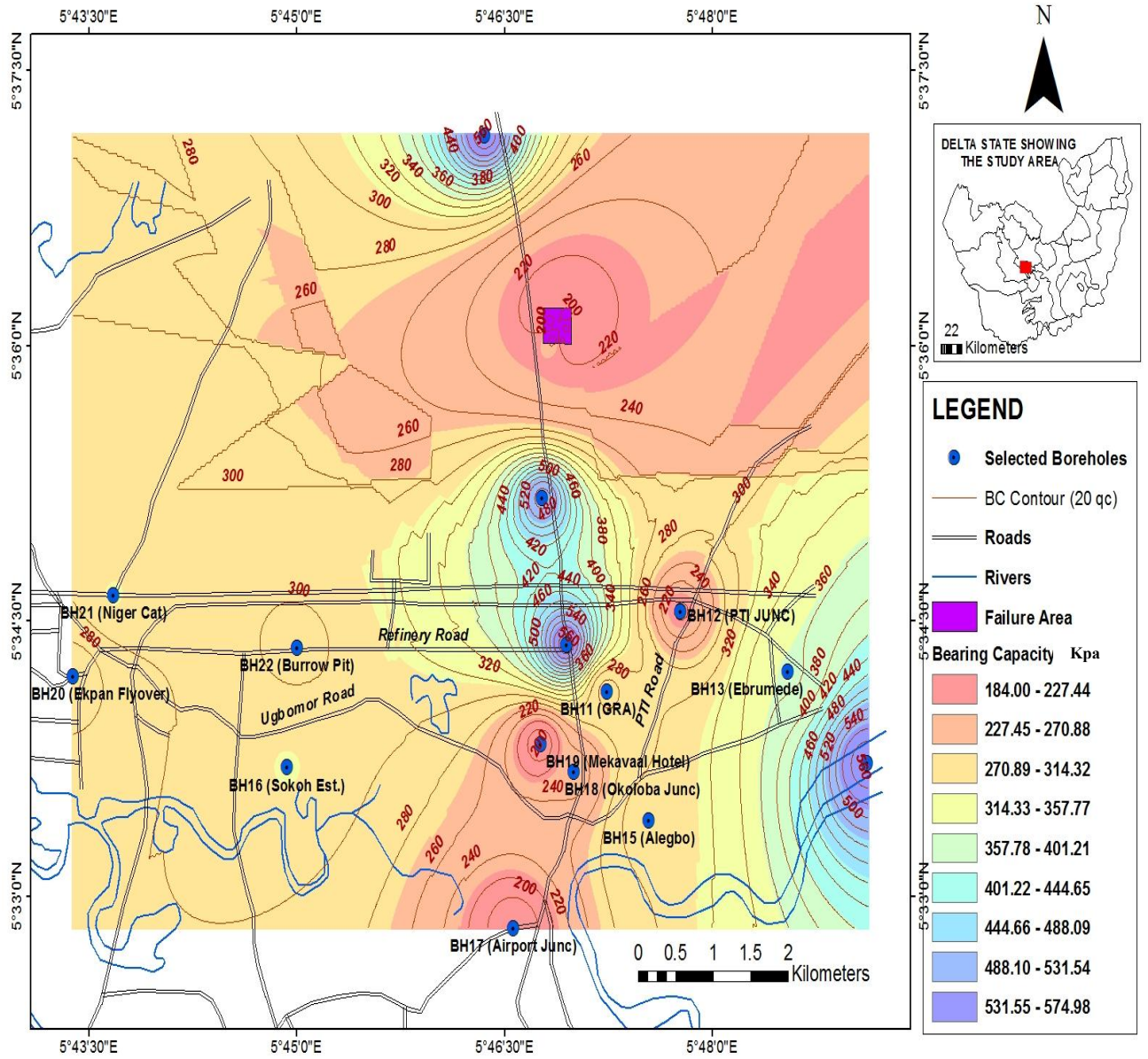


Figure 4.12: Bearing Capacity Map of Soils in Warri.

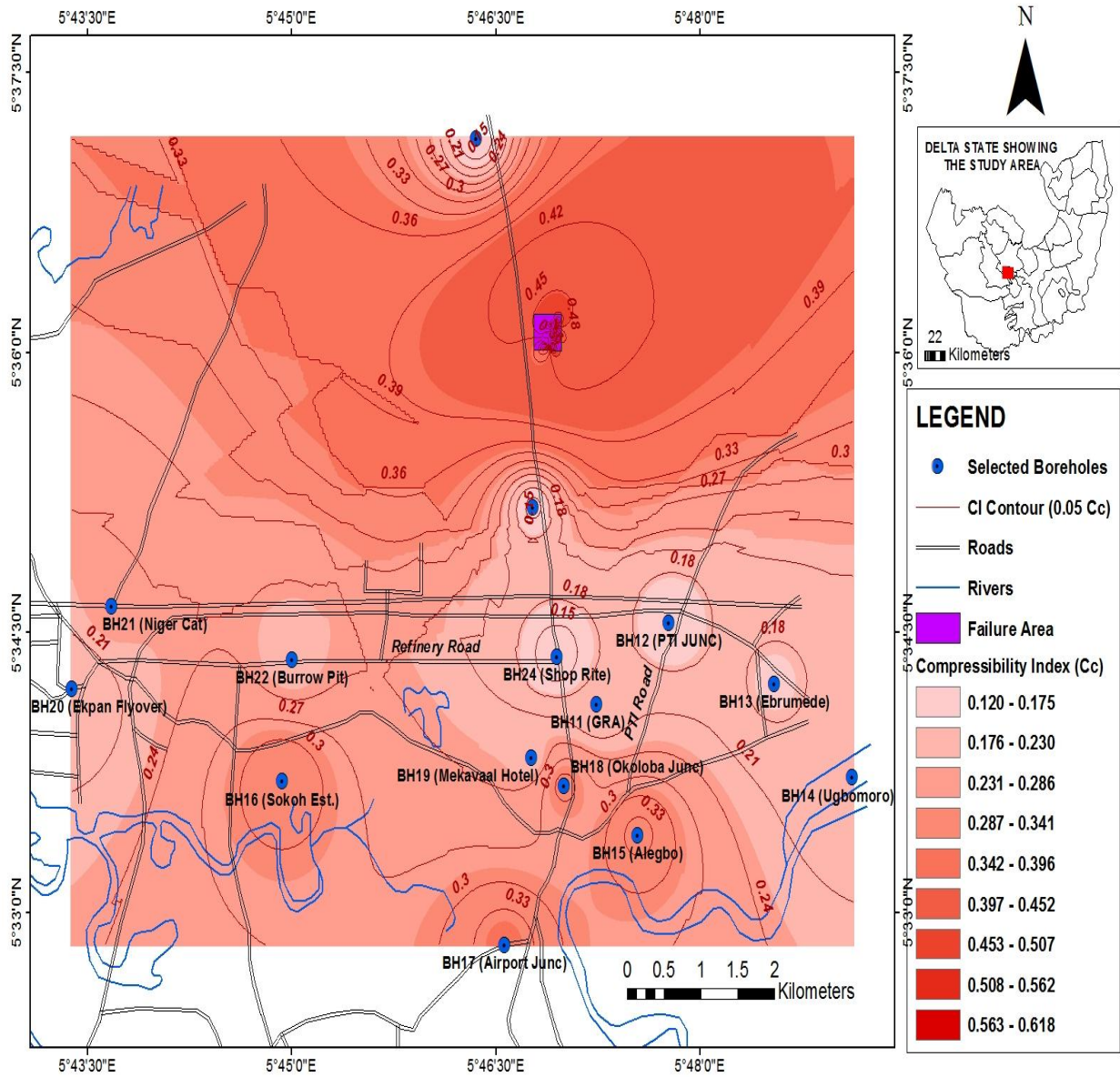


Figure 4.13: Compression Index Map of Warri.

4.9.5 Overview of the Foundation Characteristics of Subsurface Soils in Warri.

With reference to a general depth of 1m, the bearing capacity distribution of Warri ranges from 184.00-574.98Kpa. The area is predominantly characterised by medium to high bearing capacity zones (227.45-574.98) with pockets of low bearing capacity zones. The high bearing capacity zones lie in the west-central-eastern parts of Warri (such as Niger Cat, Sokoh Estate, Shoprite and Ebrumede areas) which is indicated by yellow/ blue coloration. The low bearing capacity zones lie within the southern part of Warri (precisely Airport Junction, PTI Junction) and mostly in the Northern part of Warri (specifically Mercy City/Failed area and Warri-Benin Express way) which is indicated by pink coloration.

5.9.6 Statistical Summary of Geotechnical and Mineralogical Properties of the Failed Area and Other Areas.

Overall assessment of all geotechnical and mineralogical properties of soils in the failed area using statistical tools such as standard deviation, co-efficient of variation and range show that about 68% all analysed soil/engineering properties had higher standard deviations, co-efficient of variation and ranges than those of the other areas (Table 4.7). This implies there are higher variation in engineering properties in the failed area relative to the other areas. The higher variation is due to lateral facies change evidenced by heterogeneous borehole logs and wide apparent resistivity distributions from vertical and horizontal geo-electric sounding.

Table 4.7: Statistical Summary of Geotechnical and Mineralogical Characteristics of Sub-Soils in the Failed Area and other Areas.

Soil Properties	Failed area				CV (%)	Other Areas			
	Range	Mean	Standard deviation	CV (%)		Range	Mean	Standard deviation	CV (%)
Sand (%)	3.5- 65.5	41.341	24.83	60.6	60.4-87.2	79.91	25.57	32.0	
Fine (%)	34.5- 96.6	58.66	21.02	35.8	12.8-39.9	26.03	6.90	26.5	
Silt (%)	22.5-56.6	41.20	13.93	33.8	9.8-26.9	17.93	5.79	32.2	
Clay (%)	12- 40	26.21	15.13	57.7	3-13	8.17	4.06	49.6	
Liquid limit (%)	20- 69	44.20	15.07	34.1	14.5-35.0	25.48	6.31	24.8	
Plastic limit (%)	16- 47	29.10	10.89	37.4	11.8-20.6	17.12	5.09	29.73	
Plastic Index (%)	4- 33	15.10	5.16	34.2	4.1-13.6	9.14	3.24	35.4	
Activity Index	0.43-1.34	0.70	0.24	34.2	0.47-1.36	1.00	0.41	41.0	
Optimum Moisture content (%)	14.42-17.62	17.38	8.56	49.3	9.1-12.64	10.68	4.57	42.80	
Maximum Dry Density (g/cm ³)	1.395-1.925	4.264	1.5447	0.36	1.826-1.944	6.8923	1.9013	27.5	
California Bearing Ratio (%)	3-20.5	6.25	5.106	0.82	10.1-17.9	15.02	4.27	28.4	
Bulk Density (N/m ³)	19-20.5	19.75	0.56	2.8	18-18.9	18.4	0.39	2.2	
Swelling Index (cs)	0.02-0.03	0.16	0.16	100	0.02-0.03	0.21	0.13	61.9	
Compressibility Index (cc)	0.25-0.65	0.42	0.12	28.6	0.12-0.18	0.26	0.08	30.7	
Undrained shear Strength (Kpa)	21.7- 33.14	25.89	12.93	49.9	21.83-73	41.22	18.366	44.6	
Bearing Capacity (Kpa)	185- 272	214	27.85	13.0	184-575	334	139.36	41.7	
Specific gravity	2.56-2.58	2.56	0.015	0.5	2.54-2.59	2.55	0.03	1.2	
Microcrystalline Quartz (%)	32.90-94.2	78.81	22.9	29.0	90.31-97.43	94.37	2.76	2.9	
Kaolinite Content (%)	5.79-37.31	13.4	10.48	78.2	2.57- 9.67	5.64	2.74	48.5	
Smectite Content (%)	5.42-26.10	5.56	4.28	76.9	NIL	NIL	NIL		
Microcline (%)	1.52-4.15	1.10	0.6		NIL	NIL	NIL		
Muscovite (%)	2.15-4.87	1.01	0.49		NIL	NIL	NIL		

4.9.7 Geotechnical Impact Assessment of Soil Stabilization Using Two-Sample T-Test assuming equal variance

With a view to assessing the level of impact of soil stabilization on natural/ untreated soils in the study area, a t-test was conducted (Table 4.8)

Following a comparative evaluation of statistical probability values (P) and level of significance values (α), it was noticed that the P-value was always less than the α -value in all stabilization programmes. This statistically means that there is a significant difference between CBR of the untreated soils and those of sand, cement and composite stabilized soils respectively. It also means that such difference is not by chance but by some obvious reasons. The geotechnical implication is that the soil stabilization schemes had positively impacted significantly on the pavement quality of unstabilized soil in the study area. Very strong impact was noticed in the soils response to composite and stabilization in both areas since their P values in these schemes were less than 0.001 while a strong impact of sand stabilization on soils in the failed area was observed as the P-value was between 0.001 and 0.01. The variation in impact is due to change in MDD (Maximum Dry Density) of the untreated soils on account of change in soil grade and decrease in porosity under the influence of the various stabilization schemes.

Table 4.8: Geotechnical Impact Assessment of Sand, Cement and Composite Stabilization Using two-sample T-test assuming equal variance

CBR of unstabilized soils (%)	Sand stabilization		Cement Stabilization		Composite Stabilization	
	CBR (%)	t- Test Results	CBR (%)	t- Test Results	CBR (%)	t- Test Results
3.00	11.00	t-stat:-3.89	71.30	t-stat:-14.82	130.7	t-stat:-19.97
3.50	10.00	P: 1.07E-3	73.00	P: 1.78E-11	128.2	P: 9.87E-14
4.50	9.50	α :0.05	75.20	α :0.05	133.9	α :0.05
4.50	10.70	Df = 18	76.00	Df = 18	127.3	Df = 18
6.00	26.90	t _{critical} : 2.10	103.80	t _{critical} : 2.10	179.0	t _{critical} : 2.10
4.00	11.00		90.00		156.9	
6.00	27.50		117.80		183.0	
20.50	25.40		111.00		165.0	
5.50	26.50		99.80		141.5	
5.00	28.30		108.40		177.0	
OTHER AREAS						
16.20	28.80	t-stat:-6.95	171.70	t-stat:-26.73	227.00	t-stat:-22.52
11.90	19.10	P: 1.47E-7	193.30	P: 1.78E-21	207.40	P: 1.76E-19
10.10	18.70	α :0.05	128.50	α :0.05	221.70	α :0.05
15.90	18.70	Df = 28	170.00	Df = 28	214.60	Df = 28
15.00	24.10	t _{critical} : 2.05	168.70	t _{critical} : 2.05	229.90	t _{critical} : 2.05
15.50	26.70		163.40		198.80	
17.90	27.50		168.00		215.20	
17.80	25.70		189.20		215.10	
17.30	26.20		175.60		272.50	
16.20	26.70		130.00		107.00	
15.80	26.20		150.30		219.20	
17.30	28.60		143.30		210.10	
14.10	20.40		178.90		207.60	
10.60	17.00		133.60		204.70	
13.70	20.40		185.00		229.50	

CHAPTER FIVE

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

Integrated geophysical, geotechnical and applied mineralogical investigations of sub-soils of the failed/other areas in Warri have resulted in the following findings:

- 1) Sub-soils in Warri are predominantly homogenous except for the failed area which is laterally heterogeneous.
- 2) Warri consists mostly of a three-layer soil profile which from top to bottom consist of loose sandy humus top soil (0.25m thick), reddish brown silty sand (3-5m thick) and poorly graded fine-medium grained sands (3-8m thick).
- 3) The failed area consist of a two-three layer soil profile which from top to bottom consist of very soft- very stiff sandy silt/silty sand (3m thick), dark grey very stiff-hard clay silt (15-17m) and poorly graded fine-medium grained sands (2m thick).
- 4) The plasticity of superficial soils in Warri is ultimately controlled by micro-crystalline quartz rather than clay minerals.
- 5) Sub-soils in Warri are predominantly of A2-4 and A2-6 grades with rare occurrences of incompetent soils of A7-5, A-6 and A-4 characteristics which are peculiar to the failed area.
- 6) Plain stabilisation of sub-soils in Warri generally yields subgrade quality material.
- 7) Sand stabilization of sub-soils in Warri generally yields subgrade quality materials but relatively lower quality was noticed in the failed area.

- 8) Sub-soil in Warri responds positively to cement stabilisation to produce sub-base/base quality material except the failed area which yielded sub –base material only.
- 9) Composite stabilization of subsurface soils in Warri yields almost entirely base quality material except for the failed area which yielded sub-base material only.
- 10) Clay fraction mineralogy of superficial soils in Warri is dominated by micro-crystalline quartz with accessory presence of Kaolinite, muscovite and microcline which conforms to that of the failed area except for the presence of smectite in the failed area.
- 11) Bearing capacity and compression indices of shallow foundation sub-strata (at 1m) in Warri are of better quality than those in the failed area.
- 12) Imminent building collapse in the failed area was due to lateral soil variation, poor foundation quality which translated to differential settlement.

5.2 Conclusion

The study has shown that the sub-soils of Warri are predominantly homogenous with pockets of heterogenous soil conditions which are peculiar to swampy terrain (specifically the failed area). Engineering properties and foundation quality of sub-soils are mainly influenced by well drained conditions, sands, kaolinites and microcrystalline quartz. The unstable terrain (i.e failed area) where superficial and underlying soils are marked by high fines content and smectite presence are at high risk of future building collapse and road failures. The road pavement status of superficial soils in Warri does not exceed subgrade quality under the influence of plain/normal compaction. Hence, thorough geophysical/geotechnical survey and

viable soil improvement programmes are indispensable to safe, economical and sustainable buildings and roads in the area.

6.3 Recommendations

The recommendations based on this study are presented as follows;

1. With a view to enhancing technical and economic viability, stabilization response of Warri subsurface soils to lime, marble dust and fly ash should be investigated.
2. X-ray Electron Micro-spectroscopy (XEM) would be needed to investigate the amorphous components which are suspected to influence the plasticity of superficial soils in Warri.
3. For safety of foundation substratum and road pavement protection, surface drainage pattern of Warri should be investigated.

Contribution to Knowledge

- 1) In addition to classification characteristics established by other workers. This research has shown that Warri sub-soils are also of A-4 and A7-5 characteristics.
- 2) This research has produced a geotechnical account of sand, cement and composite stabilisation of sub-soils of Warri.
- 3) Contrary to the assertion of other workers, it has been noticed that Layer II of Warri soil profile is neither clayey sand nor sandy clay but rather it is reddish brown silty sand.

- 4) Casagrande plasticity chart is not completely compatible with the sub-soils of Warri.
- 5) Contrary to the findings of other workers in the Niger Delta, the study has shown that cement stabilization of deltaic laterite to produce base quality material at 7% cement content is economically viable in parts of Warri.
- 6) The research has produced a mineralogical account of the sub-soils of Warri.
- 7) The plasticity of superficial soils in Warri is ultimately controlled by microcrystalline quartz contrary to earlier thought that clay minerals are responsible.

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