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Evaluation of Pavement Instability Section Using Integrated Geophysical and Geotechnical Methods in a Sedimentary Terrain, Southern Nigeria

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Authors' contributions

This work was carried out in collaboration between all authors. Author ADA conceived and designed the experiment, analyzed and interpreted the data, wrote the paper. Authors SOI, CAA, OAO and EGB contributed to the experiment and the writing of the paper. All authors read and approved the final manuscript.

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ABSTRACT

Integrated geotechnical and geophysical investigations was carried out in order to harness the cause of the incessant subsidence of road pavement along section of Portharcourt - Eket road Southern Nigeria. The geotechnical investigation involves boring of boreholes and collection of samples for laboratory analysis. The geophysical investigation involves the Vertical Electrical Sounding (VES) technique using the Schlumberger configuration, and the horizontal profiling/vertical electrical sounding techniques using dipole-dipole configuration. The borehole log generally delineates three subsurface layer, which are the top brown yellowish soft clayey sand and dark brown loose medium fine sand, follow by a 13.5 - 15 m thick organic shale layer. These layer is considered in-competent due to its poor engineering properties and is suspected to be potential cause of the perpetual failure of the road section. The basal layer, which consist of the

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greyish dense coarse sand formation is the only competent layer on or within which the foundation of the road pavement can be placed, due to it good engineering properties. The geoelectric section generated from the VES interpreted results shows that the study area was underlain by four geoelectric layers namely, the lateritic sand/sand, the silty/sandy shale, organic shale, and the coastal sand. The organic shale that underlain VES 1 and 6 locations, is suggestive of zone of poor engineering material and is suspected to be the cause of the perpetual failure of the pavement. However, the last observed geoelectric layer is the coastal sand. The resistivity values of these coastal sand vary from 546 ohm-m to infinity. Meanwhile the depth to this layer varies from 7.4 to 69.4 m. This layer is the only competent layer on or within which the foundation of the road pavement can be placed. The result of the 2D imaging also delineate the soft diapiric shale at the distance of 60 - 110 m and 50 – 130 m at bridge 1 and 2 respectively. It is therefore concluded that the foundation of the road within the subsiding locations should be anchor on a pile.

Keywords: Vertical electrical sounding; standard penetration test; triaxial test; chemical analysis.

1. INTRODUCTION

Flexible pavement is the most commonly used road pavement in Nigeria, and has been very useful for transportation of people, goods and services across the country, especially in developing countries where other means of transportation such as rail, underground tube, air, and water transportation are still under-develop [1]. Road transportation is an essential component in the physical development of any society as it controls the direction and extent of development. Furthermore, road plays an important role in achieving national development and contribute to the overall performance and social functioning of the community [2]. However, failed road segments, many of which are product of poor construction materials or being founded on an incompetent sub-grade and sub-base materials had been found to do more damage than good to the road. They have been responsible for many accidents, wearing down of vehicles and waste of valuable time during traffic jams. Adiat et al. [2] reported that there is a very strong positive relationship between a country's economic development and the quality of its road network, and that a country's road network should be constructed in an efficient way in order to maximize economic and social benefits.

Some factors have been reported responsible for road failures. They comprise the geological, geomorphological, geotechnical, road usage capacity, construction practices, and maintenance ([3,4,2]). Also, road failures are not primarily due to usage or design construction problems alone but can likewise arise from inadequate knowledge of the characteristics and behavior of residual soils on which the road are built and non-recognition of the influence of geology and geomorphology during the design and construction phases [3,5,4].

Consequently, experts in the field of geology and geophysics have often emphasized lack of adequate information on the nature of subsurface conditions prior to construction as a major contributor to this phenomenon. Some researchers [6,7,8,9] reported that every engineering structure is seated on geological earth materials. Studies have recognized that the non-recognition of the underlying geology in the design of these roads as a major factor causing persistent road failure in Nigeria [6,7].

Geological factors that are considered inimical to road pavements include the nature of subgrade soils and the near surface geologic sequence, existence of geological structures such as fractures and faults, existence of buried ancient stream channels, and existence of shear zones [2]. The geomorphological factors are related to topography and surface/subsurface drainage system. The geotechnical factor consists of the atterberg test, gradation test, California bearing ratio (CBR), triaxial test, consolidation test, permeability test among others. Also, the road usage capacity should also be investigated properly prior to any road design and construction work. The presence of expansive clays such as montmorillonite, chlorite, halloysite, among others, presence of linear features, such as joints, fractures and rock boundaries [6], have been suggested as the reason for the incessant failure of roads in Nigeria [10] and [5].

Geophysics has been proven to be quite relevant in highway site investigations [11]. However, in an attempt to unravel causes of continuous failure of roads across the country, various researchers have identified chiefly the underlying geologic conditions among other factors to be responsible for this mishap [6,12,8,2].

An Incessant embankment subsidence have been taking place between kilometer 58 and 61, Port Harcourt and Eket road. The displacement is at peak within the distance of 70 - 80 m and 80 – 90 m from the abutment of bridge 1 across Imo River and bridge 2 across it tributary respectively. The continuous settlement of this section of the road even under self-load, has hindered the completion of dualization of the road pavement. In view of this, the study integrated geophysical and geotechnical investigations on these portion of the road linking Port-Harcourt and Eket, Southern Nigeria., with the aim of determining the cause of the perpetual subsidence of this section of the highway. This study is carried out with the aim to determine the geotechnical properties and nature of the soil underlying the study area and to delineate the subsurface geological sequence and determine the geoelectric parameters. Also to evaluate from the above, the possible cause of the instability of the pavement and proffer a possible solution to the problem.

2. GEOMORPHOLOGY, HYDROGEOLOGY AND GEOLOGY OF THE STUDY AREA

The project site is situated in the southern part of Nigeria. It lies between Longitude 7°31'30.01" to 7°32'35.5" and Latitude 4°40'40.82" to 4°40'84.3". The study area is at the bridges across Imo river (Bridge 1), and its tributary (Bridge 2) both of which are within Kilometer 58 and 61 respectively along Portharcourt – Eket road (Fig. 1).

Geologically, the study area falls within the Niger Delta basin (Fig. 2). The basin comprises of Akata Formation (Shale intercalated with sands and silt), the Agbada Formation (Sands and Sandstones, intercalated with shale) in the middle and the Benin Formation (continental flood plain sand and alluvium deposit) at the top. Benin formations flanked the study area.

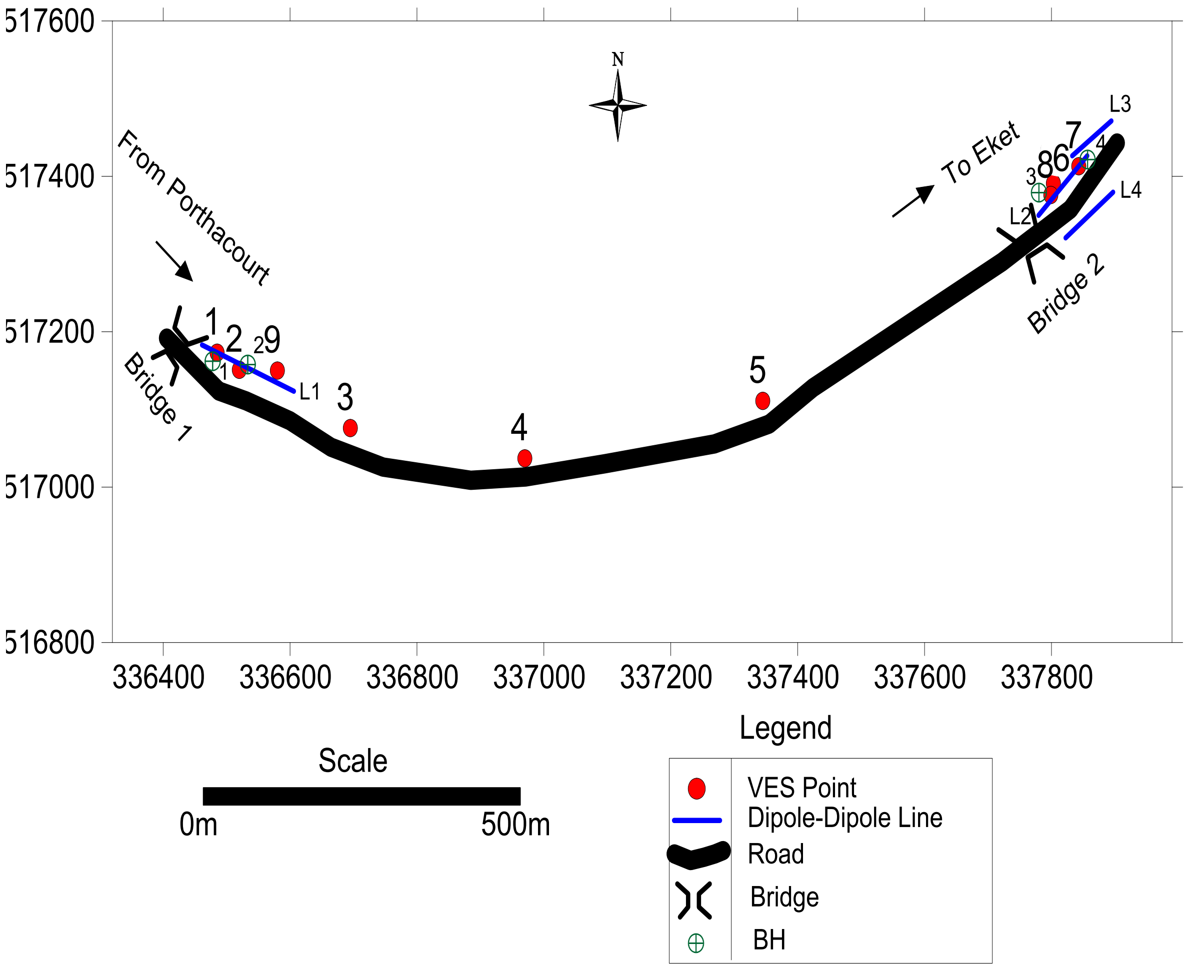


Fig. 1. Data acquisition map of the study area showing the vertical electrical sounding stations, 2-D resistivity imaging lines and geotechnical borehole sampling stations

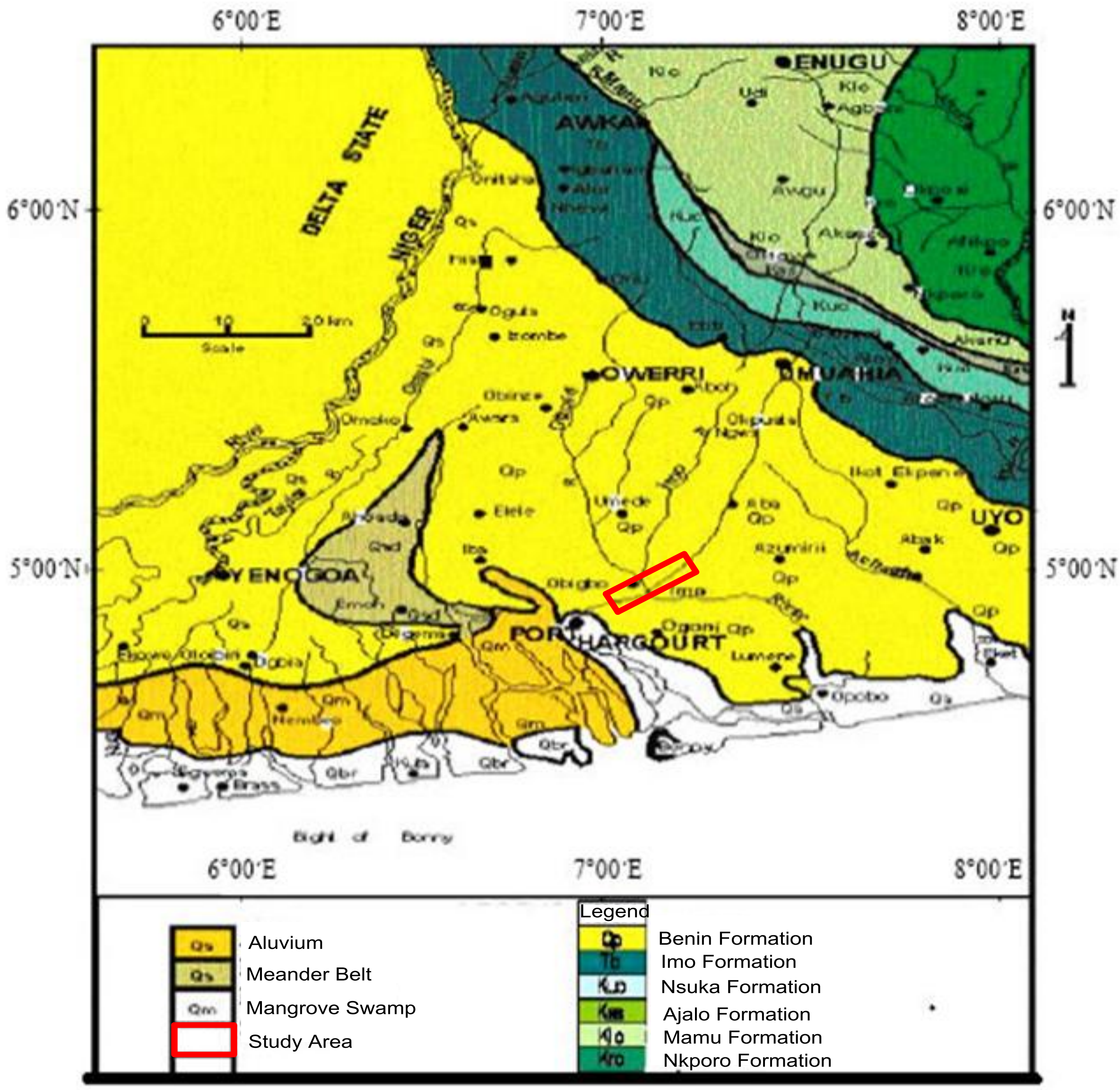


Fig. 2. Geological map of Niger delta showing the study area (Modified after [13])

3. METHODOLOGY

3.1 Geotechnical Investigation

The geotechnical investigations involved boring and describing soils generally in accordance with the British Standard Code of Practice for site investigations, BS 5930, 1981, and with methods of testing soils for Civil Engineering Purposes, BS 1377, 1990.

3.2 Borehole Boring

Four boreholes were drilled within the study area using the percussion drilling rig. Undisturbed samples at various locations were taken at appropriate intervals using a specially designed 60.5 mm internal diameter U – Type sampler. The sampler was fitted with a cutter at the open end and a waste barrel at the other end. A round steel ball in the driving head of the sampler permits the escape of air and water as the sample enters the tube. The diameter of the sample tube is 25 mm and lined with 60.5 mm plastic tube. The samples were trimmed to the desired length usually 15 cm, covered in a plastic tube. An identification label was attached. The numbers of blows required to drive the sample 15 cm into the ground was recorded. Sometimes, the regular U4 sampler was used to recover the undisturbed samples.

Boring in soil by the Shell and Auger method was based on the use of a variety of tools which, with the exception of the auger, are alternately raised and dropped to break up and recover soil. A shell, which consists of a heavy, long tube with flap valve on the bottom, was used in cohesive soils such as clayey gravels, clay and shale. Chiseling was adopted in breaking up very hard soils, boulders and other obstructions, and the fragments were removed with the shell. The tools were worked on a power winch. Chiseling was carried out using either a heavy chisel-shaped instrument or the clay cutter with heavy weight attached. Where the ground conditions were too soft and collapsing, the borehole was lined with steel casing, which were driven down the borehole by turning or hammering. The borehole diameter was 150 mm. During the boring operation, disturbed and undisturbed samples were taken at convenient intervals or at change of soil strata. The samples were sealed with wax at both ends and end caps were screwed on. The samples were transported to the laboratory for examination and testing.

3.3 Standard Penetration Test (SPT)

The standard penetration test (SPT) was developed by circa 1927 and is perhaps the most popular field test. A split barrel thick-walled sampler (split spoon) of about 35 mm internal diameter was driven 450 mm into the soil by repeated blows from a trip hammer weighing 65 kg and falling through 760 mm. The standard Penetration Test resistance (Standard Penetration Number or SPT Blow count Value (N)) is the Number of blows required to drive the sample through a full distance of 300 mm after the initial penetration of 150 mm. The blows recorded for the first 150 mm were discarded because of fall-in and contamination in the hole. The “N” value gives an empirical measure of the soil consistency and is also used to estimate the bearing capacity and compressibility of cohesive and granular soils. The cutting is often replaced with a solid cone for use in gravel. The test can also be used to provide a guide to the relative strength of weathered rock.

3.4 Geophysical Investigation

The geophysical data were acquired by carrying out the Electrical Resistivity survey utilizing Vertical Electrical Sounding (VES) and the combine Horizontal Profiling/Vertical Electrical Sounding Techniques. The electrical resistivity survey in the form of the Vertical Electrical Sounding was acquired using Schlumberger array. A total of nine (9) stations were occupied across the study area. The electrode spacing was varied between 1 and 200 m. The Abem SAS 300i resistivity meter was used to acquire the field data. The resistivity data was presented as field curves (by plotting the apparent resistivity (ρa) against AB/2 or half the spread length on a bi-logarithmic paper). The data was interpreted qualitatively by visual inspection of the field curves and further interpreted quantitatively by partial curve matching [14] using master curves [12] and auxiliary point charts ([15]; [16]) to obtain initial estimates of resistivity and thickness of the various geoelectric layers at each VES location. These geoelectric parameters were used as starting model for a fast 1-D computer-assisted interpretation [17]. The program took the manually derived parameter as a starting geoelectric model, successively improved on it until the error was reduced to an acceptable level. The improved geoelectric parameters were used to generate geoelectric cross section.

Combined Horizontal Profiling and Vertical Electrical Sounding (HP/VES) or 2-D imaging techniques were carried out across four lines. Line 1 and line 2 was carried out at the problematic locations of bridge 1 and 2 respectively. Line 3 was at the stable section of the left flank of the road while line 4 was at the right flank of the road which is stable.

4. RESULTS AND DISCUSSION

4.1 Discussion of the Geotechnical Results

The borehole log (Figs. 3 - 6) generally indicate three types of soil profile at different depths. The top layer, which is about 4.5 m thick across the four boreholes, consist of brown yellowish soft clayey sand and dark brown loose medium fine sand. This top layer is underlain by a 15 m thick layer across BH 1 and 2. 13.5 m thick layer across BH 3 and 4. These layers were considered in-competent due to their poor engineering properties (characterized by SPT (N-value) ranging from 0/0/0 to 1/1/2) and is potentially inimical to the stability of the road structure. The basal layer, which is the only competent layer on or within which the foundation of the road pavement can be placed, due to it good engineering properties (characterized by SPT (N- value) ranging from 6/9/18 to 30/40/50) is characterize by a greyish dense coarse sand formation. The depth to this layer ranges from 18 to 19.5 m across the four boreholes.

4.2 Unconfined Compressive Strength (UCS)

From unconsolidated undrained (uu) triaxial test result (Table 1), the soil cohesion (c) within the depth of 0 to 4.5 m ranges from 17 to 19 kN/m^2 and the angle of internal friction (φ) range from 20 to 23°. While the cohesion within the depth of 4.5 to 19.5 m ranges from 9 to 11 kN/m^2 and the angle of internal friction ranges from 4 to 6°. According to Okechukwu and Celestine [18], Underwood [19], the tested results show that all the samples fall under the ‘unfavourable’ for road pavement. Except for the φ of the first 0 – 4.5 m that fall under the ‘favourable’ for road pavement. These however inform that all the tested samples failed in local shear condition.

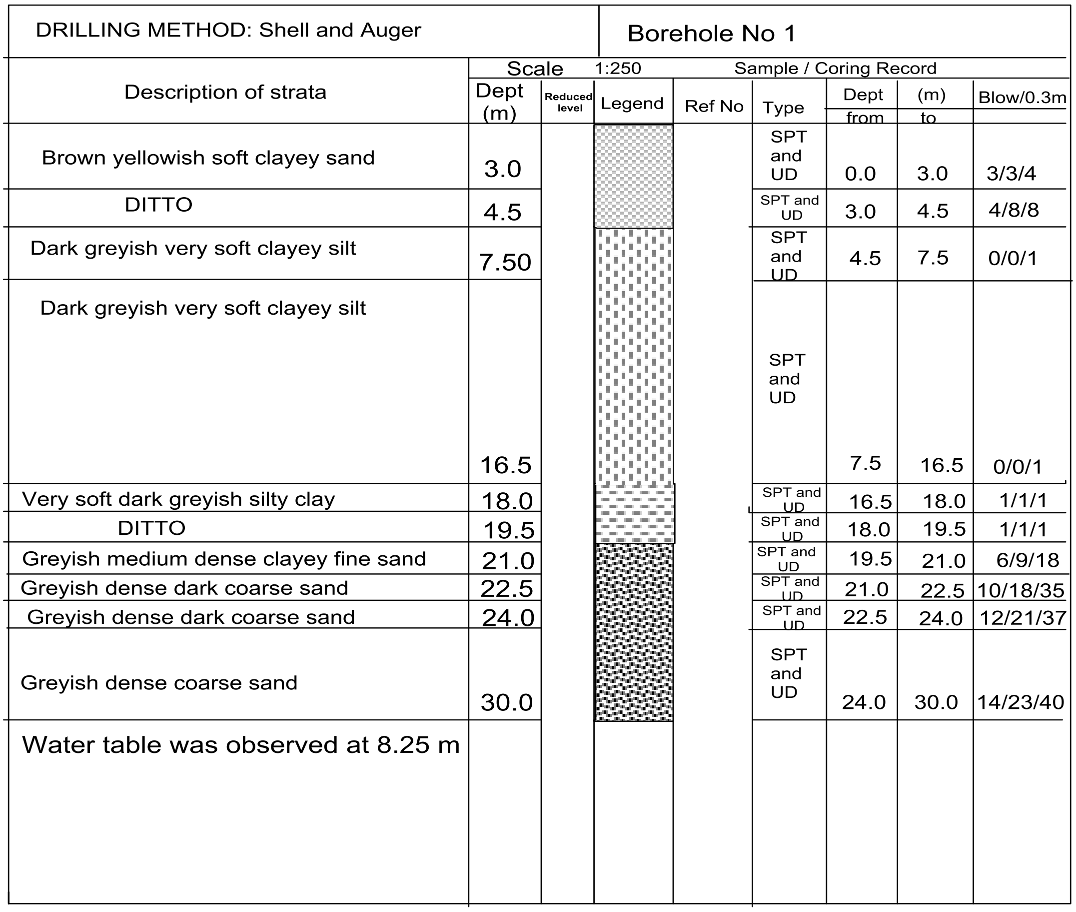


Fig. 3. Borehole Lithological Log beneath BH 1

Table 1. Triaxial test results of samples from the study area

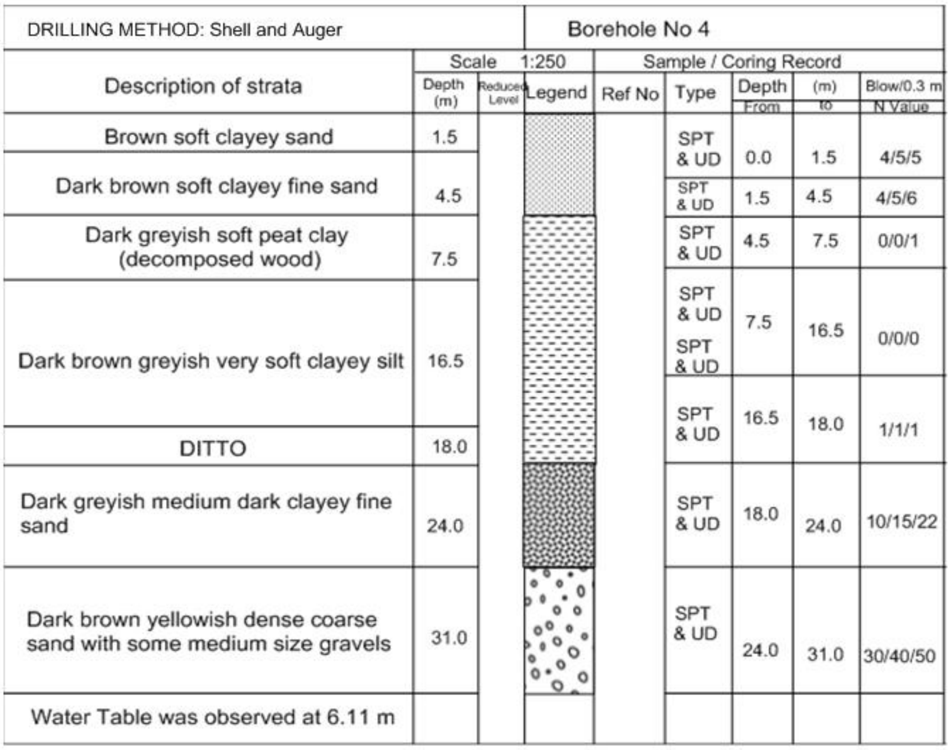
BH no	BH depth (m)	Angle of internal friction (Degree)	Soil cohesion (kN/m^2)
1	0.0 – 3.0	21°	18
	4.5 – 16.5	4°	10
2	0.0 – 3.0	21°	19
	4.5 – 19.5	6°	11
3	0.0 – 3.0	20°	17
	4.5 – 18.0	4°	9
4	1.5 – 4.5	23°	19
	4.5 – 16.5	6°	10
Specifications [19]		20 – 65°	700 – 10,500

DRILLING METHOD: Shell and Auger				Borehole No 2				
	Scale 1:250			Sample / Coring Record				
Description of strata	Dept (m)	Reduced level	Legend	Ref No	Type	Dept (m) from	to	Blow/0.3m N Value
Dark brown soft yellowish clayey sand	3.0				SPT and UD	0.0	3.0	4/6/8
Dark brown loose medium fine sand	4.5				SPT and UD	3.0	4.5	2/3/3
Dark greyish peat clay (Decomposed wood)	6.0				SPT and UD	4.5	6.0	0/0/1
Dark brown very soft clayey silt	12.0				SPT and UD	6.0	12.0	0/0/0
Dark greyish very soft clayey silt sand	13.5				SPT and UD	12.0	13.5	0/0/0
Dark greyish very soft clay	19.5				SPT and UD	13.5	19.5	1/1/2
Dark greyish little dense medium fine sand	24.0				SPT and UD	19.5	24.0	10/25/30
Very dense greyish coarse sand	30.0				SPT and UD	24.0	30.0	25/30/50
Water table was observed at 2.67 m								

Fig. 4. Borehole lithological log beneath BH 2

DRILLING METHOD: Shell and Auger				Borehole No 3				
	Scale 1:250			Sample / Coring Record				
Description of strata	Dept (m)	Reduced level	Legend	Ref No	Type	Dept (m) from	to	Blow/0.3m N Value
Dark brown yellowish very soft clayey sand	3.0				SPT and UD	0.0	3.0	2/3/3
DITTO	4.5				SPT and UD	3.0	4.5	5/7/8
Dark greyish very soft clayey silt	7.5				SPT and UD	4.5	7.5	0/0/1
Dark greyish soft peat clay (Decomposed wood)	15.0				SPT and UD	7.5	15.0	0/0/0
Very soft dark greyish clay	18.0				SPT and UD	15.0	18.0	0/1/1
Dark greyish medium/fine sand	22.5				SPT and UD	18.0	22.5	5/12/16
Dark brown medium dense coarsed sand	30.0				SPT and UD	22.5	30.0	10/19/25
Water table was observed at 6.10 m								

Fig. 5. Borehole lithological log beneath BH 3



DRILLING METHOD: Shell and Auger				Borehole No 4				
	Scale 1:250			Sample / Coring Record				
Description of strata	Depth (m)	Reduced Level	Legend	Ref No	Type	Depth From	(m) to	Blow/0.3 m N Value
Brown soft clayey sand	1.5				SPT & UD	0.0	1.5	4/5/5
Dark brown soft clayey fine sand	4.5				SPT & UD	1.5	4.5	4/5/6
Dark greyish soft peat clay (decomposed wood)	7.5				SPT & UD	4.5	7.5	0/0/1
Dark brown greyish very soft clayey silt	16.5				SPT & UD SPT & UD	7.5	16.5	0/0/0
DITTO	18.0				SPT & UD	16.5	18.0	1/1/1
Dark greyish medium dark clayey fine sand	24.0				SPT & UD	18.0	24.0	10/15/22
Dark brown yellowish dense coarse sand with some medium size gravels	31.0				SPT & UD	24.0	31.0	30/40/50
Water Table was observed at 6.11 m								

Fig. 6. Borehole lithological log beneath BH 4

4.3 Discussion of the Geophysical Results

The Vertical Electrical Sounding (VES) interpreted results in the study area are shown in Table 2. The interpreted VES results were used to generate the geoelectric section for the area. Four curve types were obtained from the area and these were the H, KH, QH and QQH curves types (Fig. 7) with KH dominating.

4.4 Description of the Subsurface Sequence across the Study Area

In the study area. Generally, the constructed geoelectric sections revealed the presence of four geoelectric layers. These layers were: the lateritic sand/sand, the silty/sandy shale, organic shale, and the coastal sand. (Fig. 8). The lateritic sand/sand layer has resistivity values ranging between 961 and 3889 ohm-m and its thickness varies from 0.8 to 2.8 m. The silty/sandy shale beneath the topsoil is characterized by resistivity values that range between 190 and 679 ohm-m. And its thickness varies from 7.4 to 33.2 m. The organic shale that underlain VES 1 and 6 locations, which falls at the problematic zone, is characterize by resistivity value that range between 22 to 53 ohm-m. And its thickness varies from 50.3 to 69.4 m. This organic shale layer is a poor engineering material (characterized by low resistivity value < 100 ohm-m) and is potentially inimical to the stability of the road structure. However, the last observed geoelectric layer is the coastal sand. The resistivity values of these coarse sand varies from 546 ohm-m to infinity. Meanwhile the depth to this layer varies from 7.4 to 69.4 m. This layer is the only competent layer on or within which the foundation of the road pavement can be placed. These can be achieved by anchoring the foundation of the road pavement on pile foundation.

4.5 Discussion of the 2-D Imaging Carried Out in the Study Area

Fig. 9a shows the 2-D subsurface geoelectrical image beneath the unstable section of bridge 1 (line 1) traversing through the unstable section to the stable section. The resistivity structure identifies four subsurface layers. These include the top lateritic sand/sand layer (reddish brown/yellow colour), which thickness varies from about 0.8 - 1.8 m and resistivity values that are > 1000 ohm-m. The second layer is composed of silty/sandy shale (Green), whose thickness varies from 5 - >30 m and the layer resistivity value are >273 ohm-m. The third layer is very low to low resistivity (< 72 ohm-m) soft organic shale in blue colour majorly observe between station 6 and 11 which falls within the subsiding zone and also between station 13 and 15. The blue colour indicates pockets of very low resistivity organic soft shale which is the major cause of the subsidence due to it swelling and diapiric nature.

Table 2. VES interpretation results and curve types

VES no.	Depth (m) $h_1, h_2, h_3, \ldots, h_n$	Resistivity (ohm-m) $\rho_1, \rho_2, \rho_3, \ldots, \rho_n$	Curve Types
1	1.8/13.1/50.3	2912/1022/53/1114	QH
2	0.8/2.6/33.2	1262/9826/324/2155	KH
3	2.8/15.5	961/190/∞	H
4	0.5/1.6/17.6	428/1977/217/546	KH
5	1.9/7.4	2571/679/2689	H
6	1.2/6.0/24.7/69.4	3889/2035/36/22/857	QQH
7	1.6/5.6/10.1	2155/5843/542/92962	KH
8	0.9/2.3/10.8	590/1798/618/14248	KH
9	1.0/2.5/38.2	2568/3157/580/8958	KH

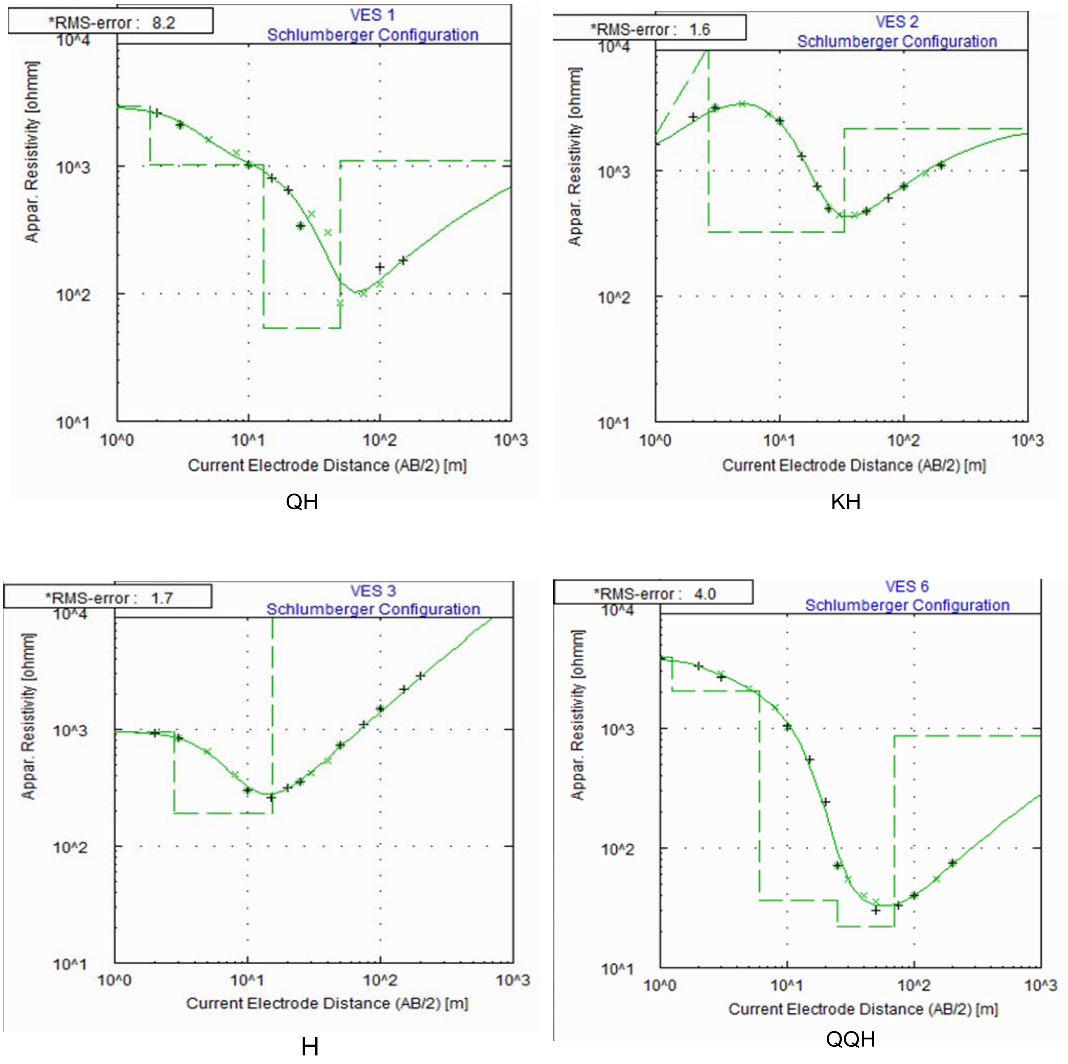


Fig. 7. Typical curve types obtained from the Study Area

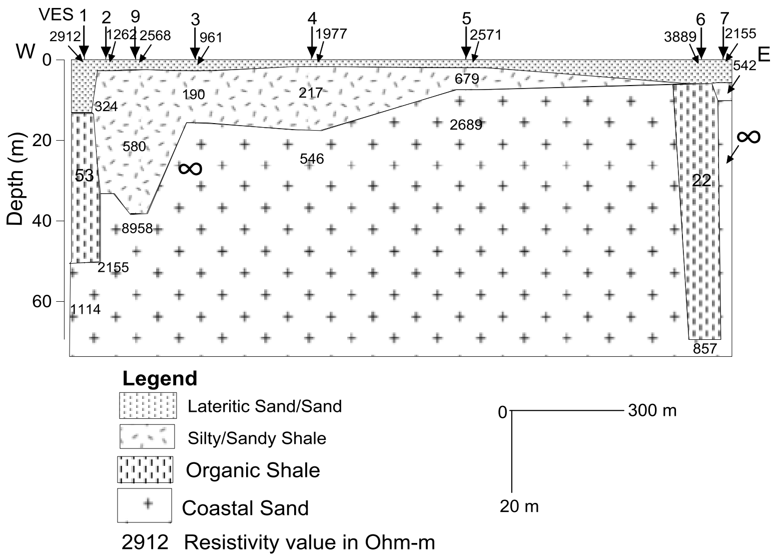


Fig. 8. Geoelectric section across the study area

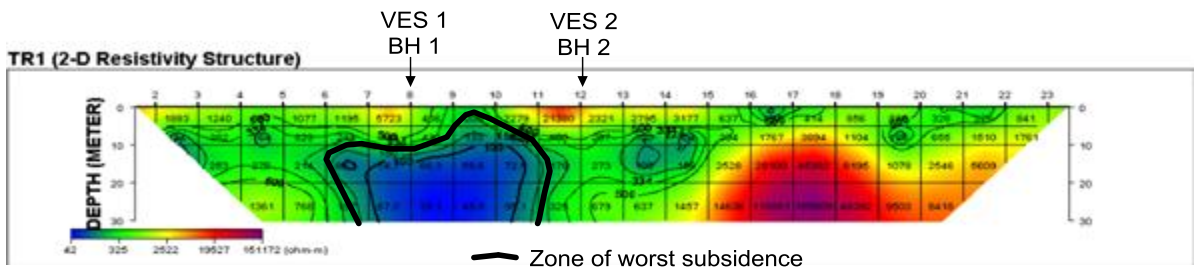


Fig. 9a. 2D resistivity structure along line 1

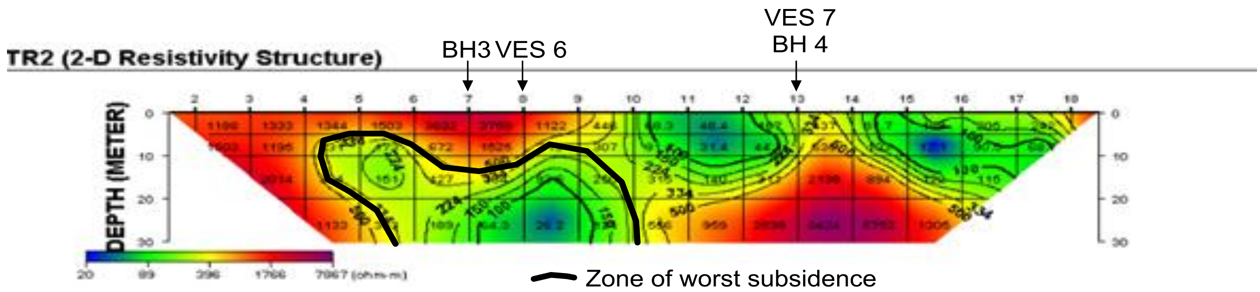


Fig. 9b. 2D Resistivity Structure along line 2

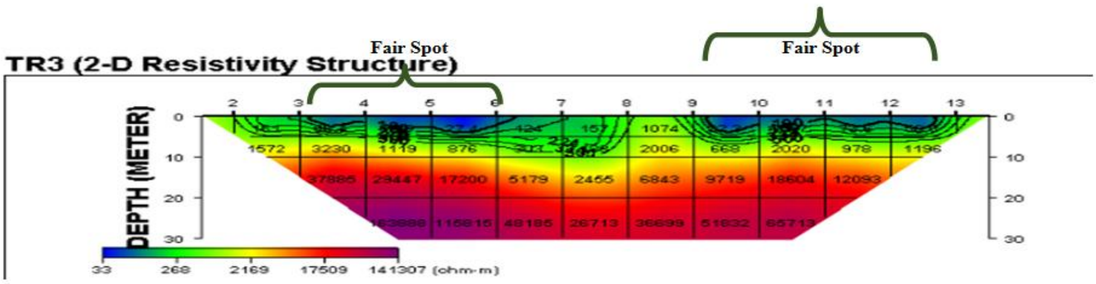


Fig. 9c. 2D resistivity structure along line 3

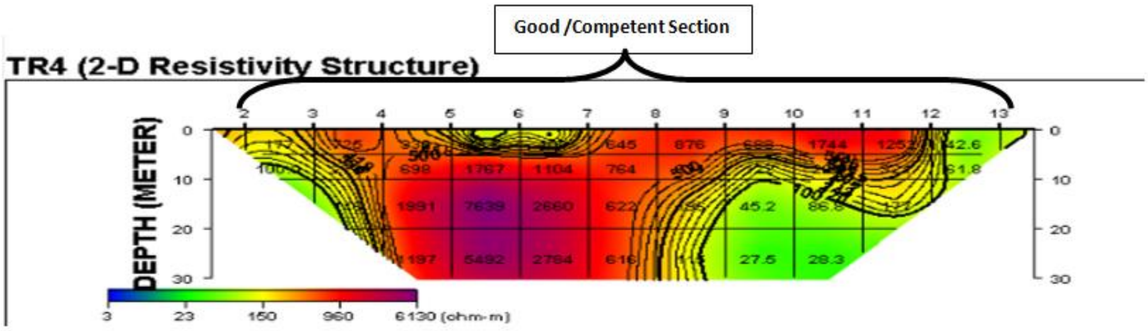


Fig. 9d. 2D resistivity structure along line 4

Fig. 9b shows the 2-D subsurface geoelectrical image beneath the unstable section near bridge 2 (line 2) traversing through the unstable section to the relatively stable section. The resistivity structure identifies four subsurface layers. These include the top lateritic sand/sand layer (reddish colour) with thickness varies from about 5 - 10 m and resistivity values that are > 1000 ohm-m. The second layer is composed of silty shale (yellowish colour), whose thickness varies from 4.5 - >30 m and the layer resistivity value are >100 ohm-m. The third layer is very low to low resistivity (< 50 ohm-m) organic shale in (green/blue) colour majorly observe between station 7 and 10 which falls within the subsiding zone and also between station 11 and 12, 15 and16. The blue colour indicates pockets of very low resistivity organic shale which is the major cause of the subsidence due to it swelling and diapiric nature.

Fig. 9c shows the 2-D subsurface geoelectrical image along the presumed stable untarred lane (line 3). The resistivity structure identifies four subsurface layers. The first layer shows a lens of shale (blue) outcropping between station 3 and 6, 9 and 12.5. Whose thickness varies from about 0.2 - 2 m and resistivity values that are < 27 ohm-m. The second layer is composed of silty shale (Green), whose thickness varies from 3 - 12 m and the layer resistivity values are >100 ohm-m. The third and fourth layer is composed of coarse sand formation (reddish brown/yellow colour). The little thickness/absence of organic shale formation results in the relative stability of the un-subsiding section of the pavement.

Fig. 9d shows the 2-D subsurface geoelectrical image beneath line 4 which was carried out on the stable asphalted lane opposite the failed portion. The resistivity structure identifies two subsurface layers. The first layer shows a competent sand formation (reddish brown/yellow colour) with resistivity value ranging from 150 - 6130 ohm-m And thickness vary from 5 - 30 m. The second layer is composed of silty/ sandy shale (Green), whose thickness is < 20 m and the layer resistivity value are < 100 ohm-m. The large thickness of the sand formation and the absent of organic shale is responsible for the stability of the stable asphalted lane.

6. CONCLUSION

Integrated geophysical and geotechnical methods have been undertaken to investigate the cause of road subsidence between kilometer 58 and 61 Portharcourt – Eket road, Southern Nigeria.

The geotechnical investigations involve boring of four boreholes in the study area. Generally, three soil types were delineated by the log, it includes; the Clayey sand (SC), organic silt of high compressibility (OH) which is suspected to be the cause of the high rate of subsidence within the road section, and poorly graded sand (SP) which is considered the only competent layer on which the foundation of the road pavement can be placed. The triaxial test was carried out on the samples and the results revealed that all the tested samples (from 0 to 19.5 m soil depth) failed in local shear condition.

Nine (9) VES were acquired along the investigated road segment using Schlumberger array with half current electrode separation varied between 1 and 200 m. The geoelectric parameters obtained from the quantitative interpretation of VES results were used to generate the geoelectric section for the area. The geoelectric section reveals that the study area was underlain by four geoelectric layers namely; lateritic sand/sand topsoil, silty/sandy shale, soft organic shale and coarse sand. The 2-D subsurface geoelectrical imaging also identifies four subsurface layers. These include the top lateritic sand/sand layer (reddish brown/yellow colour), silty/sandy shale (Green), soft organic shale (blue colour) and the coarse sand (Red colour). The soft organic shale is concentrated within 60 and 150 m from bridge 1 and between 70 and 160 m from bridge 2. These is suspected to be the cause of the high rate of subsidence within these sections of the road.

The soft organic diapiric shale is considered the cause of the perpetual subsidence of the road pavement in the study area. Based on the detailed study of the borehole logs, unconfined compression test result and geophysical survey, the proposed pavement cannot be supported on shallow foundations. Therefore, the foundation of the road within the subsiding locations should be anchor on a pile. The pile foundation is to be driven to the depth of 30 m or to refusal. Piling within the distance 70 and 100 m from the abutments of both bridges 1 and 2 should be preferably avoided as the depth to competent layer delineated by the geophysical method is presumably high (53 – 65 m).

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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