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Engineering Geophysical Investigation of Oka-Isua-Ibillo Highway Failure; Remedy and Road Sustainability in Nigeria

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Abstract: **Oka-Isua-Ibillo highway in southwestern Nigeria has been in bad condition despite several rehabilitation and reconstruction works. Thus, Very low frequency electromagnetic (VLF-EM) and electrical resistivity methods adopting fifty-one Schlumberger sounding locations using vertical electrical sounding (VES) technique and 2-D geoelectrical resistivity imaging utilizing dipole-dipole array were conducted along some unstable and stable sections of the road, to characterize the subsurface geological condition and causes of its persistent failure. VLF-EM 2-D models and resistivity sections of the subsurface profiles revealed existence of near-surface structures and four distinct lithologic units in suspected structurally weak zones. The varying trends and geometry of structural features are indication of structural instability of the underlying rocks. The road pavement is constructed on deep weathering bedrock of low resistive (< 100 Ωm) water saturated clayey subgrade which caused its failure. Uneven bedrock topography coupled with depressions, fractures and near surface aquiferous zones pose threat to the stability of the highway. Subgrade soil beneath the road should be replaced with high quality material and effective drainage provided for stability of the road. Engineering geophysics should be emphasized in pavement design and road construction, as geophysical techniques are invaluable tools for pre/post civil engineering solutions for road sustainability.**

Index Terms: Electrical resistivity, Engineering geophysics, Post-construction study, Road failure, Very low frequency

I. INTRODUCTION

Roads link towns, states and countries and enable people to access education, health and social services, thus, boosting socio-economic development. The quest for growth of economic activities prompted the need to improve roads. Failure of civil engineering works makes no news as this happens on a daily basis in different geologic settings throughout the nation. The understanding of the subsurface materials (rocks or soils) properties and parameters from surface geophysical measurements provide subsurface information to solve civil engineering problems. Most structural failures can be attributed to inadequate understanding of the physical characteristics and subsurface features relating to engineering suitability of the soil materials used in construction. Civil engineering structures are constructed on soil or rock which supports and determines the engineering behaviour and performance of the structures. Transportation system in African nation is intended to improve trade and interrelationship with neighbouring countries. Some roads in Nigeria fail within few days of being opened to traffic despite huge investment.

Geophysical methods have been effectively used in near-surface engineering and foundation assessment (Sharma, 1997; Ademila, 2015). Geophysical methods are used separately or combined in determining variety of physical properties of soil and rock for engineering site investigation. These investigative methods have the capability to offer substantial information relating to significant geo-engineering material properties required in evaluating the suitability of subsoil for road pavement construction (Ademila et al., 2020). Nigerian roads are generally constructed with no detailed information of the subsoil which acts as basic geo-material for road structures. Road failures are related to substandard structural materials and poor plan with no consideration of the subsoil (Ademila, 2018; Ademila, 2021).

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Integrated geophysical investigations provide the basic information of the subsurface sequence and structural disposition necessary for foundation design. Ademila et al., 2020 and Ademila, 2021 used geophysical approach to establish reasons for construction works failure in Nigeria. They reported that poor subbase materials and poor compaction during construction account for the failure of rigid pavements in Nigeria. Their studies demonstrated the applicability of different geophysical techniques in mapping subsurface geological, hydrogeological and engineering conditions of complex geological settings for in-depth knowledge of subsurface structural disposition for stable and sustainable civil engineering works. VLF-EM survey has been effectively utilized in geological mapping and its usefulness extends to detection of subsurface conductive features. Electromagnetic and electrical resistivity methods have been able to solve some challenging geological problems using the conceptual inversion model techniques (Loke and Barker, 1996; Ademila et al., 2020). Due to the deplorable state of roads in many African nations, traffic accidents increase daily with resultant loss of lives and properties. Ademila and Olayinka, 2020 emphasized the importance of engineering geological investiagation towards a sustainable highway construction. They recommended proper investigation of the geologic condition of the subsoil which forms foundation of road structures. They also concluded that subsoil investigation is essential to determine the suitability of subsurface materials for stable and sustainable civil engineering works.

Lack of geophysical research on the causes of highway failure in Nigeria has prompted this study to investigate the subsurface geologic conditions of Oka-Isua-Ibillo highway. The highway serves as a vital road that promotes transportation of goods, services, links states in southwestern Nigeria and neighbouring towns and cities to the Federal Capital Territory (Abuja) and northern parts of Nigeria. As a result of the deplorable state of Oka-Isua-Ibillo road, some sections were abandoned after consistent maintenance. Integrated geophysical investigation of some unstable and stable sections of the roadway was, therefore, undertaken in an attempt to unravel the intrinsic reasons responsible for the continuous pavement failure along this road. This serves as a post-construction study to proffer significant solutions to the road defects.

II. DESCRIPTION AND LITHOLOGY OF THE STUDY AREA

Oka-Isua-Ibillo highway is located in the Northern region of Ondo and Edo States, Nigeria. It is between latitudes 7° 10' N and 7° 30' N and longitudes 5° 35' E and 6° 05' E (Fig. 1). The area being investigated is in the tropical rain forest region. It is distinguished by rainy and dry seasons with the average yearly rainfall of above 1,550 mm. Average daily temperature is 27°C and humidity is above 75%. The road pavement under investigation spans through Ondo and Edo States, Nigeria. It is bordered by Igarra at the extreme north, Idogun at the east, Oke-Agbe Akoko to the west, and Owo at the south. It is drained by the following Rivers; Ogbese, Ojomirin, Ose, Asawa and Ukpessi. The drainage pattern of the area is dendritic with dominance of the rivers. The area is characterized with undulating topography with relative elevation between 355 and 450 m above sea level. The vegetation is categorized as evergreen forest.

A. Geology of the area

The study area falls within the lithologic unit of the Precambrian basement complex of Nigeria. Precambrian rock units of Nigeria are migmatite-gneiss-quartzite complex. This unit has undergone cycles of erosion and deposition having influenced by diverse orogenies associated with several phases of metamorphism and deformation (Ajibade and Fitches, 1988). The major lithologic units recognized in the area based on field observation are: migmatite and grey gneisses, granite gneiss, charnockitic rocks, pegmatitic rock and diorite (Fig. 1). Granite gneiss (metamorphosed granites) is of two types; the biotite rich gneiss and the banded gneiss. The biotite rich gneiss is fine to medium grained and show strong foliation usually dark in colour. There are signs of alteration and alignment in the banded gneiss which occurs as boulders, hills and surface outcrops having porphyroblastic texture with dark grey colour. Migmatite gneiss is the major rock unit underlying the study area (Fig. 1**)**. Different textural varieties of grey gneiss have been recognized but the most common type is a medium grained rock with regular and persistent banding of varying thickness. The area of investigation has undergone series of transformations which resulted in formation of geological features. These hydrogeological structures aid the accumulation of groundwater in the basement terrain. The water bearing units in the basement terrain are consequent of the weathered layer and fractured units beneath the weathered layer. Groundwater resource in form of hand-dug wells serves as source of water for residents in the area. Overall depth of hand-dug wells in the area ranges from 3.11 - 8.57 m. This shows that the water table is close to the surface which permits contact of the subsoil with water resulting in road failure (Ademila, 2019).

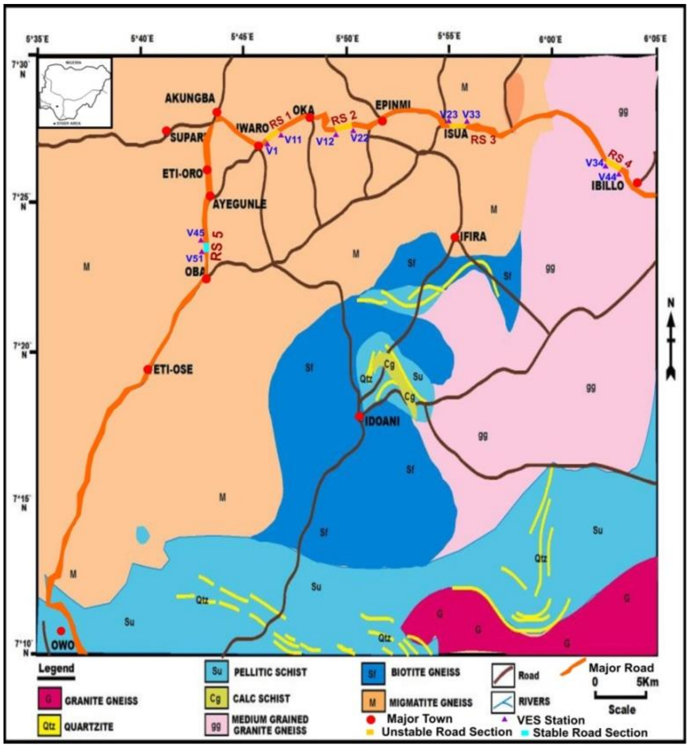

Fig. 1. Geological map of the area under study showing the Oka-Isua-Ibillo Highway and the distribution of the VES stations across each road section

III. MATERIALS AND METHODS

The study involves comprehensive geologic field mapping to determine lithological unit in the study area and spot failed and stable sections of the highway. The geological survey involves description of the geology and encountered rock units. Five geological traverses ranging from 300 – 500 m were established parallel to four major failed sections: Iwaro – Oka-Akoko (Road Section 1), Oka – Epinmi-Akoko (Road Section 2), Epinmi – Isua-Akoko (Road Section 3), Isua – Ibillo (Road Section 4) and one stable section; Eti-Ose – Oba-Akoko (Road Section 5) of the road (Fig. 1). Combined geophysical survey using very low-frequency electromagnetic method (VLF-EM), vertical electrical sounding (VES) and 2-dimensional electrical resistivity tomography using dipole-dipole electrode array were utilized along unstable and stable sections of the highway. The VLF-EM method is a geophysical tool used in determining earth electrically conductive features. The observed field data assess the amplitude of geomaterials in response to the primary electromagnetic field, which in-turn determines the extent of conductivity of geomaterials. VLF–EM survey was carried out along the highway pavement with 10 m distance using ABEM WADI instrument. In-phase (real or tilt-angle) and out-of-phase (imaginary or quadrature) components were recorded at each station. The in-phase values which are more indicative of near surface geologic features were processed. The filtering of raw real data was done with the use of an in-built filtering program in the ABEM WADI equipment and software known as KH Filt version 1.0 (Karous and Hjelt, 1983; Pirttijärvi, 2004). The filtered data accounts for secondary currents present in the ground and boost the signal for easy identification of tilt-angle crossover. Intersection points of inflection of the raw real and positive peak of filtered real are identified conductive zones. Results of the VLF-EM were inverted and presented as pseudosections with the aid of KH Filt software. VLF is used primarily as a reconnaissance tool to identify anomalous areas for further investigation, either with other geophysical methods or drilling. Shortcomings of the method include; VLF measurements are sensitive to "cultural interference" from pipelines, utilities, fences, and other linear, conductive objects. Data interpretation is generally qualitative in nature; quantitative modeling requires a high data density and a well constrained model. Topographic effects can bias the data, which are difficult to remove, and are model dependent. VLF transmitters are subject to outages for scheduled or unscheduled maintenance. Unfavorable ionospheric conditions may compromise the quality of the data (McNeill and Labson, 1992).

The VES measurements determine vertical distribution of electrical resistivity with depth while the electrical resistivity imaging (using dipole-dipole array) determines 2D apparent resistivity sections below each traverse. Depth of penetration using Schlumberger array increases as the current electrode spacing, AB/2 increases, while the spacing at the centre between the potential electrodes is fixed until the measured potential becomes exceptionally low. Half total length (AB/2) is in the range 1 to 150 m. Sounding stations were established along each traverse at 50 m. Measurement of fifty-one (51) VES stations were undertaken along unstable and the stable portions. Sounding data are plotted as apparent resistivity (ρ_a) versus electrode spacing on log-log graph. Field curves were interpreted qualitatively and quantitatively with the aid of partial curve matching (Koefoed, 1979) and master curves (Orellana and Mooney, 1966) with appropriate supplementary graphs (Zohdy, 1965; Keller and Frischnecht, 1966) to acquire first values of geoelectrical parameters at different stations. Curve matching approach was used to estimate the true resistivities of the geological materials. This is a technique adopted to match the apparent resistivity (ρ_a) (field measurements) and scaled electrode spacing to theoretical curves, calculated for various layer thicknesses and resistivities. The final interpretation was done using WinResist software (Vander-Velpen, 2004). The quantitative interpretation of the VES curves resulted in the construction of geoelectric section, which provides detailed information of the different lithological units encountered at depth. These differing subsurface geomaterials can be attributed to endogenetic (geological factors related to rock characteristics; rock strength/hardness, mineral and chemical composition, colour, rock texture and rock structure) and exogenetic (external environmental factors; climate, temperature, vegetation, relief/topography, time and human activities).

Electrical resistivity tomography (ERT) with the adoption of dipole-dipole array, and station interval of 10 m was used with expansion factor ‘n’ in the range 1 to 5. This entails systematic 2-D sequential measurement of separated traverses on the same line with increase in electrode spacing for increased depth of penetration. The distance between current electrode and potential electrodes are smaller than the separation between the pairs of electrodes, which resulted to 2-D image of the subsurface. Low EM coupling between current and potential circuits and sensitivity to horizontal resistivity changes of the dipole-dipole array (Loke, 2002) prompted its use for this study to detect subsurface structures. Pseudosections were generated from the measured apparent resistivities, processed and inverted with DIPROfWIN 4.01 (DIPRO for Windows 2001), from which three image responses were generated, out of which the inverted subsurface resistivity structures provide detailed information of the subsurface geological features.

IV. RESULTS AND DISCUSSION

The engineering considerations used to characterize the subsurface units include the detailed geologic field mapping of the study area which involved establishment of geomorphology, topography and drainage pattern that may affect the suitability of the subsoil for road construction. Also, the geophysical methods engaged in this study are non-invasive and non-destructive methods used to obtain information of the near-surface interior for solving engineering/geotechnical related problems ranging from building ground investigations to the inspection of dams, roads and dikes (Soupios et. al., 2006). This is used in determining soil stratification or layering, verifying constructed pavement thickness and identifying potential problem areas.

The VLF-EM technique proves to be effective in mapping near-surface, steeply-dipping conductors (faults/fractures). The 2-D VLF-EM inverted models give the distribution of subsurface conductive geologic features. The conductivity is shown as colour codes; green to red on the 2-D model sections (Figs. 2, 5 and 8) with the response (conductivity) increasing from left to right (i.e. from negative to positive). The 2-D model sections of the VLF-EM revealed points showing conductive zones with varying amplitude which is a measure of anomaly changes in the subsurface, showing differences in conductivity range of the subsurface materials. The major conductive bodies in green to yellow to red colours on the 2-D model sections indicate the presence of geologic features such as fractures, faults, geologic contacts or weathered basement. Major conductive features of different range of conductivity trending NW – SE and NE - SW were identified as conductive zones (green to red) and interpreted as fault/fracture zones and sheared zones within the bedrock. The VLF sections are characterized by alternating bands of low and relatively high conductive materials of varied depths trending in different directions. Areas of high conductivity, as reflected in the K-H pseudosections, are classified as zones of weakness (Ademila et al., 2020), which tend to influence the failure of the road pavement. Some of the very thick subsurface conductive features with their dip directions indicated as F–F’, F1–F1’, F2–F2’ … F8–F8’ (Figs. 2, 5 and 8) across the study area are suggestive of fractured bedrock. These are distinctive zones of weakness responsible for structural deformation of the basement, precipitating the failure of the highway. These conductive zones are relevant in the groundwater development of an area as they serve as potential sites for groundwater supply. They are the possible causes of foundation based failures of civil engineering structures as they expose the foundation to the ingress of water with resultant reduced strength/load bearing capacity of the subsoil (Ademila et al., 2020).

The 2-D electrical resistivity imaging using dipole-dipole electrode array in this study, allowed investigation of lateral and vertical variations in resistivity of the subsurface to deduce the electrical and geologic properties of the subsurface geomaterials. Suitability of subsoil for civil engineering construction works was assessed from the distributed layer resistivity, as higher layer resistivity indicates higher competence and stability of subsoil. The 2-D subsurface resistivity structures were interpreted in terms of subsurface lithology using the resistivity distribution. They are conductive subsurface substratum of clayey material/water absorbing clayey layer/weathered basement with resistivities ≤ 100 Ωm, partially weathered/conductive fractured bedrock with resistivities between 120 – 950 Ωm and fresh bedrock with resistivities > 1000 Ωm. Results from the electrical resistivity method revealed the pattern of resistivity variations within the study area with insight to the geoelectric characteristics of the geologic units giving the engineering competency/suitability of each layer. Evaluation of geological profiles over crystalline rocks using geophysics entails an in-depth knowledge of geoelectrical characteristics (Telford et al., 1990). Four (4) layer curve types (HA, AA and KH) are acquired from the geoelectric sections. These present four distinct lithological units of the area; topsoil, weathered layer, partially weathered/fractured bedrock and fresh bedrock. The HA-curve type is predominant with a percentage frequency of 56.86% followed by AA (39.22%) and KH (3.92%) curve type. There exists a link between electrical resistivity of earth materials and the subsurface competence to support civil engineering structures. The geological sections (Figs. 4, 7 and 10) give the representation of the geologic sequence mapped with depth, from which engineering suitability of subsoil are interpreted.

A. Iwaro - Oka-Akoko Road Section (RS) 1

Geological features with different range of high conductivity are detected on failed section 1 at distances 20 – 200 m, 270 – 310 m and 400 – 500 m (Fig. 2). These suspected linear features of different conductivity ranges in different azimuthal directions are indicative of weak zones of clayey overburden, fractures/faults and aquiferous zone on which the road pavement is constructed. They are indicative of incompetent geologic formation which could lead to instability of the road pavement. The 2-D resistivity structure displayed low resistivity (< 100 Ωm) across the section above 20 m depth (Fig. 3). The weathered zone is an indication of water absorbing clay. It identifies linear features of about 20 m which characterized subsurface structures; fault/fractures, lithological contacts or water bearing formation at distance 20 – 280 m. A low resistive portion at the depth between 5 – 15 m specifies clay composition on 2-D structure at distance 40 – 180 m and 210 – 310 m, correlates with weathered layer on the geoelectric section. Also, the linear features on the 2-D subsurface resistivity structure correlate the result from VLF-EM section. Four subsurface layers are delineated at this location (Fig. 4). The topsoil and weathered layer (subsoil) at the depth between 0 – 6 m are largely composed of clay (resistivity values < 150 Ωm) with sandy clay and clayey sand in place as topsoil beneath VES stations 1, 5 and 6 with resistivity values < 200 Ωm (Fig. 4). The clay composition of the weathered layer with < 100 Ωm indicates water saturated zone. This clay composition and water saturation of the subsoil are responsible for observed highway pavement failure. Also, the closeness of the weathered layer which constitutes the aquiferous zone to the surface in some locations of the road section poses threat to the stability of the highway. This suggests that the highway structure is constructed on incompetent/weak subgrade which accounts for the continuous failure along the road even shortly after maintenance and reconstruction works. The basement topography is irregular and forms depression at VES station 3 with depth to bedrock from 10.2 – 29.7 m (Fig. 4). Highway pavement failure at this locality is as a result of incompetent clayey subsoil, near-surface and subsurface linear features.

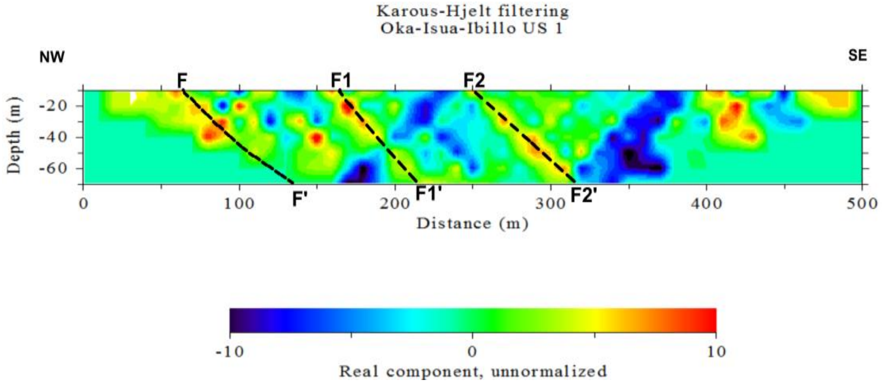

Fig. 2. VLF-EM 2-D inverted model along Road Section 1

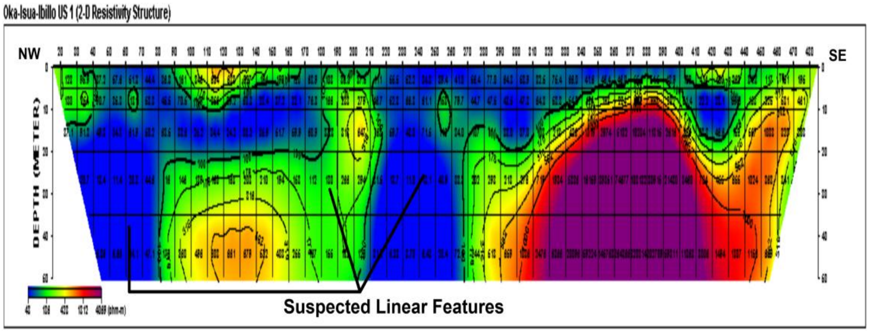

Fig. 3. 2-D resistivity image of the subsurface from dipole-dipole resistivity survey along Road Section 1

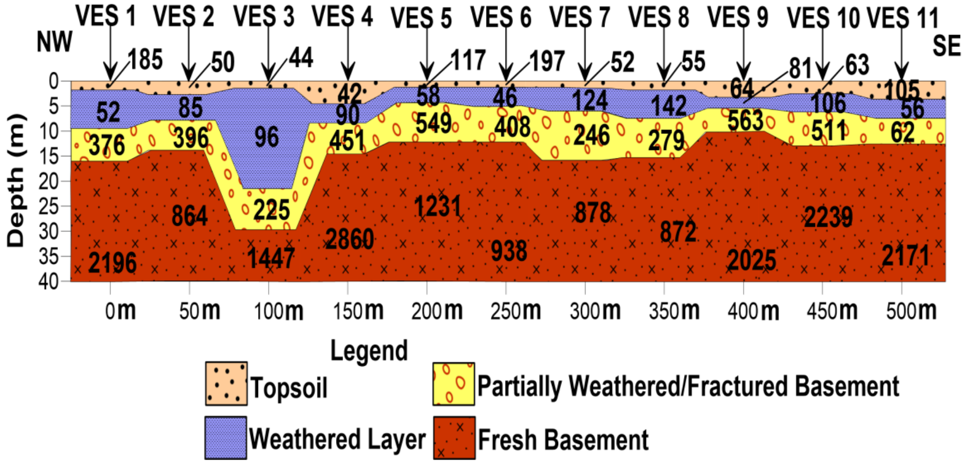

Fig. 4. Geological section obtained from interpretation of VES curves 1 to 11 along Road Section 1

B. Oka – Epinmi-Akoko Road Section 2

Conductive bodies traversing between stations 10 – 50 m and 190 – 400 m on VLF-EM section indicate near-surface structures such as fractures, lineaments, lithological contact, shear zones, or clay bodies (Fig. 5). The presence of conductive zones at different points is indicative of incompetent layer across the road section. The conductive zones are typical of linear features (fractures) which coincide with the suspected fractures on the 2-D resistivity structure (Fig. 6). These are characteristic zones of weakness responsible for structural instability in a basement terrain. The 2-D resistivity structure majorly shows low resistive zones (< 100 Ωm) at several locations signifying the presence of water absorbing clay (Fig. 6). These low resistive zones indicate high saturated region and poor engineering geomaterials exhibited in the area. Low resistive structures, characteristics of fault/fracture/aquiferous zones are observed on the 2-D resistivity structure at distance between 60 – 130 m, 150 – 260 m and 310 – 360 m at the depth above 30 m (Fig. 6). They fall within intensively fractured basement on the geoelectric section and fairly high conductivity region on the 2-D VLF-EM model. The low resistivity values generally (< 60 Ωm) indicate the presence of clay enriched water absorbing substratum. It also identifies near vertical/vertical low resistivity features having significant depth extent (> 40 m) typical of faults/fractures, aquiferous zones/buried stream channels at surface distance expression of 150 – 200 m. The presence of water saturated clayey substratum and vertical discontinuity may have been responsible to extremely failed section of the road pavement. Four different lithologic units were established. The resistivity values of subgrade vary between 31 – 207 Ωm corresponding to clayey composition, and thickness which varies between 0.6 – 6.9 m. The subsoil is majorly composed of clay (resistivity values from 51 - 109 Ωm) except beneath VES station 15 with resistivity value of 157 Ωm indicating clayey sand nature of the soil. The third layer is partially weathered/fractured basement with resistivity values that vary from 126 – 521 Ωm beneath the VES stations (Fig. 7). These resistivity values correspond to water-bearing unit/aquiferous zone beneath the subsurface that contribute to the failure of the road pavement observed in the area. The presence of this layer constitutes weak zones that facilitate failure of the highway pavement. The bedrock topography is undulating with pronounced depression observed at sounding stations 14, 18, 19 and 22. Depth to basement varies from 10.8 – 30.7 m (Fig. 7). Clayey nature of the subsoil (both topsoil and regolith) and bedrock depression are the reasons for the highway failure.

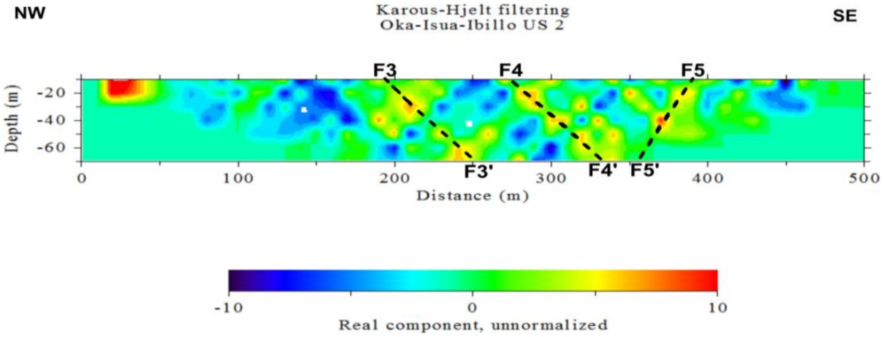

Fig. 5. VLF-EM 2-D inverted model along Road Section 2

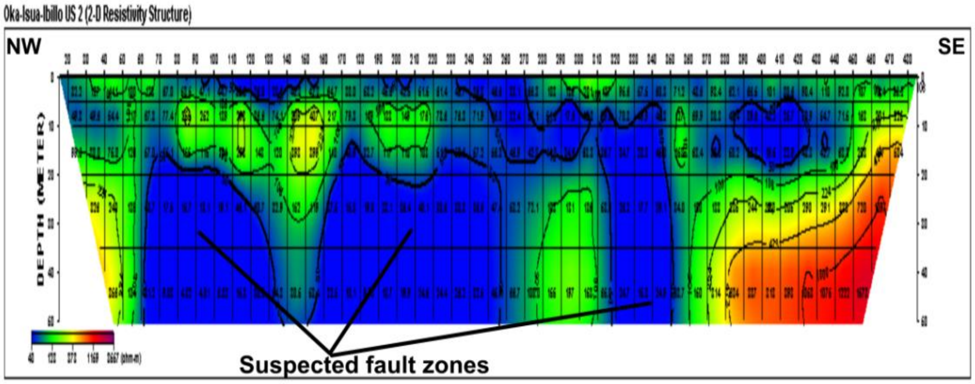

Fig. 6. 2-D resistivity image of the subsurface from dipole-dipole resistivity survey along Road Section 2

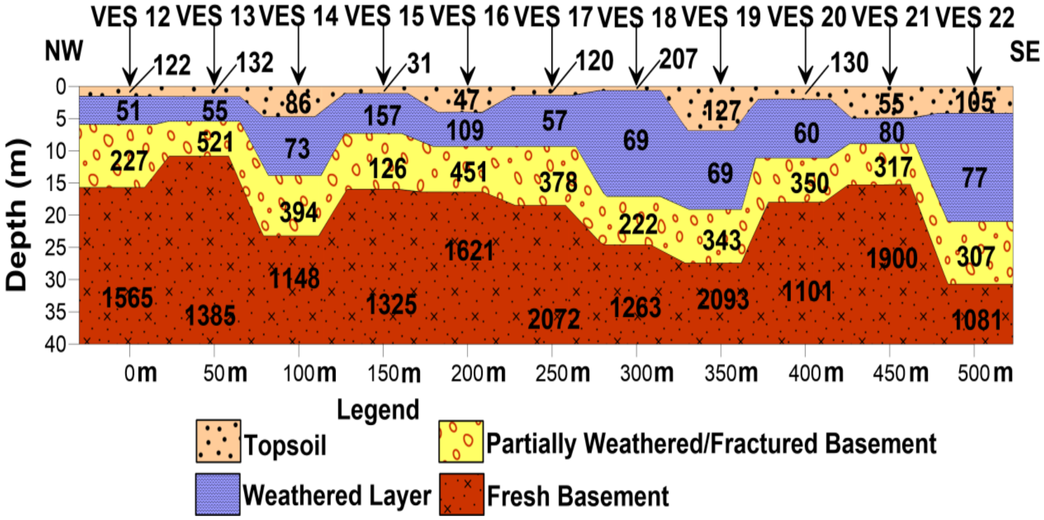

Fig. 7. Geological section obtained from interpretation of VES curves 12 to 22 along Road Section 2

C. Epinmi – Isua-Akoko Road Section 3

Conductive bodies traverse within the unstable section suspected to be geologic features (fault, fracture, aquiferous zone or clay) with different ranges of conductivity at distance between 70 – 130 m, 160 – 320 m and 370 – 500 m (Fig. 8), indicative of incompetent geologic unit across the road section. These conductive regions on 2-D VLF-EM model at depth greater than 20 m suggest aquiferous units, fractures and lithological contacts. The observed conductive features on the VLF-EM 2-D inverted model signify incompetent geologic unit with potential subsurface structural foundation problem (Fig. 8). The 2-D subsurface resistivity structure (Fig. 9) recognizes linear features within the unstable section at distances 20 – 150 m, 240 – 300 m and 410 – 480 m. This coincides with depression and fractured basement observed on the geoelectric section. Lithologic units delineated are topsoil, with resistivity values in the range 33 – 112 Ωm corresponding to clay, with thickness which varies between 0.7 – 5.6 m. Weathered layer beneath topsoil is characterized with resistivity values ranging between 17 - 132 Ωm with the thickness values ranging between 6.0 – 21.4 m. Typical clayey nature of the weathered unit with resistivity values below 135 Ωm (Fig. 10), makes it an incompetent construction soil that poses threat to integrity/strength of highway pavements. Resistivity values of this layer is an indication of very high level of saturation corresponding to the aquiferous zone in the area, suggesting the reason the section of the road is extremely bad. Water absorbing clay composition of the subsoil from the geoelectric section accounts for the exceptionally bad portion of the road with possibly high moisture content. The closeness of fractured basement to the surface beneath VES station 30 also precipitated the failure of the road pavement in the area as it corresponds to water-bearing unit beneath the subsurface. The bedrock topography is uneven, forms depression at VES points 24, 29, 30 and 33 with depth to bedrock varying from 13.1 – 29.3 m. This basement depression also threatens the strength of the highway structure. Instability of road pavement at this locality may have been as a result of incompetent clayey subsoil, near-surface and subsurface structures; fracture, aquiferous zone, shear zones or lithological contacts. These geologic features serve to enhance water storage, causing reduction of strength of subsoil with resultant road pavement failure.

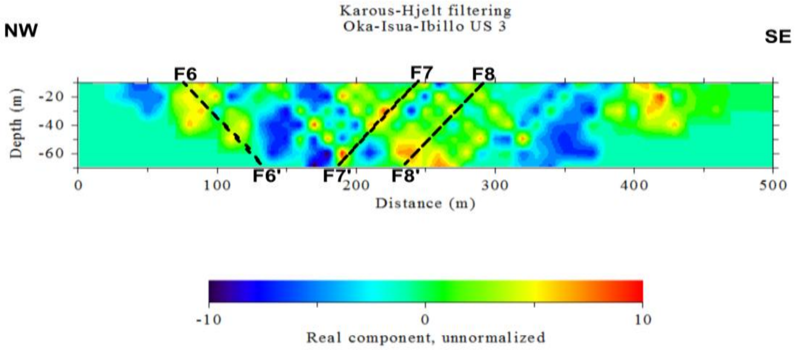

Fig. 8. VLF-EM 2-D inverted model along Road Section 3

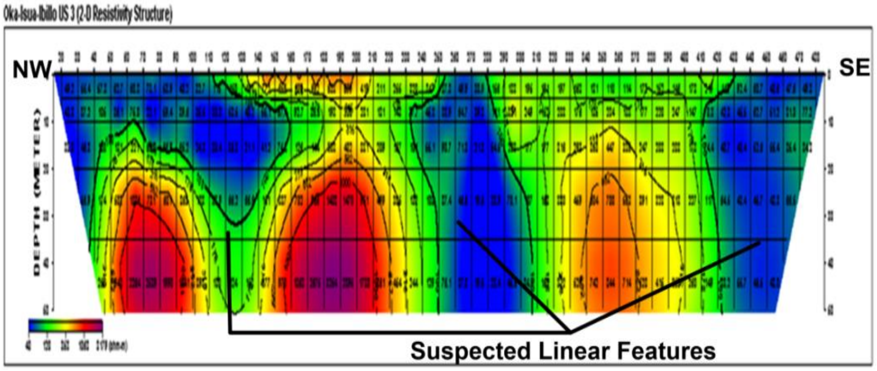

Fig. 9. 2-D resistivity image of the subsurface from dipole-dipole resistivity survey along Road Section 3

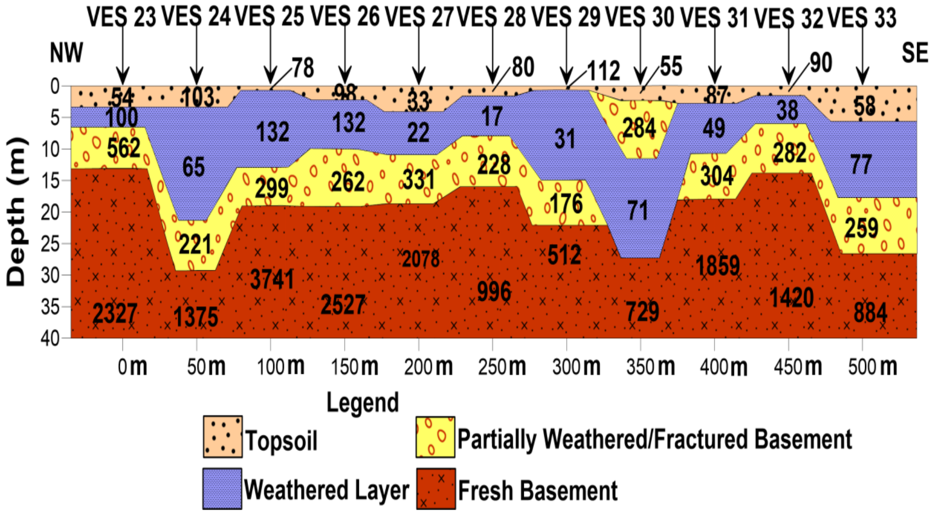

Fig. 10. Geological section obtained from interpretation of VES curves 23 to 33 along Road Section 3

D. Isua – Ibillo Road Section 4

The same process of interpretation was adopted for the remaining VLF-EM 2-D inverted models, 2-D resistivity images of the subsurface from dipole-dipole resistivity survey and the geological sections obtained from interpretation of VES curves 34 to 44 and 45 to 51 along Road Sections 4 and 5. Linear features of high conductivity are displayed on the 2-D VLF-EM section at distance 20 – 125 m and 200 – 430 m which are fault/fracture, aquiferous zone or lithological contacts (Fig. 13). The inverted section along this Road section 4 depicts an uneven subsurface topography reflecting different degree of conductivities. The observed conductive linear features at this location suggest conductive materials at depth, indicating the presence of fractures and basement depressions constituting water collection zones and saturated clay which are unsuitable to sustain road pavement. The Identified conductive bodies correspond to the conductive zones delineated as fractured zones, which are engineering incompetent zones that would pose significant threat to structural foundation of road construction works in the study area (Fig. 13). Thus, it has to be taken into consideration in road design and construction to enhance durable roads. The presence of these structures indicate unsuitable geologic unit on the highway section. The 2-D resistivity structure displayed low resistive geomaterials below 100 Ωm at distance 20 – 130m, 220 – 310 m and 360 – 410 m above 30 m of depth (Fig. 14). This is an indication of saturated clay layer. It however identifies linear features; lithological contacts and water bearing units. The suspected linear features on the 2-D resistivity structure (Fig. 14) also fall within fractured layer on the geoelectrical section. Four subsurface units are likewise delineated (Fig. 15). The low resistive topsoil layer of 21 - 86 Ωm, typically clay with thickness varying from 1.0 – 5.1 m attributed to weak zones responsible for instability of the road pavement. The weathered formation has resistivity values ranging from 24 – 123 Ωm with thickness 5.2 – 15.6 m. The clay composition and water saturation of the subgrade constitute the observed highway pavement failure. There is an indication of high degree of saturation corresponds to the aquiferous zone in the area. This suggests that the road pavement is constructed on incompetent water absorbing geologic layer which accounts for the continuous failure along the road even shortly after maintenance and reconstruction works. The partially weathered/fractured basement has resistivity values varying from 200 – 422 Ωm. The resistivity relates to aquiferous zone beneath subsurface as this also contributes to the highway failure in the location. Bedrock topography is uneven and its depth in the range 14.1 – 29.0 m (Fig. 15). The bedrock forms depression between VES stations 35 – 36 and 42 – 43. Highway pavement failure at this locality is as a result of incompetent clayey subsoil, basement depression, near-surface and subsurface linear features.

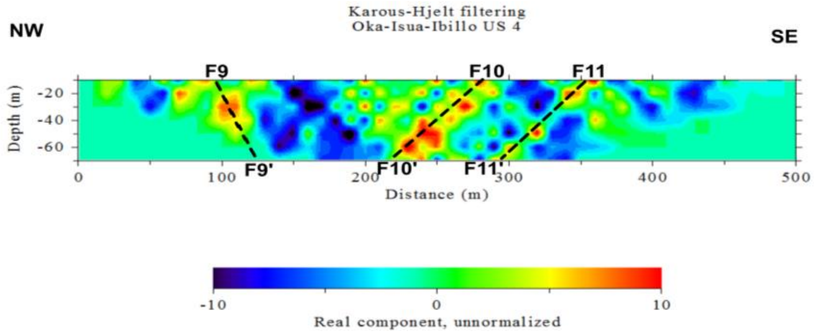

Fig. 13. VLF-EM 2-D inverted model along Road Section 4

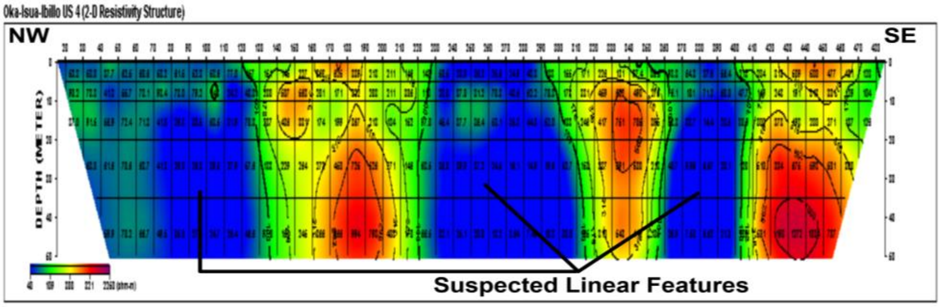

Fig. 14. 2-D resistivity image of the subsurface from dipole-dipole resistivity survey along Road Section 4

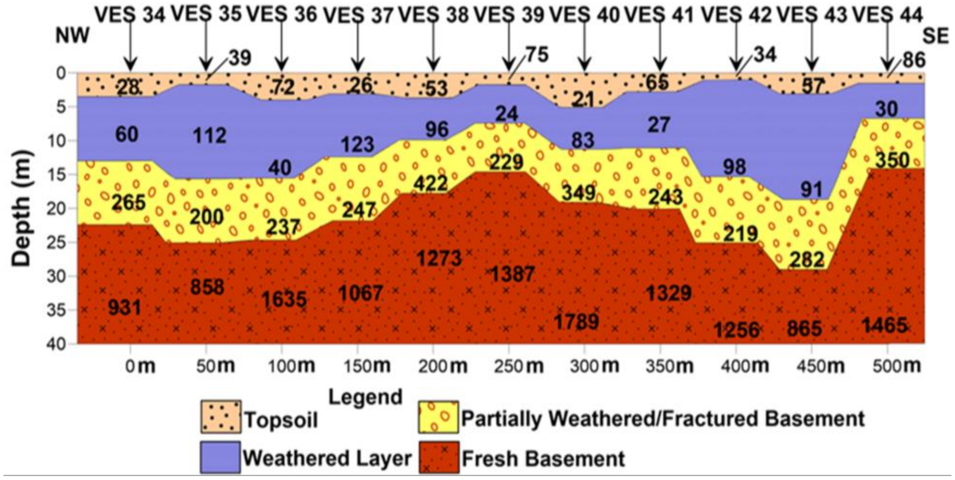

Fig. 15. Geological section obtained from interpretation of VES curves 34 to 44 along Road Section 4

E. Eti-Ose – Oba-Akoko Road Section 5

The 2-D inverted model shows that the stable section is characterized with features of low conductivity at distance between 40 – 100 m, 130 – 205 m and 260 – 300 m. The 2-D subsurface structure has no sign of subsurface geological structures that could precipitate failure of the road. This confirms the field observation as no sign of distress are noticed on this section of the road. The 2-D resistivity structure corroborates the high resistive topsoil and the underlying weathered layer composition of clay with resistivity values < 100 Ωm displayed by the geoelectric section. Four subsurface units are also observed. The high resistive topmost layer is composed of laterite/sand with resistivity and thickness values varying between 172 – 319 Ωm and 0.9 – 3.0 m respectively. The resistive topsoil layer is accountable for integrity of the highway pavement at this location. Presence of underlying clay materials of resistivity values in the range 60 – 75 Ωm with thickness variation of 4.0 – 7.1 m is an indication that the road section would fail in future. The low resistive subsoil formation is characteristics of the migmatite gneiss in the location of study. It shows that unstable sections of the highway are composed of clay subgrade unsuitable for highway structure at shallower depth than the stable section. The bedrock relief of geoelectric section also confirms the VLF-EM inverted model and the 2-D resistivity structure that is devoid of significant linear feature are indications of a near homogeneous subsurface sequence. The road is underlain by migmatite gneiss which weathers into clay composition materials. Subgrade of the unstable sections is clay, and this implies that geological rock type of the area has influence on stability of the road. Thus, persistent failure along the sections of the road is precipitated by clayey nature of the subsoil, faults, fractures, aquiferous zones and absence of drainage network system of the study area. The results of the engineering geophysical investigation showed that the failure of the road pavement in the area is precipitated by deep weathering, fracturing of the bedrock and closeness of water table to the surface. Also, subsurface geological structures which constitute structural deformation of the underlying geology, poor engineering design and lack of effective drainage system for runoff contribute to failure of the road pavement.

CONCLUSION

Engineering geophysical investigation of some unstable and stable sections of Oka-Isua-Ibillo highway was undertaken in an attempt to unravel the intrinsic reasons responsible for the continuous pavement failure along this road. This serves as a post-construction study to proffer significant solutions to road defects. Results of the investigation show the existence of geologic structures; faults, fractures and aquiferous units in the subsoil beneath the road pavement which are structurally weak zones that cause failure along the road. The topsoil exhibits relatively low resistivity values suggesting clayey topsoil with possibly high moisture content contributing to the road failure. The weathered layer of clayey nature beneath the topsoil has resistivity values < 100 Ωm which are poor subgrade and subbase construction materials. The low resistivity values are consequence of clay, water or both. The shallow water table in the area also contributes to the failure of the road, while the weathered layer (water bearing unit) close to the surface suggests the construction of the road structure within the water table. The road pavement is constructed on clayey subgrade suggestive of weak zones precipitating failure of the road. The clayey and saturated nature of the subgrade implies that geologically incompetent materials cause the failure of the road. The basement topography is uneven, characterized by depressions and water-bearing fractured basement beneath the failed sections which poses threat to the solidity of the highway structure.

2-D resistivity models of the subsurface showed major geologic features as confirmed by the VLF-EM 2-D inversion models. The distress observed in the failed sections would persist due to low resistive water absorbing clay of the subsoil beneath the road pavement. Thus, appropriate drainage is needed for free flow of run-off. This will prevent water accumulation leading to reduction of strength of the subsoil. The soils beneath the failed sections should be replaced with more suitable geological material during reconstruction for stability of the road structures. The subsurface geology of the area has been characterized based on this geophysical approach with in depth knowledge of the engineering condition of the subsurface soil for durable road. This study has provided detailed information on the subsurface profile to avert the risk of road failure shortly after construction. It forms baseline information and reference for further investigation in a basement complex terrain. Thus provide basic knowledge for civil engineers on subsurface characterization in road construction and maintenance.

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