ZIBELINE INTERNATIONAL™ PUBLISHING
ISSN: 2521-5035 (Print)
ISSN: 2521-5043 (Online)
CODEN: ESMACU

Earth Sciences Malaysia (ESMY)

DOI: http://doi.org/10.26480/esmy.01.2022.24.31

CrossMark

RESEARCH ARTICLE

VERY LOW FREQUENCY ELECTROMAGNETIC GEOPHYSICAL SURVEY ALONG FAILED SECTIONS OF SANGO-OTA-IDIROKO HIGHWAY AND SELECTED FEEDER ROADS IN OTA, SOUTHWEST NIGERIA

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ARTICLE DETAILS

Article History:

Received 07 December 2021
Accepted 09 January 2022
Available online 12 January 2022

ABSTRACT

Very low frequency electromagnetic (VLF-EM) survey was conducted along failed segments of some roads in Ota, southwest Nigeria to reveal the geologic dispositions of subsurface material underlying the road pavements. Geonics EM-16 VLF was employed for data acquisition across a total distance of about 2.6 km. Fourteen traverses were positioned along failed road segments with one control traverse arranged along stable road segments. Real and quadrature field data components were processed via Fraser and Karous-Hjelt filtering to suppress noise and enhance signal strength. Positive peaks of filtered real component on Fraser plots depict the presence of conductive subsurface materials. Good correlation exists between positive peaks on Fraser plots and conductive zones on 2-D current density at several lateral distances and depths across all the traverses. Delineated VLF anomalies represent weak zones that might pose serious threat to road stability. These conductive anomalies are presumably composed of clayey bodies (laterite/lateritic soil) in the subgrade soil used for road construction or unexcavated host materials in the subsurface. Changing volume of clayey materials under varying climatic conditions is a major cause of distress to engineering structures. Clayey materials by virtue of their pore characteristics (high porosity and low permeability) tends to undergo alternating series of expansion and contraction under different climatic conditions. These seasonal dispositions would eventually manifest as cracks and potholes on road pavements. Uneven distribution of different adjacent subsurface lithologies contributes to differential settlement, which is a possible catalyst of road failure.

KEYWORDS

Sango-Ota-Idiroko Highway, road failure, very low frequency, Fraser plots, clayey bodies

1. INTRODUCTION

Road infrastructure is the most important of all public assets because it open up more areas and communities for sustainable socio-economic activities, thereby contributing to the overall improvement in the living conditions and life-expectancy of human beings (Ayogu, 2007; Fedderke and Garlick, 2008; Ajakaiye and Ncube, 2010; Caldérón and Servén, 2010; Hong et al., 2011; Tatyana, 2015; Caldérón et al., 2018; Azolibe and Okonkwo, 2020). In rural communities and developing nations, roads are lifelines to survival. Despite the fact that Nigeria's main industrial hubs are concentrated within Lagos and Ogun States, inadequate road networks and recurring collapse of few available roads have plagued the two states for many decades. Ota town in Ado-Ota Local Government Area of Ogun State, is a strategic location for several reasons: it links Nigeria to other West Africa countries; it hosts a large fraction of industries in the country; and its proximity to Lagos State, Nigeria's major commercial state. The Sango-Ota-Idiroko highway is a very busy road that directly connect to the Idiroko international border with the Republic of Benin. This road is also an important link road to other nearby industrial and business hubs such as the Agbara Industrial Park. However, this highway with the several renovation projects executed to ease traffic flow and movements, has been in a very deplorable state for many years whic has resulted in many fatal crashes/accidents involving heavy duty vehicles, with the resultant colossal loss of lives and goods.

Many problems arising from engineering projects are often the consequence of the outright failure to incorporate subsurface geophysical investigation in the planning and execution of some infrastructural facilities, or collection of inadequate, incomplete, or inaccurate data (Cummins and Kenton, 2004). Failure to involve geophysical survey in geotechnical projects has often resulted in increased costs that are oddly and disproportionately high in comparison to the savings likely gained by such neglect. Frequent foundation issues occurring in dams, bridges, and other gigantic engineering structures are usually and directly connected to the local geology of the area where the structures are built. The deployment of geophysical characterization methods in geotechnical projects demands a critical role and a calculated integration with geotechnical investigations will go a long way in ensuring a long lifespan for infrastructural and development projects.

Geophysical methods and techniques equip geotechnical engineers with detailed subsurface data that can assist in design, planning and construction, and emplacement of structures on or within the appropriate medium of the subsurface sequence at a site (Keller, 1974; Massaarch,

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Cite The Article: Olatinsu Olawale Babatunde, Omodiagbe, Onuwabhagbe (2022). Very Low Frequency Electromagnetic Geophysical Survey Along Failed Sections of Sango-Ota-Idiroko Highway and Selected Feeder Roads in Ota, Southwest Nigeria. *Earth Sciences Malaysia, 6(1): 24-31.*

2000). In general, for wide and rapid coverage, geophysical survey has been proved to be the most, cost-effective and fast procedures for acquisition of subsurface geotechnical information. Various geophysical techniques/methods that are already developed (electrical resistivity, induced polarization (IP), ground penetrating radar (GPR), gravity, electromagnetic induction magnetics, and seismics) have achieved great success in geotechnical site investigation. These methods are able to reveal the distribution of subsurface materials along with their physical, mechanical, and chemical properties suitable for evaluating and assessing the stability of natural and anthropogenic subsurface conditions (Dobrin and Savit, 1988; Telford et al., 1990; Kearey and Brooks, 1991; Reynolds, 1998; Lowrie and Fichtner, 2019). This information plays important role which cannot be neglected in designing and construction of earthworks such as foundations, embankment, canal, channel etc.

Geophysical methods have some benefits when compared with conventional geotechnical investigations. These techniques can be conducted over large areas, can explore large soil volume, are non-invasive, and can delineate material properties, subsurface boundaries and contrasts in space and time (Olorunfemi and Meshida, 1987; Massarch, 2000; Anderson et al., 2008; Sudha et al., 2009). Other advantages include site accessibility and portability of geophysical equipment, workable data acquisition scheme in areas ordinarily unreachable by traditional geotechnical approach, such as spaces in heavy forest, steep slopes, or ecologically sensitive or restricted areas (Anderson et al., 2008; Rahimi et al., 2021). Geophysical techniques may be adopted to fill the gaps between boreholes whose number is often limited by costs or find subsurface features which might not be detected by standard drilling and cone penetrating test (CPT) programmes. Regardless of these numerous advantages, geotechnical geophysics is not a substitute for drilling, rather it can complement a well-planned, cost-effective sampling exercise for complete integrated site characterization (Rahimi et al., 2021).

Due to the busy nature of Sango-Ota-Idiroko highway, the deployment of active geophysical technique to probe the subsurface conditions along the route is to some extent not feasible. This is as a result of the requirement to artificially generate signals (current, vibration etc), which is impossible without having to use devices such as electrodes, geophones etc., which usually should be in direct contact with the ground. Therefore, a rapid and non-contact passive techniques such as the very low frequency electromagnetic (VLF-EM) is the appropriate survey method in such environment (Parasnis, 1986; McNeill and Labson, 1991). VLF-EM technique is the simplest scheme to image the shallow subsurface conducting structures (Oskooi and Pedersen, 2005). Readily accessible primary field signals from worldwide VLF transmitters make the VLF method very convenient and efficient for field data collection, processing and interpretation (Ogilvy and Lee, 1991; Beamish, 1994; Chouteau et al., 1996; Gharibi and Pedersen, 1999; Beamish, 2000; Becken and Pedersen, 2003; Pedersen and Becken, 2005; Sharma et al., 2014).

Several workers have employed the VLF-EM technique in the investigation of road failure in both sedimentary and basement complex terrains in Nigeria. Anomalous electrical response from joint electromagnetic (VLF-EM) and electrical resistivity (ER) surveys was employed to probe bad sections of the Ijebu-Ode-Eruwon road in Ogun State, southwest Nigeria (Osinowo et al., 2011). Data from the two techniques were correlated and interpreted in terms of structures, lithology and water saturation. Positive peaks identified on the plots of filtered real amplitudes agreed with the existence of major and minor linear fractures within the basement rocks. A group of researchers applied VLF-EM technique as part of an integrated geophysical and geotechnical investigation of Akure-Ipinsa road in southwest Nigeria (Adiat et al., 2017). VLF-EM profile generated from the data analysis revealed the occurrence of linear features that could pose potential risk to the stability of pavement structure above subgrade soil. A joint geophysical study involving very-low-frequency electromagnetic, ground magnetic and electrical resistivity imaging was conducted at some portions of Ogbomosho-Ilorin dual carriage way in the basement complex terrain of southwestern Nigeria (Adesola et al., 2017). Qualitative interpretation of the VLF-EM and ground magnetic profiles suggested the presence of typical fracture zones. This was confirmed by the results obtained from the VES and 2-D resistivity imaging of the subsurface which showed major geologic features, which are typical of fractures, faults, joints, cavities and voids. The existence of poor clayey subgrade of low resistivity has been established as one of the underlying factors responsible for the instability of Owo-Ikare highway in southwest Nigeria (Ademila, 2020). Geotechnical properties such as moisture content, liquid limit, plasticity index, percentage fines, linear shrinkage, low compacted density etc of the tested soil samples from the site also supported the geophysical results.

Similar conditions characteristic of investigated roads from previous works is presently manifested in the neglected Sango-Ota-Idiroko Highway, notwithstanding its significance as an international route of utmost importance to the economy of southwest region and Nigeria as a developing nation. Hence, the aim of this present study is to employ VLF-EM technique to evaluate subsurface characteristics and structural features of the sub-grade soil /host subsurface materials that constitute the weak zones along this road and adjoining feeder roads in the study area. This will assist in discovering the geological and geotechnical factors responsible for the persistent failure of these roads and as well fast track future geotechnical engineering evaluation in its rehabilitation and renovation projects.

2. Description and Geology of Study Location

Ogun state, often refer to as the gateway state, lie within latitude 6.2° N to 7.8° N and Longitude 3.0° E to 5.0° E, in the tropical rainforest zone of southwest Nigeria. It has a total landmass of about 2200 km^2 and is bounded by Lagos state in the south, by Benin Republic in the west, by Oyo state in the north and in the east by Ondo State (Oladehinde et al., 2018). Ota is an industrial hub in Ado-Odo/Ota local government area (latitude 6°41′00″N and longitude 3°41′00″E) in Ogun state. The L.G.A. came into existence following the merging of Ota, part of the defunct Ifo/Ota Local Government area with Ado-Odo/Igbesa in the Yewa South Local Government area. The southern region of Ado-Odo/Ota L.G.A. directly shares a border with metropolitan Lagos state. Ado-Odo/Ota as the second largest L.G.A. in the state is well populated with most roads in very poor condition (Figure 1). Part of the geophysical survey site is along Sango-Ota-Idiroko Highway, an international route to the Republic of Benin and as such vehicular traffic is high with hundreds of heavy-duty vehicles plying the route on daily basis to and from Republic of Benin. Hence, the significance of this road is not an overstatement even now with the establishment of the ECOWAS Trade Liberalization Scheme (ETLS) which is a scheme that offers unhindered market access to the fifteen member countries in order to promote economic relations and activities within the sub-region. Therefore, this international route which is very important for economic activities coupled with good road networks, is a key factor in harnessing the business opportunities and activities that abound in this border town.

Figure 1: Failed section of Sango-Ota-Idiroko Highway; (b) Abandoned section of Sango-Ota-Idiroko Highway; (c) Dilapidated inner road off Sango-Ota-Idiroko Highway.

The geology of Ogun State (Figure 2) is partly underlain by Basement Complex rock units, mainly of crystalline rocks origin and partly underlain by sedimentary rocks mainly from eastern Dahomey Basin (Jones and Hockey, 1964; Oyawoye, 1972; Rahaman, 1989; Wright, 1992). The crystalline rocks are majorly of rock of Archean age such as porphyritic granite, granite gneiss, biotite granite, undifferentiated schist, granodiorite, muscovite granite and migmatite (Rahaman, 1989). The sedimentary rocks are majorly from the Ilaro Formation, Recent alluvium, coastal plain sands (Benin Formation), Oshosun Formation, Ewekoro Formation, and Abeokuta Formation (Omatsola and Adegoke, 1980; Okosun, 1998). The Abeokuta Formation lies directly above the basement complex. Ewekoro, Oshosun and Ilaro Formations in turn overlie this, which are all overlain by the coastal plain sands (Benin Formation). The late Cretaceous predominantly sandy strata of the Abeokuta Group is the oldest. The Tertiary strata directly above the Abeokuta Group include limestone of the Ewekoro Formation, shale of the Akinbo Formation, mudstones/shale of the Oshosun Formation, and sandstone of the Ilaro Formation. Other younger stratigraphic strata are the Oligocene to Recent

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continental sands of the Benin Formation as well as Recent alluvial sediments (Adegoke et al., 1980; Onyeagocha, 1980; Omatsola and Adegoke, 1981; Adewuyi, 1984; Okosun, 1990; Adediran et al., 1991; and Nton et al., 2009). Ota town is mainly underlain by coastal plain sands of the Benin Formation.

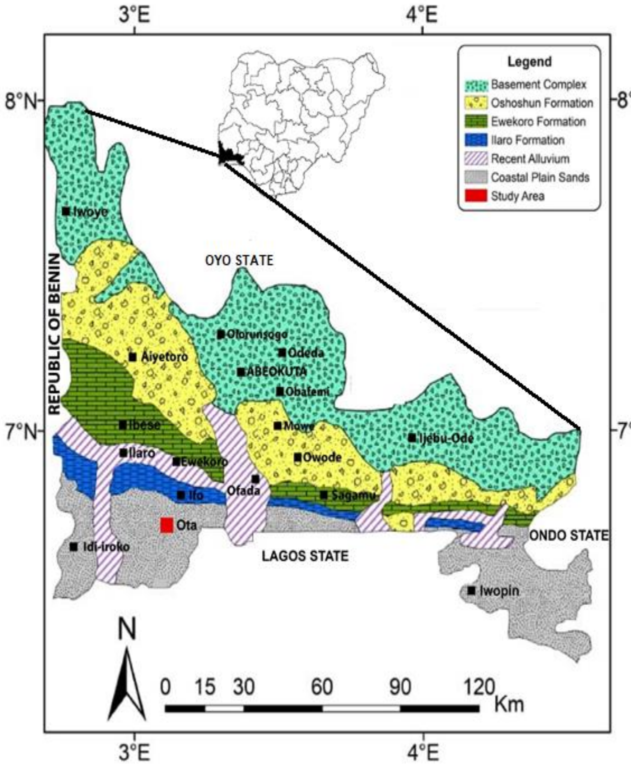


Figure 2: Geological map of Ogun State showing the study location. (Adapted from Badmus and Olatinsu, 2009).

3. Methodology

3.1 Data Acquisition

In order to investigate the subsurface condition of the identified failed portions of roads in the study area, measurements using Geonics EM16 (Geonics Ltd. Ontario, Canada) VLF-EM data were taken at several stations at regular interval of 5 m, along fifteen (15) traverses (Figure 3) each spanning between 100 and 250 m in length. While five of these traverses (3-7) were positioned at some distances away and parallel to identified failed sections of Sango-Ota-Idiroko Highway, nine traverses (1, 2, 8-11, 13-15) were arranged along nearby feeder roads off the highway. Traverse 12 was positioned parallel to a road in a comparatively stable condition to serve as the control traverse. The VLF instrument (Geonics EM16) compares the magnetic field of the primary signal from radio transmitters to that of the secondary signal (induced current flow within subsurface electrical conductor) thereby providing relevant geological data (in-phase and quadrature) on subsurface layer conditions (McNeill, 1980, 1988, 1991; McNeill and Labson, 1991; Chouteau et al., 1996). The EM16 VLF receiver is a very popular and easy to use model among electromagnetic geophysical instrument commercially available for electromagnetic survey. Tilt angle and ellipticity of VLF signals can be recorded and separated into the corresponding in-phase (parallel) and quadrature (perpendicular) components. Standard VLF data acquisition procedures were adhered to achieve the objectives of the investigation. The equipment was held horizontally and then turned in a clockwise sense at the first station of each traverse until the highest resonant frequency and direction of signal generated from the transmitting station was obtained. This point of highest resonance was noted, after which the equipment was further turned to 90^{o} in relation to the point of highest resonant frequency to get the "in-phase" and "quadrature" data. Station coordinates (longitude, latitude, and altitude/elevation) were also recorded using a global positioning system (GPS).

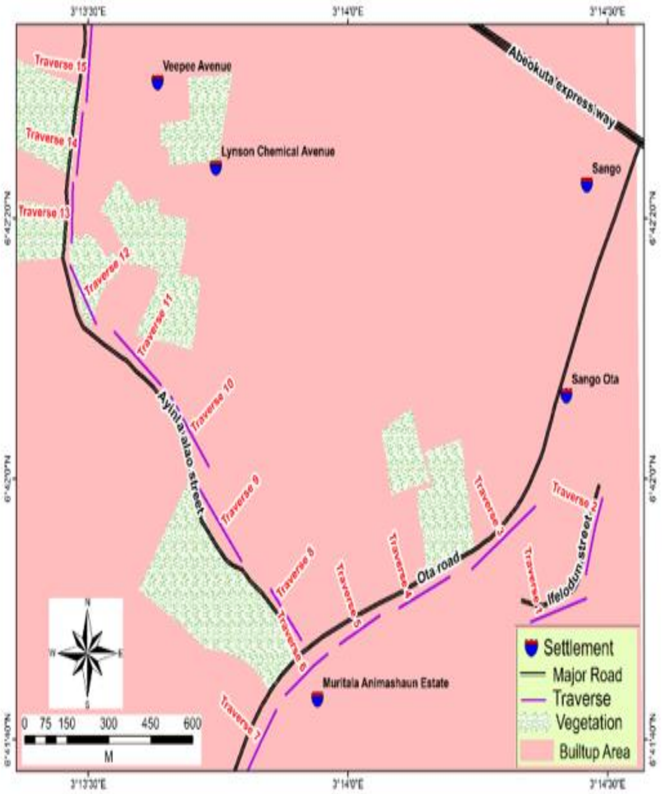


Figure 3: Data acquisition map showing the layout of the traverses along Sango-Ota-Idiroko Highway and nearby adjoining roads.

3.2 Data Processing

Data processing for noise suppression and signal enhancement was carried out using Karous-Hjelt and Fraser Filtering (KHFfilt) geophysical software. KHFfilt which is an extension of Fraser filter is a suitable geophysical software that modulates data using linear filtering to analyse VLF in-phase and quadrature data and represents the output as a 2-D image (Karous and Hjelt, 1977; 1983; Fraser, 1969). This procedure is semi quantitative and involves filtering of VLF data set at various depths to generate a 2-D representation of the variation of current density with depth. Areas with high current density indicate the presence of geological material with good/high conductivity. The apparent current density pseudosection provide a visualization of the depths of various concentrations that correspond to the spatial distribution of subsurface geologic features.

4. Results

Fraser filtering plots (Figures 4 - 8) depict the filtered real component of the VLF response versus station distance and is commonly interpreted qualitatively and semi-quantitatively. The changing amplitude of the VLF profile represents the variation in the conductivity of subsurface materials (Sharma and Baranwal, 2005; Gnaneshwar et al., 2011; Jayeoba and Oladunjoye, 2013). The positive peaks of the filtered real component indicate the presence of conductive subsurface bodies. The 2-D current density cross-section from Karous-Hjelt filtering procedure arranged below their respective Fraser plots (Figures 4 - 8), shows the lateral and vertical conductivity distributions along the traverses. There is good correlation of positive peaks on Fraser plots with conductive zones (red regions) on 2-D current cross-sections at several lateral distances and depths across all the traverses with the exception of traverse 12 which serves as the control traverse. These delineated near-surface VLF anomalies suggest possible weak zones that might pose serious risk to the stability of roads. Consequently, the presence of conductive anomalies shown in the pseudo-sections is attributed to clayey subsurface bodies in the subgrade soil used for the road construction or host clayey bodies in the subsurface sequence of geological materials.

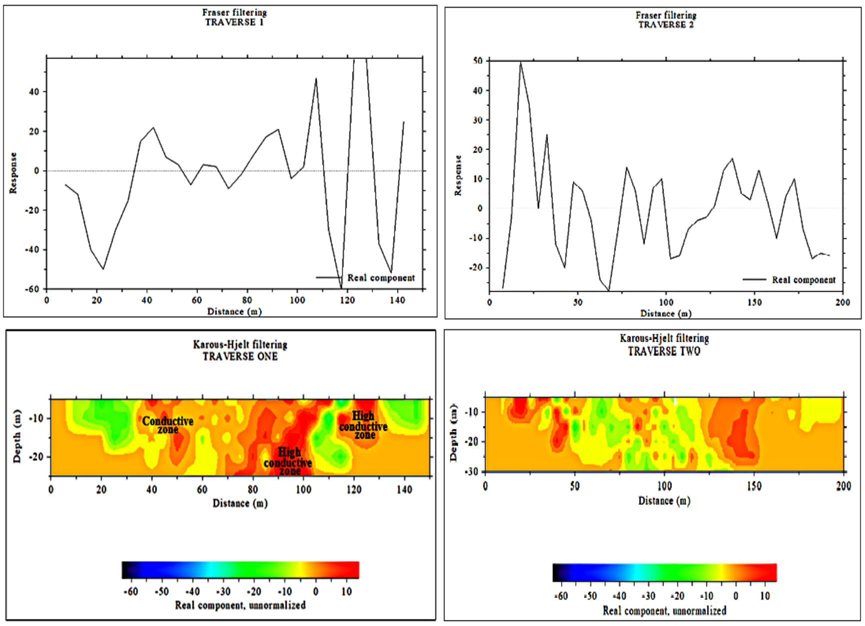


Figure 4: Fraser filtering plots and equivalent Karous–Hjelt current density pseudo-sections for traverses 1 and 2 showing several conductive (red) zones.

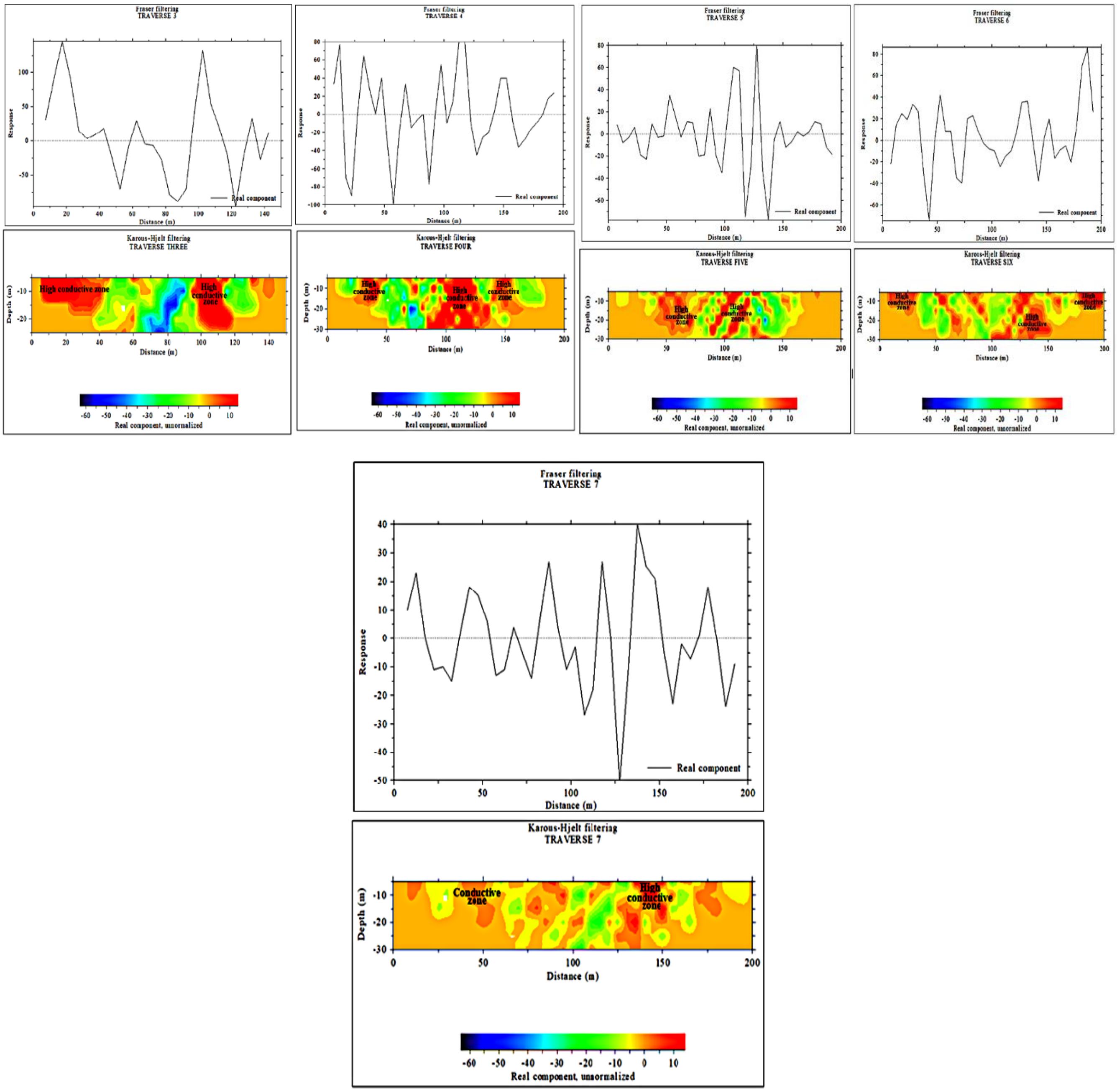


Figure 5: Fraser filtering plots and equivalent Karous–Hjelt current density pseudo-sections for Traverses 3-7 showing several conductive (red) zones.

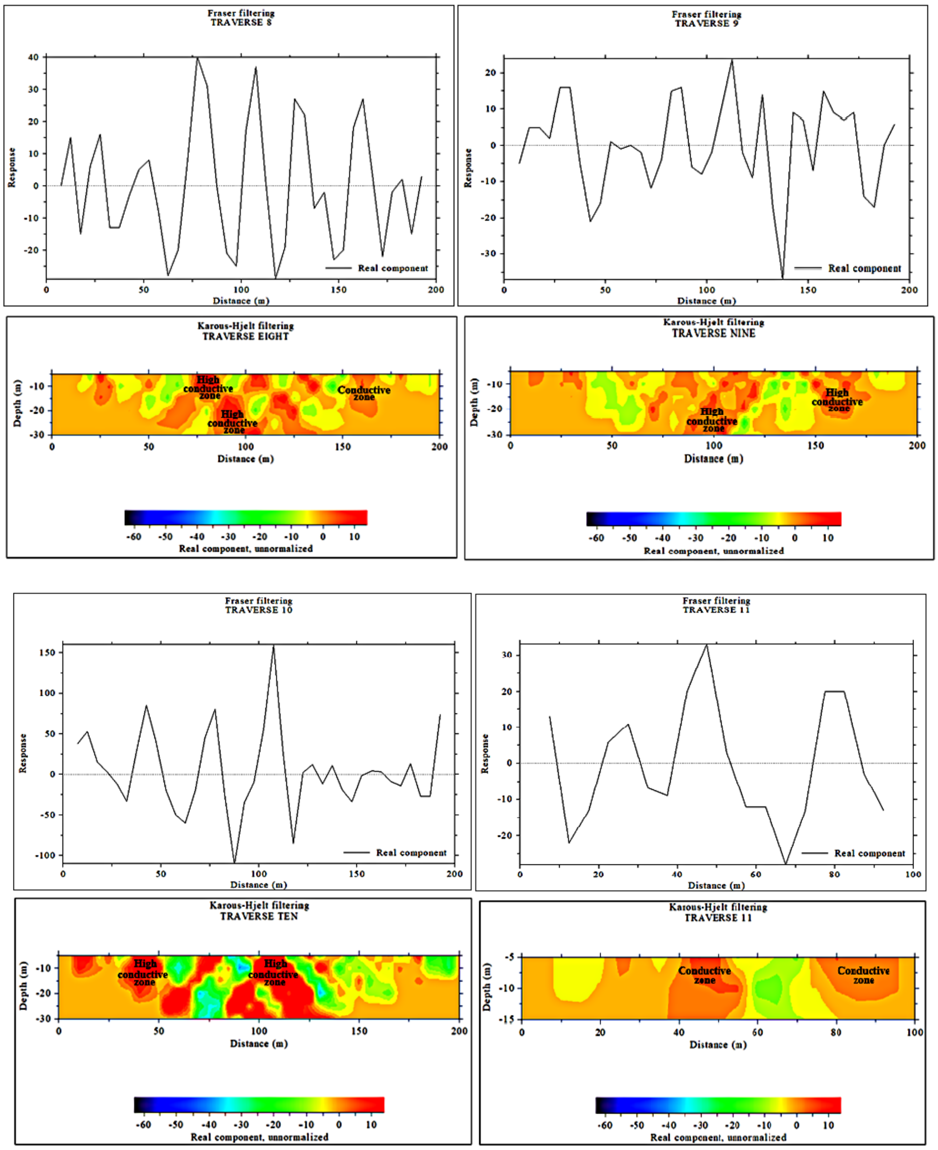
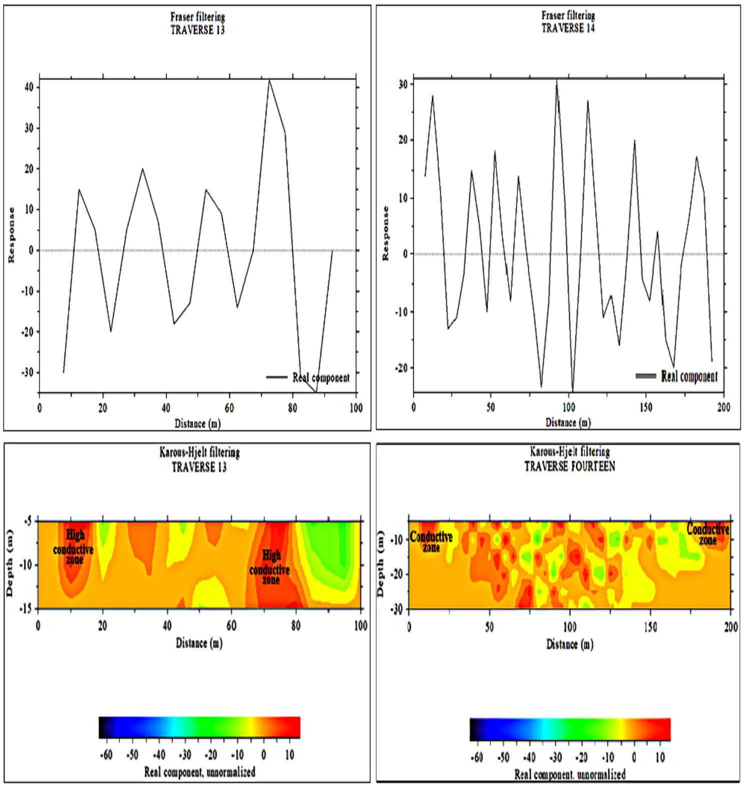


Figure 6: Fraser filtering plots and equivalent Karous–Hjelt current density pseudo-sections for Traverses 8-11 showing several conductive (red) zones.



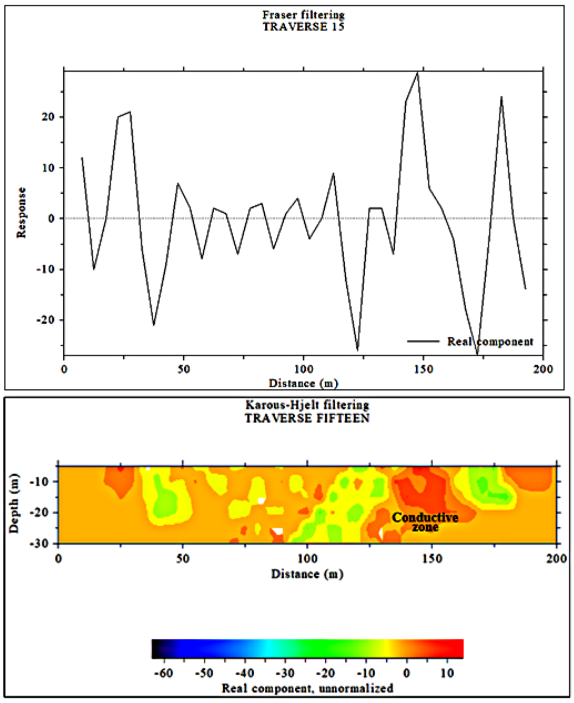


Figure 7: Fraser filtering plots and equivalent Karous–Hjelt current density pseudo-sections for Traverses 13-15 showing several conductive (red) zones.

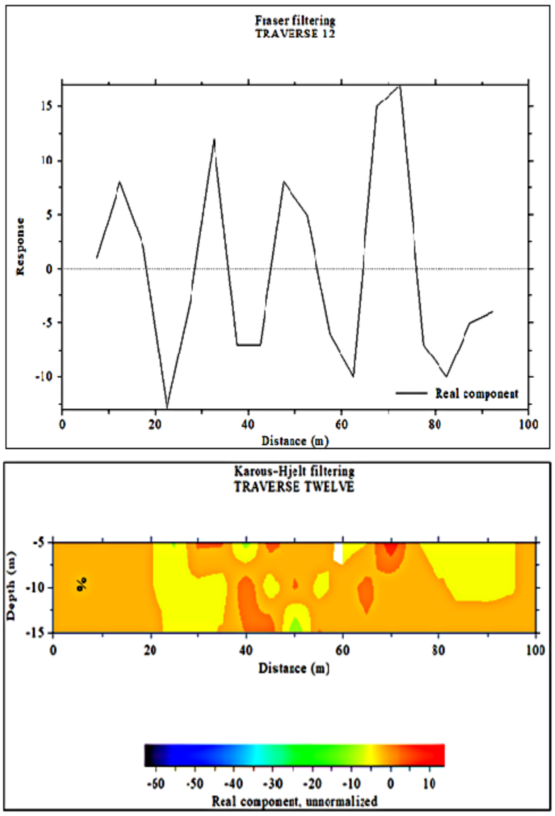


Figure 8: Fraser filtering plots and equivalent Karous–Hjelt current density pseudo-sections for traverse 12 (control traverse) along a stable road with conductive (red) almost absent.

5. Discussion

The regions with predominantly red colour on the 2-D image of traverses 1 to 11 and 13 to 15 clearly represents a high current density zone i.e., a zone with high conductivity/low resistivity. These are geologically weak zones presumably composed of clayey bodies (laterite/lateritic soil). Laterite as a soil/rock type is rich in iron and aluminum and abound mostly in tropical African countries and in most parts of Nigeria. They are formed through severe and continuous weathering of the underlying parent rock under conditions of high temperatures and heavy rainfall with alternating wet and dry periods. This soil group play a unique role in geological and geotechnical engineering by virtue of their widespread occurrence and distinctive properties. Most laterite/lateritic soil found in Nigeria are composed of kaolinite and illite clay minerals with some quartz and feldspar and are rich in SiO_2, Fe_2O_3 and Al_2O_3. They tend to yield maximum strength when compacted and dry (Ola, 1980, 1983; Alao, 1983).

Shrinkage due to climatic conditions is a major source of distress which can result in serious damage to engineering structures (Ola, 1980). The soils are not expected to perform very well as concrete aggregates since they contain high amounts of SiO2 and Fe2O3. Conductive zones are depicted on the 2-D pseudo-sections at lateral distances across the traverses: 35 - 60 m, 70 - 110 m and 115 - 130 m (traverse 1); 10 - 100 m and 125 - 200 m (traverse 2); 5 - 45 m and 90 - 120 m (traverse 3); 25 - 50 m and 75 - 175 m (traverse 4); 35 - 60 m and 85 - 140 m (traverse 5);10 to 35 m and 50 to 200 m (traverse 6); 10 to 110 m and 125 to 185 m (traverse 7); 25 to125 m (traverse 8); 10 to 125 m and 145 to 200 m (traverse 9); 10 to 135 m (traverse 10); 20 to 55 m and 70 to 100 m (traverse 11); 60 to 75 m (traverse 12); 5 to 55 m and 65 to 85 m (traverse 13); 10 to 150 m and 185 to 200 m (traverse 14); 25 to 35 m, 125 to 160 m and 185 to 200 m (traverse 15). Only the control traverse 12 in which the red zones is almost completely absent, is indicative of a low conductive zone of yellow colour (stable zone).

Clayey materials as a result of their pore characteristics (high porosity and low permeability) usually undergo alternating series of expansion and contraction (shrinkage) under different climatic conditions. This season-dependent dispositions of underlying soil will sooner or later lead to the appearance of cracks and potholes on road pavements. Furthermore, it has been observed that when foundations of buildings/structures are erected laterally on different lithologies (sand/clay/clayey sand/sandy clay), vertical displacement of soil (settlement) is possible due to building load. Similarly, when road pavements are directly underlain by uneven lateral spread of subsurface materials with some clayey bodies present, then the occurrence of differential settlement is inevitable. At the investigated roads in Ota environs, the clear delineation of soil of different lithological characteristics with different conductivities and deformation strength/compressibility (intermingling of regions - green, yellow, orange, red), is undoubtedly a contributing factor to the recurring road failure/collapse.

6. Conclusion

Very low frequency electromagnetic (VLF-EM) geophysical technique has been employed to investigate the subsurface conditions and patterns along Sango-Ota- Idiroko Highway and other nearby roads in Ota, Ogun State, Southwest Nigeria. Data processing based on semi quantitative VLF filtering procedure was carried out using Karous-Hjelt and Fraser Filtering (KHFfilt) geophysical software. Positive peaks of the filtered real component on Fraser plots depicts the presence of conductive subsurface material. The 2-D current density cross-section from Karous-Hjelt filtering procedure also depicts the lateral and vertical conductivity distributions along the traverses. Good correlation of positive peaks on Fraser plots correlates well with conductive red zones (high conductivity anomalies) on 2-D current cross-sections at several lateral distances (corresponding to failed road sections) and depth across all the traverses except traverse 12 (corresponding to stable road segments) used as the control traverse, has regions of low conductive zone (yellow areas). These delineated near-surface VLF anomalies of high conductivity is suggestive of the presence of geologically weak zones that might pose serious threat to stability of roads and other engineering structures. Accordingly, these depicted conductive anomalies in the pseudo-sections is attributed to clayey subsurface bodies (laterite/lateritic soil) in the subgrade soil used for the road construction or unexcavated host materials in the subsurface. Expansion and shrinkage of these supposed clayey medium due to varying climatic conditions is a major cause of distress which may lead to serious damage in the foundation of engineering structures. Clayey materials by virtue of their pore characteristics (high porosity and low permeability) tends to undergo series of expansion and contraction under different climatic conditions. These season-dependent dispositions would eventually manifest in the creation of cracks and potholes on road pavements. Also the uneven lateral spread of several subsurface materials with different lithologies adjacent to one another across the investigated traverses in the study location, is again a major contribution to differential settlement which is a possible catalyst of road failure.

Ethics Approval and Consent To Participate

This article does not contain any studies involving life, whether animal or human, performed by any of the authors.

Consent for Publication

The two authors mutually agreed and gave their consent for this article to be published.

Availability of Data and Material

The data used for this study are confidential.

Competing Interests

The authors of this article declare that there are no competing interests in any way in relation to the work carried out in the research.

Funding

No funding was received to accomplish this study.

Authors' Contributions

Mr. O. Omodiagbe carried out the fieldwork, processing and analysis in the course of his M.Sc. project. Dr. O.B. Olatinsu provided the mentorship, guidance and prepared the manuscript for publication.

Acknowledgements

The authors wish to appreciate the assistance of field personnel who provided technical support during the field work for data acquisition and other colleagues of the second author for contribution to the overall success of the project.

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