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Probability functions of road failures in a typical basement complex region, South-western Nigeria: A case study of Akure - Oba Ile Airport Road

Oyedele Akintunde Akinola[1], Bawallah Musa Adesola[2], Ozegin Kesyton Oyamenda[3*], Ilugbo Stephen Olubusola[2], Ajayi Christopher Ayodele[4] and Aigbedion Isaac[3]

[1]Department of Physics, Ekiti State University, Ado – Ekiti, Ekiti State, Nigeria.
[2]Department of Applied Geophysics, Federal University of Technology, Akure, Ondo State, Nigeria.
[3]Department of Physics, Ambrose Alli University, Ekpoma, Edo State, Nigeria.
[4]Department of Geology, Ekiti State University, Ado Ekiti, Ekiti State, Nigeria.

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In this study, effort has been made to achieve a comprehensive geophysical investigation on immediate and remote causes of structural/foundation failures, specifically highway(s) within the southwestern basement complex region of Nigeria. Geophysical survey involves the use of Very Low Frequency Electromagnetic method (VLF-EM) which was complemented with electrical resistivity method using two techniques; 2D Electrical Resistivity Tomography (ERT) and Vertical Electrical Sounding (VES) along Akure/Oba-Ile Airport Road, which covers a pilot test of 600 m. The VLF-EM survey produced EM anomalies and identified possible linear features along the study area. The results obtained from the VES were used to determine the second order parameters for determination of subsurface integrity/competence. The geoelectric sections identified three to five geoelectric/geologic subsurface layers along the traverse. The ERT gave information on the subsurface characteristics whose section delineated five major geologic layers comprising of the topsoil, weathered basement, fractured zone, partly fractured basement and the fresh basement. This shows that fracture and weathering are responsible for the structural failures along the study area which are products of probability functions of geodynamics. The methodology can be adopted as a model to proficiently and quickly detect changes in subsurface resistivity, integrity and identify anomalous zones which can serve as useful tool in the understanding of the probability functions of geodynamics that can bring structural and foundation failures within the basement complex region.

Key words: Road, longitudinal conductance, subsurface integrity, dipole-dipole, geoelectric section, very low frequency.

INTRODUCTION

A road is a thoroughfare, way, or route on land between two places, which in general has been paved or otherwise,

*Corresponding author. E-mail: ozeginkess@yahoo.com

enhanced to allow travel by some transportation. However, the presence of discontinuities such as cracks, surface deformation (rutting), disintegration (potholes), surface defects (ravelling) on a road network is regarded as road failure (Ozegin et al., 2016). Road failures in Nigeria is almost becoming a national nightmare attributable mostly to geological problem, poor engineering design, poor constructions, occasioned by sharp practices and corruption, and many a times, environmental factors associated with local and regional variations in rain pattern, temperature changes, greenhouse effect and global warming. However, little or no attempt has been made to consider most variables, if not all that are associated with structural and foundation failures including roads. Even though geological variables are the major factors affecting structural failures, however road failures like every other structural problem are but probability functions of many geodynamic parameters and processes amongst which includes; weathering, fracturing greenhouse effects temperature, pressure and the gradual but continuous earth movement, all are probability functions whose combine effects often bring about structural and road failure. Therefore, this paper attempt at critically considering some of these probability functions and parameters that are often responsible for most structural failures. Bearing in mind that roads play cardinal roles in the socio-economic development of a nation. The provision of a good and sustainable road that would stand the test of time is vital economic indices for growth and social development that can serve as a way to meeting the basic demand for sustainable mobility of the populace goods and services. Hence, the road transport industry remains the backbone of strong economies and dynamic societies (Ozegin et al., 2019; Adebiyi et al., 2019). The huge financial and human resources committed to road construction demand that road pavements do not fail soon after commissioning. It is however observed that several segments of our highways fail perpetually and are objects of rehabilitation with the associated financial burden (Okpoli and Bamidele, 2016; Afolayan and Abidoye, 2017). Prominent research works emphasized the need for thorough knowledge of the characteristics and behaviour of subgrade layer on which structures are built through geological, geotechnical and geophysical investigations (Okigbo, 2012; Ugwu and Ezema, 2013; Adelekan et al., 2017). Inadequate investigations of subgrade and other pavement materials prior to the commencement of road projects constitute pitfalls in road construction (Andrews et al., 2013; Aizebeokhai and Oyeyemi, 2014; Odunfa et al., 2018). Adequate knowledge of the geotechnical characteristics of underlying soils at construction sites has become a pre-requisite for foundation design and construction of civil engineering structures to mitigate failure of structures (Adigun et al., 2014; Awang et al., 2016). It has therefore become a matter of great concern and necessity to find out which of the factors responsible for incessant road failure and perennial problems, with a view to finding a lasting solution. This is given the growing concerns over the unprecedented number of avoidable road accidents, loss of life, human valuables and the huge financial loss on a dwindling national economics fortune, where road re-work, reconstruction and rehabilitation is taking a chunk of the annual national budget to the detriment of the entire nation. Subsequently, this research holistically raises issues as it affects all the probability functions of geodynamics, as well as causes of structural/ road failure in this part of the world using an integrated geophysical approach.

Site description and geology of the study area

The study was carried out at Oba-Ile, Akure North, Ondo State, Nigeria. It is situated between latitudes 7° 14′ N and 7° 17′ N and longitudes 5° 14′ E and 5° 15′ E, (Figure 1). The area falls within the Precambrian Basement Complex terrain of the country (Rahaman, 1988). The main rock types found in Oba Ile area are migmatite, undifferentiated granite gneiss, quartzite and porphyritic granite with schist impregnation (Figure 2). Oba-Ile enjoys a tropical climate with the natural vegetation of rain forest. The mean annual rainfall in the area ranges from 700 to 800 mm approximately. The evaporation in the area is high due to the humidity, relatively high sunshine hours and low precipitation. The area is drained by River Ala, River Ogijan and other tributaries (Adeyemi, 2015; Ogunrayi et al., 2016).

MATERIALS AND METHODS

A traverse of about 600 m was established in an approximate E - W direction (Figure 3). Electrical resistivity and very low frequency electromagnetic (VLF-EM) geophysical methods were employed for this study. The VLF-EM method was adopted as a fast reconnaissance tool to map possible linear features such as faults and fracture zones. The VLF-EM data were collected at 9 m intervals along the road segment using ABEM WADI equipment with transmitter frequency range of 24.8 – 27.6 kHz. The equipment measured the raw real, R (in phase) and the imaginary, I (quadrature) components of the vertical to horizontal magnetic field ratio on the field. An in-built filtering program provided in the ABEM WADI equipment and a software package KHFfilt Version 1.0 enabled the conversion of the raw real VLF data into filtered real data in which anomaly inflections appear as peak positive anomalies and false VLF anomaly inflections as negative anomalies of the profile. Further processing yielded corresponding pseudosections (Olorunfemi et al., 2005; Pirttijärvi, 2004; Taiwo et al., 2016). The VLF data was separated into two sections, the negative and positive data which were later classified into class distribution in term of conductivity and resistive materials. The ERT measurements were taken using the dipole-dipole array with a unit of OHMEGA campus SAS 1000 Resistivity meter and its accessories. Coordinates and elevations were recorded using a hand-held Garmin GPS device. The survey was conducted at an inter-electrodes spacing of 5 m. The terrameter gave the apparent

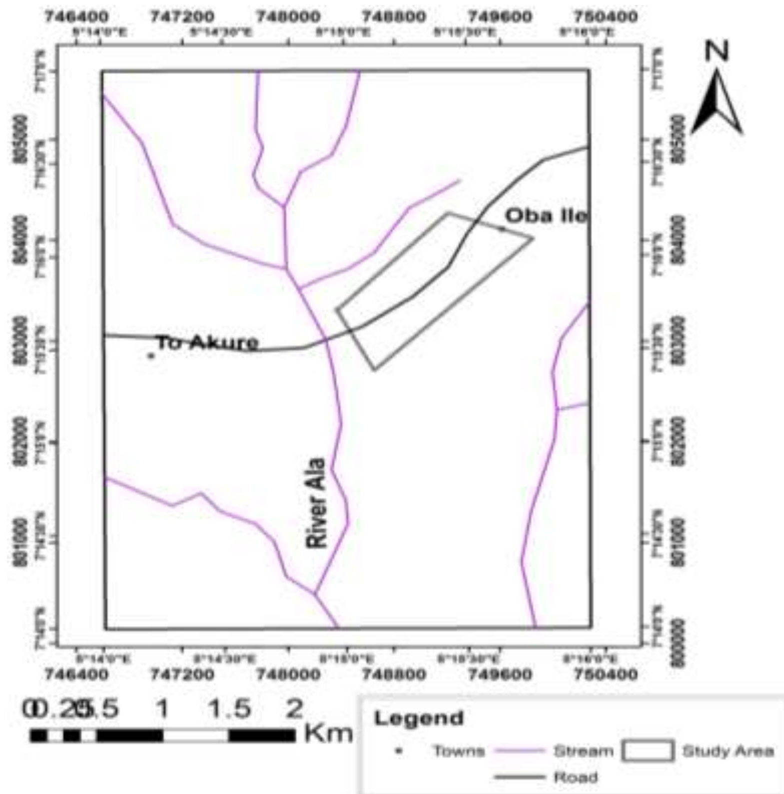

Figure 1. Base map of the study area.

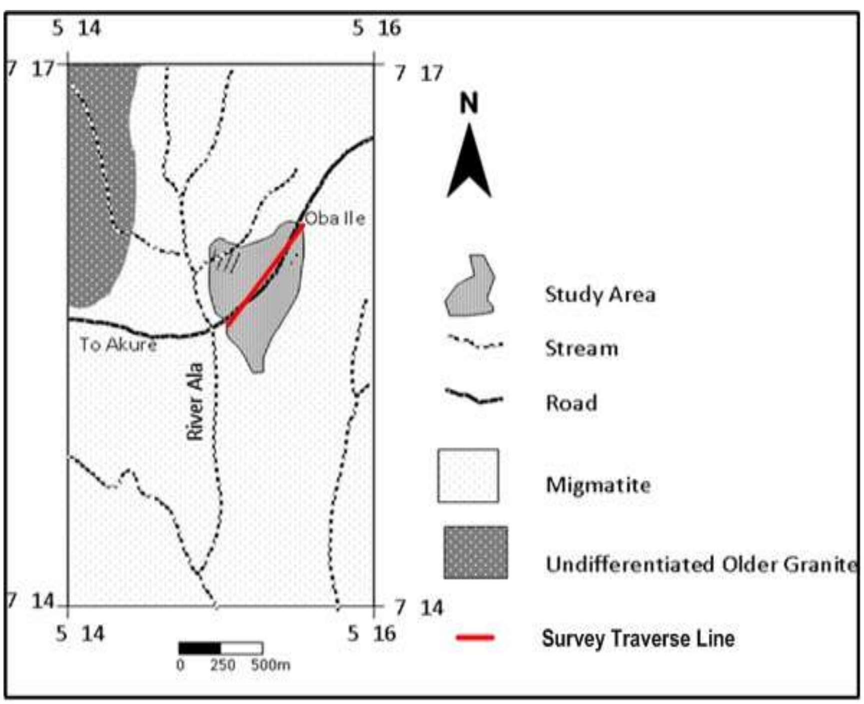

Figure 2. Geological map of Oba-Ile showing the study area.
Source: Modified from Ogunrayi et al. (2016).

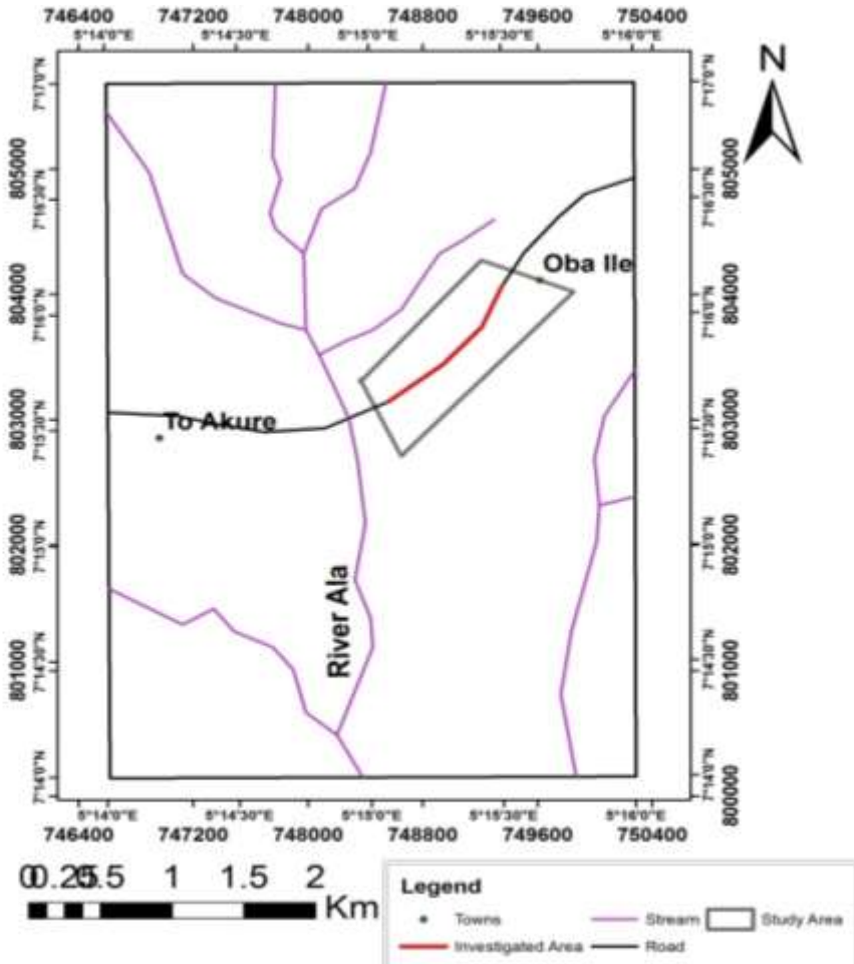

Figure 3. Data acquisition map of the study area.

resistivity values digitally as computed from Ohm's law. The apparent electrical resistivity data were subsequently inverted into the true electrical resistivity distributions by the RES2DINV software to obtain a subsurface image of the electrical resistivity pattern (Aizebeokhai, et al., 2010; Sibula et al., 2017). The software employs an optimization algorithm that adjusts the 2-D electrical resistivity model by iteratively reducing the difference between the calculated and measured apparent electrical resistivity values. The VES involved the use of Schlumberger array. Twelve (12) sounding stations were occupied along the established traverse, and the current electrode spacing (AB) was varied from 1 to 200 m. In order to process the electrical resistivity data, the apparent resistivity values were plotted against the electrode spread (AB/2). This was subsequently interpreted quantitatively using the partial curve matching method and computer assisted 1-D forward modeling with WinResist 1.0 version software (Vander, 2004). The results from the VES interpretation were used to determine the second order parameters such as the total transverse resistance (T) and the total longitudinal conductance (s). The second order parameters were used to determine subsurface integrity of the road. The results from the three techniques were integrated in order to determine the consequences of the differential settlement and their degree of correlation.

RESULTS AND DISCUSSION

The results of the study were presented as geoelectric sections, pseudo sections, sections and graphs.

Electrical resistivity tomography

The inverted resistivity-depth model (the inverted 2D resistivity structure along the road) is shown in Figure 4. The section delineated five geoelectric layers comprising of the topsoil characterized by low resistivity values indicated by bluish colour band, the weathered zone of light-greenish colour bands, the fractured zone denoted by deep-green colour bands, partly fractured zone characterized by moderately high resistivity values of yellowish band and the fresh basement characterized by high resistivity values of reddish colour band. The thickness of the topsoil is generally less than 2.5 m. The low resistivity spectrum (resistivity < 100 Ωm) observed

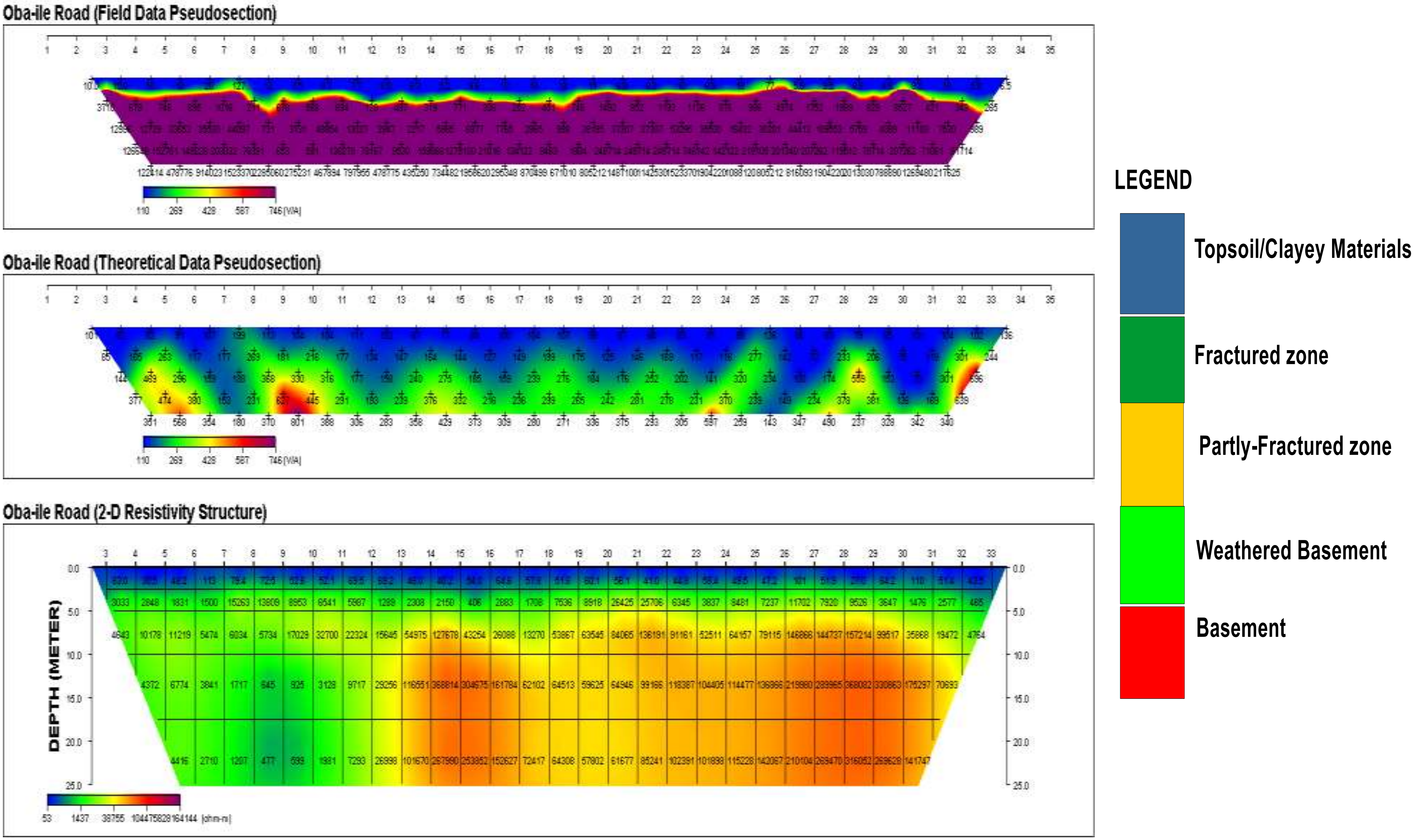

Figure 4. The 2-D resistivity inversion model of the study area.

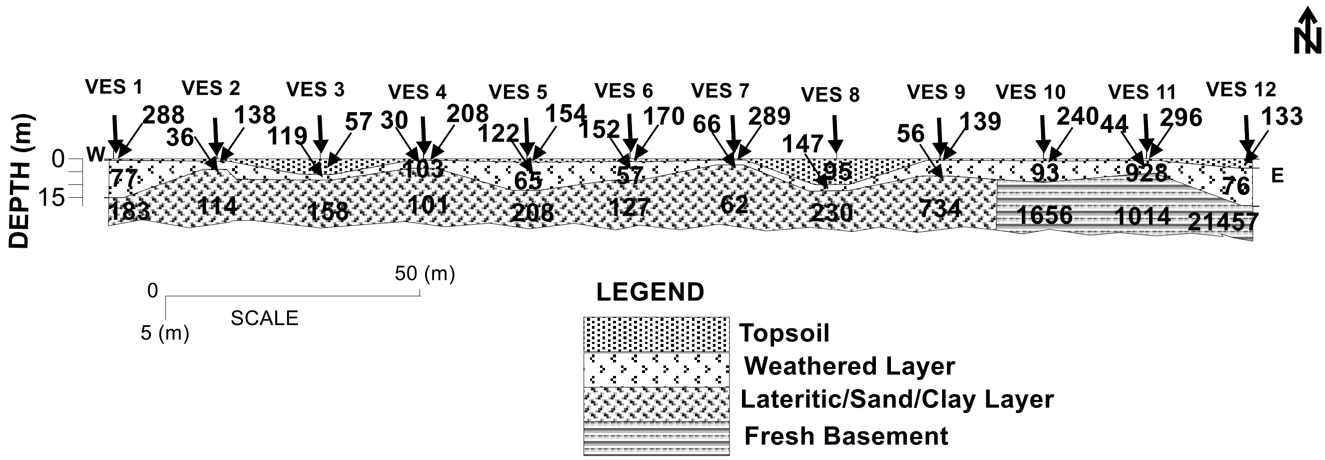

Figure 5. Geoelectric section along the traverse.

along the entire profile line to a depth of about 2.5 m indicates that the topsoil is characterized by clayey materials. This is underlain by the unsaturated substratum of high resistivity with clayey intercalations, indicating localised lateral resistivity inhomogeneities in the near surface material. A major fracture zone is located between distances of 160 and 200 m at a depth range of 15 - 20 m. Partly fractured zones are located between distances of 340 and 420 m within a depth of 5 – 20 m. The basement is observed within distances 240 – 340 m and 480 – 600 m. The observed moderately low resistivity zones are typical fracture zones within the host basement environment. The decrease in resistivity at about 12 m depth suggests the presence of a saturated geomaterial/geologic structure and correspondingly the presence of a low static water level. The basement is revealed at an average depth of 10 m up flank while it tails into a depression down flank.

Characteristic of the VES curves

Curves types identified ranges from H, A, HK, QH and HKH varying between three to five geoelectric layers. The H curve type was predominant.

Geoelectric and lithological characteristic along the traverse

The geoelectric sections were represented by the 2D view of the geoelectric parameters (depth and resistivity) derived from the inversion of the electrical resistivity sounding data. The geoelectric section along the traverse (Figure 5) correlates the geoelectric sequence across the study area. The geoelectric sections along the traverse identified three to four geoelectric/geologic subsurface layers. From the geoelectric section, the top soil, weathered layer, lateritic layer/sand/clay layer and fresh basement were determined. The topsoil comprising of clay, clayey sand and sandy clay with the resistivity values ranging from 57 to 296 Ωm with its thickness varying from 0.4 to 9.9 m while the weathered layer comprising of clay, clayey sand and sandy clay with resistivity varying from 30 to 2926 Ωm and its thickness varying from 1.1 to 14.8 m. The lateritic/sand/clay layer has a resistivity values ranging from 62 to 734 Ωm and thickness value of 13 m while the fresh basement has a resistivity value ranging from 1014 to 21457 Ωm with depth to basement ranging from 2.3 to 19.3 m. The resistivity values of the topsoil are indicative of clay, sandy clay and clayey sand. This layer may not be of any special interest since topsoil is normally excavated. Hence, road construction cannot be found on this layer.

Dar Zarrouk parameters

Result obtained from the VES interpretations were used to determine the second order parameters (Table 1). Second order parameters were involved in order to be able to have a better understanding of the dynamics of layers parameter in studies of this nature (Bawallah, et al*.,* 2019). The findings illustrate that the total longitudinal conductance (S) varies from 0.0181 – 0.2211 Ω-1 in the area with high total longitudinal conductance between distance of 90 to 110 m, 180 to 250 m, 320 to 430 m and low total longitudinal conductance at distance between 110 to 179 m, 251 to 319 m, 432 to 530 m (Figure 6). The qualitative use of these parameters is to demarcate changes in total thickness of low resistivity materials. The total transverse resistance (T) ranges from 236 to 1745 Ωm,

Table 1. Result showing Dar Zarrouk parameters.

VES Nos.	Total longitudinal conductance (S) (Ω^{-1})	Total traverses resistance (T) (Ωm)
VES 1	0.1901	1261
VES 2	0.0926	236
VES 3	0.1229	592
VES 4	0.0585	343
VES 5	0.1583	1048
VES 6	0.0971	884
VES 7	0.0302	241
VES 8	0.1205	1293
VES 9	0.1215	439
VES 10	0.0894	936
VES 11	0.0181	1745
VES 12	0.2211	1590

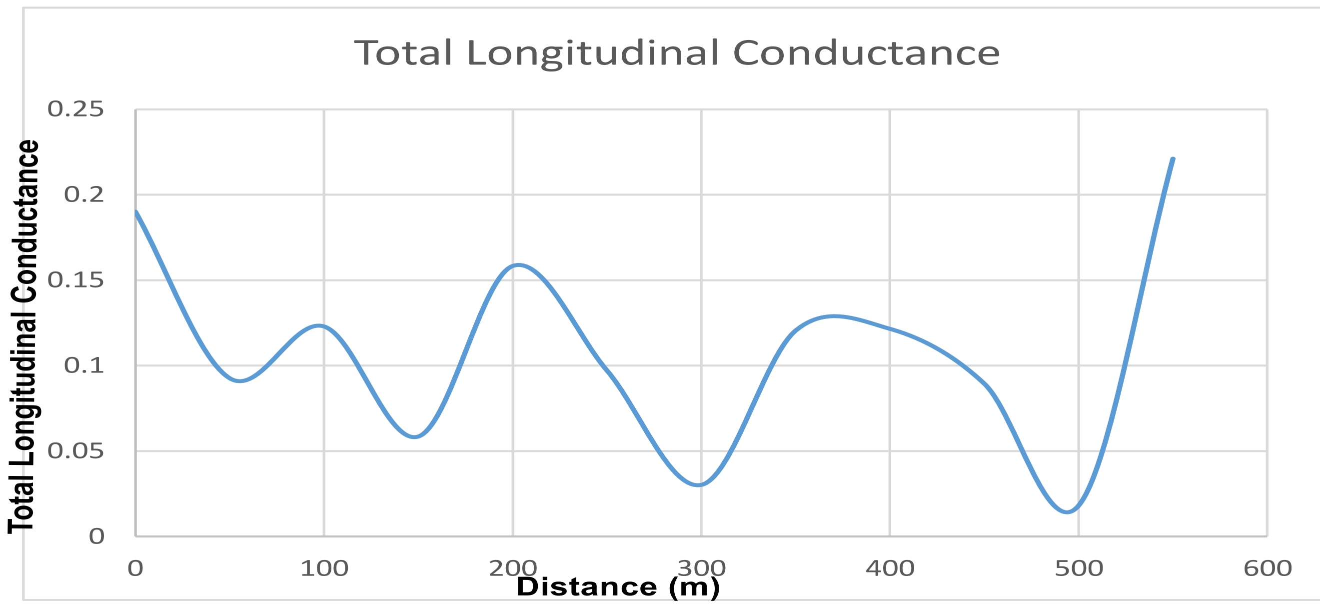

Figure 6. Total longitudinal conductance profile of the study area.

which gives information both about the thickness and resistivity of the area. The lower the longitudinal conductance, the greater is the probability of the road to failure (Ozegin, et al., 2019). The total longitudinal conductance reveals that the road has chance of 40% susceptibility to failure.

Subsurface integrity

The product of the S and T was used to determine subsurface integrity/competence (Table 2) (Bawallah et al., 2019). The result revealed the subsurface integrity varies from 7.3 to 351.5 m with high subsurface integrity between distance of 0 to 50 m, 80 to 110 m, 160 to 280 m, 310 to 480 m and low subsurface integrity at distance between 50 to 79 m, 110 to 150 m, and 281 to 309 m (Figure 7). The results exhibits that the values from low subsurface integrity/competence are indicative that this layer is weak.

VLF-EM

Figure 8 shows the VLF-EM profiles of raw real component, the filtered real component and the corresponding

Table 2. Result showing subsurface integrity values.

VES Nos.	Total longitudinal conductance (S) (Ω^{-1})	Total traverses resistance (T) (Ωm)	Subsurface integrity values [S × T] (m)
VES 1	0.1901	1261	239.6
VES 2	0.0926	236	21.8
VES 3	0.1229	592	72.8
VES 4	0.0585	343	20.1
VES 5	0.1583	1048	165.9
VES 6	0.0971	884	85.9
VES 7	0.0302	241	7.3
VES 8	0.1205	1293	155.9
VES 9	0.1215	439	53.3
VES 10	0.0894	936	83.6
VES 11	0.0181	1745	31.5
VES 12	0.2211	1590	351.5

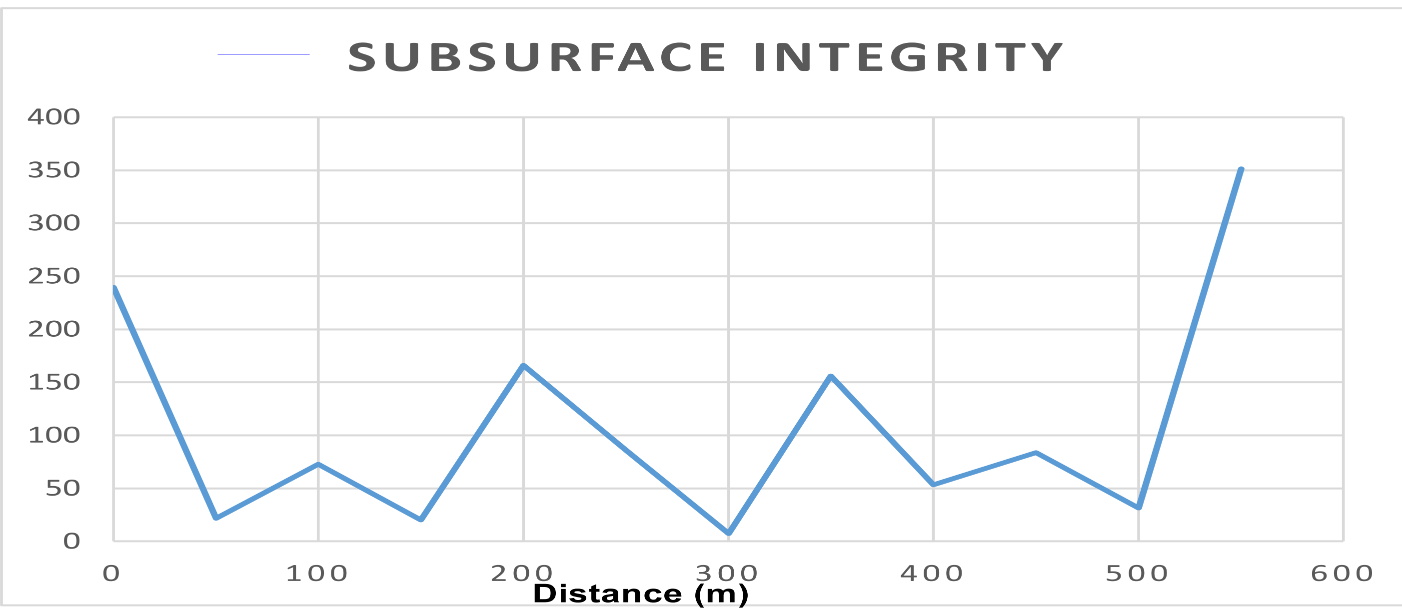

Figure 7. Subsurface integrity profile of the study area.

Karous-Hjelt (K-H) filtered 2-D structure along the traversed road. The K-H pseudo-section reflects the conductivity of the subsurface as a function of depth. Features of varying degree of conductivity trending in different directions were delineated. The raw-real/filtered-real profile of the study area is presented to aid detection of the fracture zones along the traversed route. Areas of positive peak of the filtered-real component corresponding to the points of inflection of the raw-real along the profile suggest the presence of fracture zones. Possible fracture zones are indicated at distances 60, 120, 250, 280 and 560 m within the study area. The conductivity is indicated as colour codes with conductivity increasing from left to right; increasing from negative to positive values. The amplitudes of the Fraser filtered real component vary from -17.7 to 15.7%. Conductive zones are deciphered between distances 100 - 125 m, 220 - 270 m and 500 - 530 m along the road. A likely fracture zone, indicated by a highly conductive linear feature trending NW – SE is observed between distances 100 and 150 m to a depth beyond 60 m. A near surface conductive vein trending NE – SW is delineated between

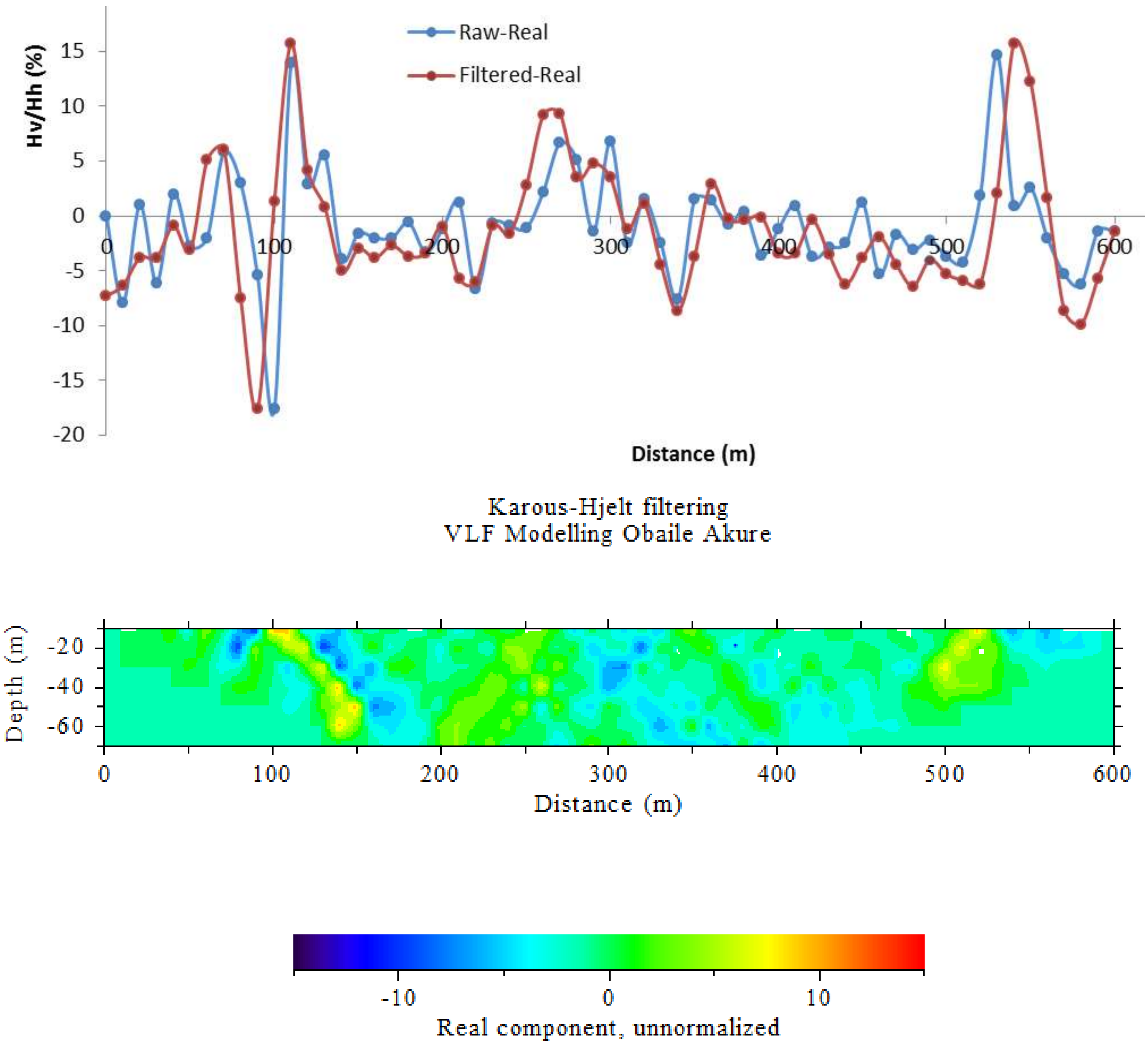

Figure 8. The profile of the real and filtered component obtained along the Traverse-and its 2-D inversion model.

distances 500 - 530 m to a depth of 30 m. Hence, there is a presence of the low conductivity zones occurring in the regions of 0 - 50, 150 - 200, 330 - 520 m along the proposed road route. These areas are considered to be the stable zones while the remaining parts along the traverse have low competence which may be susceptible to failure in due course. The regions demand adequate attention.

Integration of results

Figure 9 shows the correlation of the geophysical results obtained within the study area. It provides for integration of results from VLF-EM and electrical resistivity method along the traversed road alignment. The total longitudinal conductance is low at distance from 80 to 100 m, 280 to 310 m which coincide with the low subsurface integrity at

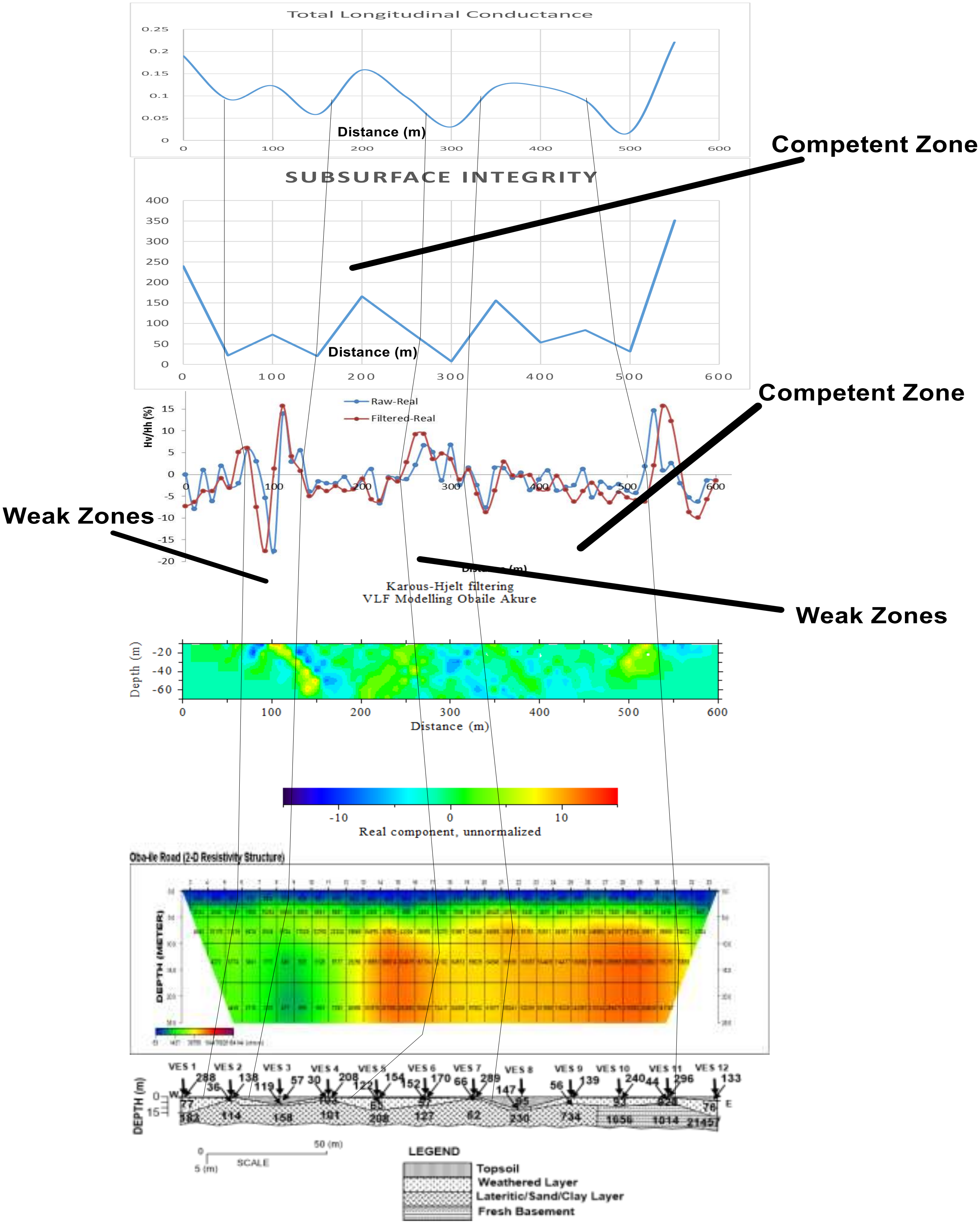

Figure 9. Longitudinal conductance profile, subsurface integrity profile, VLF-EM profiles, 2-D inversion model, resistivity pseudosections and geoelectric section along the study area.

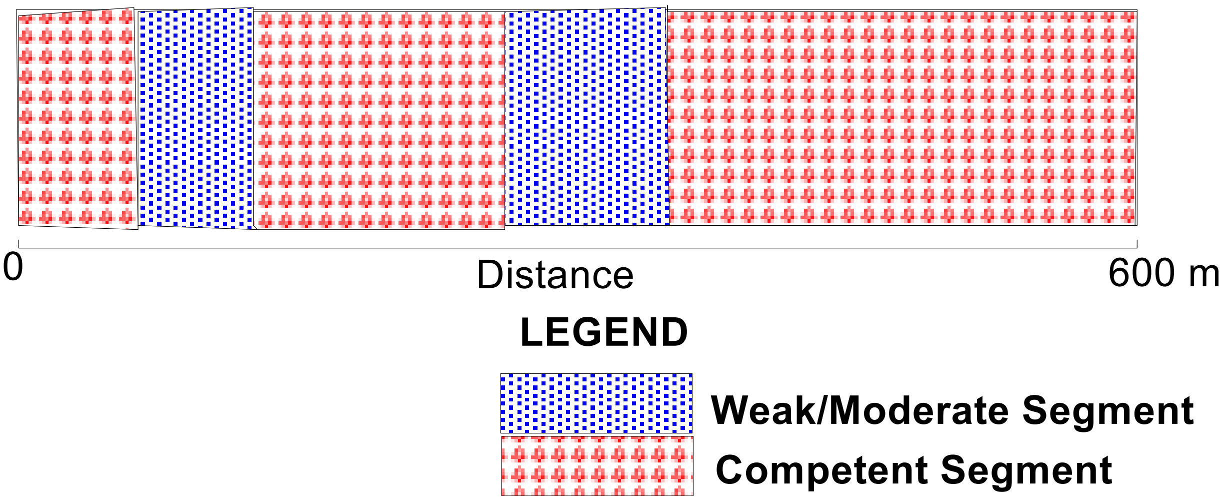

Figure 10. Road section of the study area.

distance between 80 to 110 m, and 280 to 310 m. The high conductive zones delineated by the VLF-EM section at distance between 78 to 112 m, 240 to 305 m also agrees with the low resistivity zone observed on the dipole-dipole pseudosection at a distance 20 to 70 m, 270 to 308 m and geoelectric section at a distance 10 to 80 m, and 260 to 300 m which indicate low integrity and high susceptibility to failure. The total longitudinal conductance is high at distance from 180 to 280 m, and 320 to 460 m which coincide with the high subsurface integrity at distance between 150 to 280 m, and 310 to 480 m. The low conductive zones delineated by the VLF-EM section at distance between 130 to 240 m, and 305 to 520 m also agrees with the high resistivity zone observed on the dipole-dipole pseudo-section at a distance 140 to 170 m, 320 to 510 m and geoelectric section at a distance 80 to 170 m, and 300 to 450 m which indicate high integrity and low susceptibility to failure. These results showed that the techniques used for this study are complementary. So the need to construct our road with a minimum number of years as a guarantee before any failure can occur has never been of priority to our road builders. However, before construction of any road, there must be adequate studies of this nature and bedrock depressions, lateral and vertical inhomogeneities and other diastrophic features on the road alignment should be addressed and accommodated in the design to avoid differential settlement and ensure pavement stability. Figure 10 illustrates the section generated from the integration of the results. The section shows that the competent segment will survive years of stretch durability and stability without any form of intervention program except the weak/moderate segment which needs a proper attention. The weak/moderate segment must be filled with a competent material for proper stability and durability of the road to prevent differential settlement in due time. However, before construction of any road, there must be adequate studies of this nature. All these submission and findings are without prejudice to other probability functions of road/structural failures that are closely related or associated to other geodynamic factors; such as gradual and continuous earth movement, global warming, greenhouse effect which are also of interest to this study but may not have effectively addressed due to limitation beyond the scope of the work and facilities available.

Conclusion

The study has shown the significance of geophysical site investigation for road construction. Geophysics, therefore, remains a very veritable tool which can be applied in civil engineering work. The research shows that a geophysical tool remains a very viable option and a lasting solution to road construction problems anywhere in the world, as all the techniques that were used showed effective correlation. Integration of results from VLF-EM and electrical resistivity method along the road alignment shows that total longitudinal conductance is low at distance from 80 to 100 m, and 280 to 310 m which coincide with the low subsurface integrity at distance between 80 to 110 m, and 280 to 310 m. The high conductive zones delineated by the VLF-EM section at distance between 78 to 112 m, and 240 to 305 m also agrees with the low resistivity zone observed on the dipole-dipole pseudosection at a distance 20 to 70 m, and 270 to 308 m and geoelectric section at a distance 10 to 80 m, and 260 to 300 m which indicate low integrity and high susceptibility to failure. The total longitudinal conductance is high at distance from 180 to 280 m, and 320 to 460 m which coincide with the high subsurface integrity at distance between 150 to 280 m, and 310 to 480 m. The low conductive zones delineated by the VLF-EM section at distance between 130 to 240 m, and 305 to 520 m also agrees with the high resistivity zone observed on the dipole-dipole pseudo-section at a distance 140 to 170 m, and 320 to 510 m and geoelectric section at a distance 80 to 170 m, and 300 to 450 m which indicate high integrity and low susceptibility to failure. These results showed that the techniques used for this study are complementary. The study further revealed that not only clay (which is a process of fracture and weathering), but the nature of clay, is a most probable factor responsible for road failure. No road can be constructed successfully in this area and most other parts of the world with similar formation where clay is a major factor without a thorough geophysical studies and information that will assist the construction engineers. The combination of these techniques has proved effective and useful in road construction projects and in shallow subsurface investigations. The added advantage of this integrated approach in road construction is the location of geomaterials that could be used as aggregates. This is crucial to the success and overall economy of the project. The methodology can be adopted as a mode to efficiently and quickly detect changes in subsurface resistivity, integrity and identify anomalous zones which can then be investigated by baseline or other complementary technologies. It should be applied to reduce the costs and increase the efficiency of site characterisation in road construction projects.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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