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Evaluation of road failure vulnerability section through integrated geophysical and geotechnical studies



K.A.N. Adiat, A.A. Akinlalu*, A.A. Adegoroye

Applied Geophysics Department, Federal University of Technology, Akure, Ondo, Nigeria

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ABSTRACT

In order to investigate the competence of the proposed road for pavement stability, geotechnical and geophysical investigations involving Land Magnetic, Very Low Frequency Electromagnetic (VLF-EM) and Electrical Resistivity methods were carried out along Akure-Ipinsa road Southwestern Nigeria. The magnetic profile was qualitatively and quantitatively interpreted to produce geomagnetic section that provides information on the basement topography and structural disposition beneath the proposed road. Similarly, the VLF-EM profile was equally interpreted to provide information on the possible occurrence of linear features beneath the study area. These linear features pose a potential risk to the proposed road as they are capable of undermining the stability of the pavement structure. The geoelectric parameters obtained from the quantitative interpretation of the VES data were used to generate geoelectric section. The geoelectric section generated shows that the study area was underlain by four geoelectric layers namely the topsoil, the weathered layer, the partly weathered/fractured basement and the fresh basement. The major part of the topsoil, which constitutes the subgrade, is characterized by relatively low resistivity values ($<100 \Omega\text{m}$) suggestive of weak zones that are capable of undermining the stability of the proposed road. This therefore suggests that the layer is composed of incompetent materials that are unsuitable for engineering structures. Furthermore, fractured basement was also delineated beneath some portion of the proposed road. Since fracture is a weak zone, its presence can facilitate failure of the proposed road especially when it is occurring at shallow depth. The geotechnical results reveal that most of the investigated soil samples are clayey in nature. Integration of the results demonstrates that there is a good correlation between geophysical results and the geotechnical results. Furthermore, a vulnerability section that divided the road segments into three zones based on the degree of vulnerability was produced. These zones were high, moderate and low vulnerability zones. It is estimated that about 60% of the road segments constitutes moderate degree of vulnerability while 30% and 10% of the segments respectively constitute high and low degree of vulnerability.

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1. Introduction

Although virtual connectivity has become increasingly important with the emergence of new communication avenues, a good

and reliable transport network remains vital. Roads are integral part of the transport system. Road transportation is an important element in the physical development of any society as it controls the direction and extent of development. Furthermore, road plays a significant role in achieving national development and contribute to the overall performance and social functioning of the community. It is acknowledged that roads enhance mobility, taking people out of isolation and therefore, leads to poverty. Since there is a very strong positive correlation between a country's economic development and the quality of its road network, a country's road network should be constructed in an efficient way in order to maximize economic and social benefits (Ighodaro, 2009).

Though road usage, construction practices and maintenance have been reported to be responsible for road failures (Adegoke-Anthony and Agada, 1980), field observation and laboratory

* Corresponding author.

E-mail addresses: kanadiat@futa.edu.ng (K.A.N. Adiat), aaakinlalu@futa.edu.ng, ayokunleakinlalu@gmail.com (A.A. Akinlalu), aaadegoroye@gmail.com (A.A. Adegoroye).

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experiments have shown that road failures are not primarily due to road usage, inadequate supervision, poor construction materials, non compliance to specifications/design problems alone but can equally arise from inadequate knowledge of the characteristics and behaviour of residual soils on which the roads are built (Ajayi, 1987). Consequently, geological and geophysical experts have often emphasized lack of adequate information on the nature of subsurface conditions prior to construction as a major contributor to this phenomenon. After all, every engineering structure is seated on geological earth materials (Mesida, 1987; Ajayi, 1987; Momoh et al., 2008; Oladapo et al., 2008; Adiat et al., 2009., Adeyemo and Omosuyi, 2012). Studies have identified that the non recognition of the underlying geology in the design of these roads as a major factor causing incessant road failure in Nigeria (Momoh et al., 2008; Oladapo et al., 2008). Geological factors such as the nature of topsoil (subgrade) and the near surface geologic sequence, existing geological structures such as fractures and faults, existence of ancient stream channels, and shear zones constitute geohazards that can impair stability of any road structure. Hence, it is imperative that these factors are properly investigated prior to any road construction. In view of this, the study attempts to undertake geophysical and geotechnical investigations of a proposed road linking Akure and Ipinsa, Southwestern Nigeria.

A lot of reasons have been suggested for the incessant failure of roads in Nigeria. These include presence of expansive clays such as montmorillonite, chlorite, halloysite, etc. (Mesida, 1986; 1987), heterogeneity of the subgrade materials (Adeleye, 2005; Mesida, 1987), presence of undetected linear features, such as joints, fractures and rock boundaries (Momoh et al., 2008). In the past two decades, the field of geophysics has proved quite relevant in highway site investigations (Nelson and Haigh, 1990). However, in an attempt to unravel causes of persistent failure of roads across the country, various researchers have identified chiefly the underlying geologic conditions among the other factors to be responsible for this mishap (Momoh et al., 2008; Oladapo et al., 2008; Adiat et al., 2009). It therefore becomes imperative to investigate the subsurface geology upon which a road structure is to be founded rather than having recourse to a post-construction investigation and remedies. In this study, the geophysical and geotechnical techniques were integrated to examine conditions of subsurface beneath a proposed road within the basement complex of Southwestern Nigeria. This study is carried out with the following purposes:

- i. To determine the nature of soils and the near-surface geologic sequence that characterize the proposed road segment.
- ii. To identify the presence of geologic structures such as fractures, faults, geologic contacts/joints and other weak zones that can make the road vulnerable to failure after construction.
- iii. To determine the geotechnical properties of the soil underlain the proposed road and their implications on the integrity/stability of the proposed road.
- iv. To demonstrate that there is a good correlation between geophysical and geotechnical results and
- v. To produce the Road Failure Vulnerability Section (RFVS) through the integration of the geophysical and geotechnical results; this hitherto had not been reported in the literatures.

It is important to add that RFVS will serve as a conceptual model that can be easily interpreted and understood by the engineers. Furthermore, such section will be extremely useful for the engineers in the final design and development of the road without having to understand the technicalities that are often involved in the interpretation of geophysical results presentation formats.

1.1. Geology, hydrogeology & geomorphology of the study area

The proposed road is located in Akure, capital city of Ondo State, Southwestern Nigeria. It is expected to link the city with Ipinsa town within the metropolis. It lies within latitudes 7°18'20"N and 7°19'25"N and longitudes 5°8'15"E and 5°8'48"E. The proposed road is about 1030 m long. The terrain is gently undulating with topographic elevation ranging between 350 and 353 m above sea level (Fig. 1).

The proposed road is underlain by the Precambrian Basement Complex of Southwestern Nigeria (Rahaman, 1988), comprising of two major petrologic units namely biotite granite and migmatite gneiss (Fig. 2). The biotite granite essentially covers the major part of the study area, occurs as a flat-lying shallow rock mass in most places. The migmatite gneiss however, is observed to occur within a small section of the area in the northern part (Fig. 2). This lithologic unit is characterized by bands of quartzite that extends over 500 m. These rock units have weathered extensively especially, the biotite granite, where shallow units are observed to crumble easily during geotechnical sampling.

Granite is defined by the American Society for Testing and Materials (ASTM) as a visibly granular, igneous rock. Generally, it varies in colour from pink to light or dark grey, and it is mostly consists of quartz and feldspars and always accompanied by one or more dark minerals. This definition thus suggests that some dark granular igneous rocks, though not properly granite, are included in the definition.

In addition to the quartz and feldspars, granite may also contain other minerals such as mica, hornblende and occasionally pyroxene. Unlike calcareous sandstones, marble and limestone, granite is not an acid soluble stone and is much more resistant to the effects of acidic solutions, rainwater or cleansing agents. Granite is often characterized or associated with some geotechnical problems; such problems, among other things, can make any engineering structures founded on it to be vulnerable to failures. Such problems include but not limited to the following:

- i. Blistering: This is a swelling on the surface resulting from a rupturing of a thin, uniform skin. Although it is mostly common in sandstone, problem of blistering may also occur with granite. It is typically caused by de-icing salts and/or ground water; hence, it is usually localized near ground level. This condition may stabilize and remain constant. Currently, there is no any established treatment except to rectify the conditions that cause the blisters.
- ii. Chipping: This refers to as the separation of small pieces or larger fragments from a masonry unit, in most cases, at the corners, edges or mortar joints. These fractures are generally caused by the impact of deterioration and repairs, especially the use of too hard a pointing mortar, or by accident or vandalism.
- iii. Cracking: This includes the occurrence of narrow fissures ranging from less than 1/16 to 1/2 in. or more wide in the stone. Structural overloading due to settlement, among other factors, can be the cause of cracking. Though, cracking may not be a problem in and of itself, but it can be an important early indication of structural problems. This is because cracks can be a point of entry of water into the interior of the stone, and thereby constituting a weak zone that will undermine the integrity of any structure built on it.
- iv. Erosion: This is the wearing away of the material surface by the natural action of wind, windblown particles and water. This can occur in granite just as it can occur in any exposed material. When it occurs, the erosion plane will constitute geotechnically dangerous zone that must be avoided or taken care of during construction process. Furthermore, the

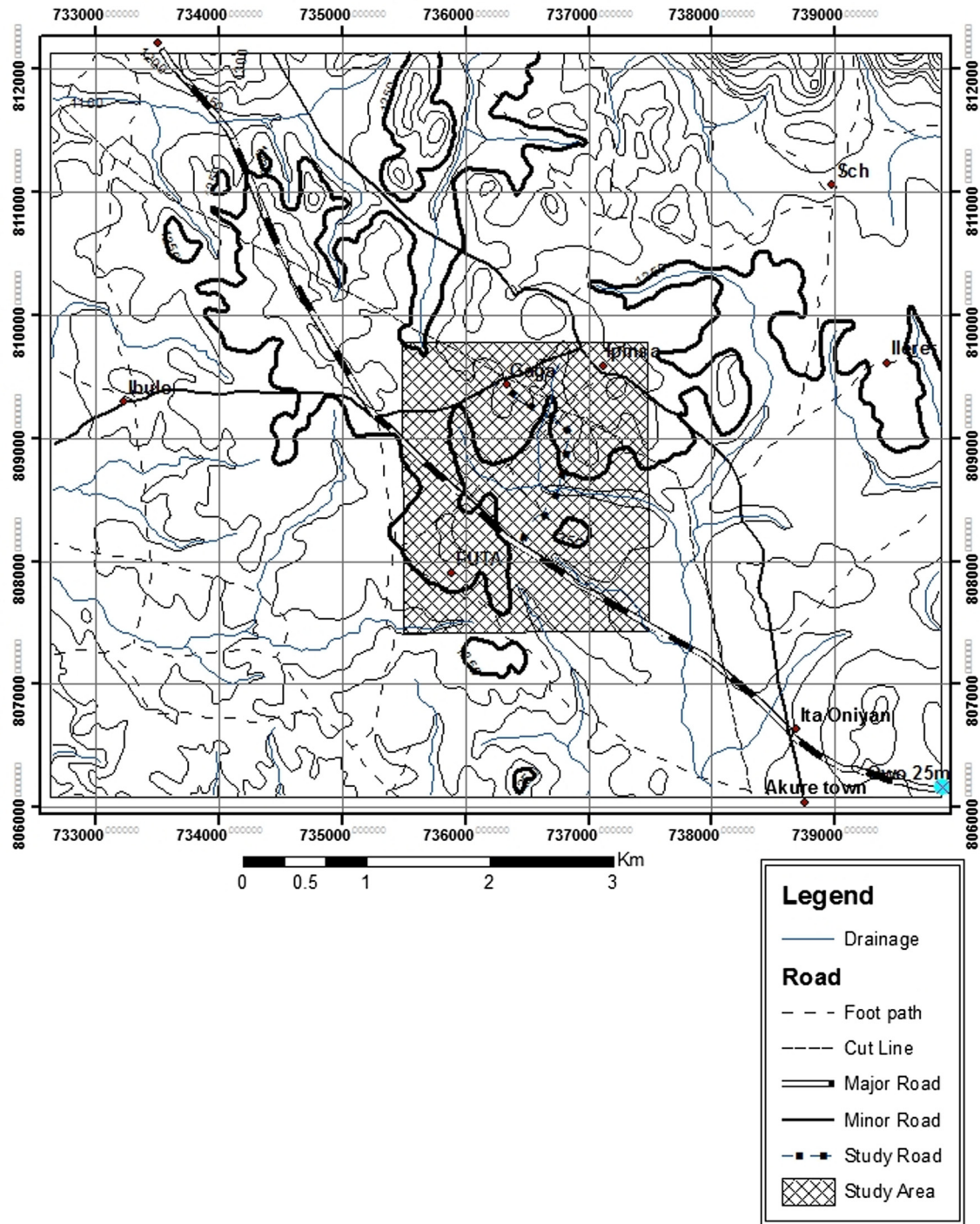


Fig. 1. Topographical map of the study area and its environment (NGSA, 2004).

erosion product will be largely clayey in nature because the mineralogical compositions of granite (i.e. quartz, feldspars, mica, hornblende and pyroxene) are essentially similar to those of clay.

From the reports obtained from previous studies in the area and field observation, it is established that groundwater is abstracted from the weathered regolith and the fractured zones below the weathered layer or within the fresh basement (i.e. weathered regolith and fractured basement aquifer types). These aquifer types usually characterize typical basement complex of the

Southwestern Nigeria (Olorunfemi and Fasuyi, 1993). It was however observed that hand dug wells are the major source of water for the resident of the area. In most cases, the weathered regolith is the major aquifer unit for these wells and the total depth of the wells varies from 3 m to 10 m. This therefore suggests that the water table in the area is relatively shallow and this might facilitate the vulnerability of the proposed road to failure.

Akure is characterized by two seasons, the wet and dry seasons. The wet/raining season extends from April and October, while the dry season lies between November and March. The average annual rainfall is about 1300 mm while the annual mean daily

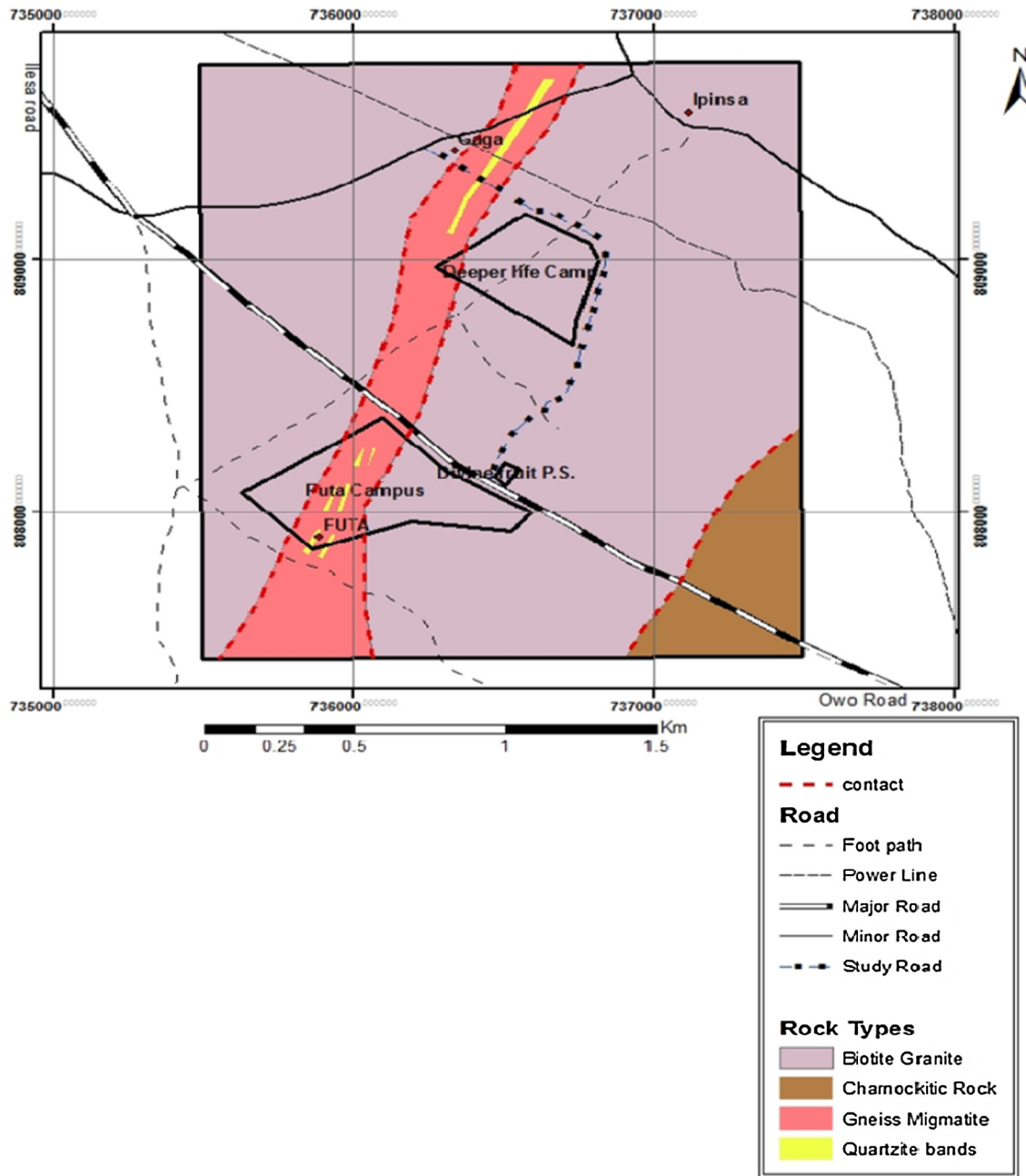


Fig. 2. Geological map of the study area (after, NGSA, 2004).

temperature is 33 °C. Evaporation is usually low from June to September, ranging from 3.3 mm to 4.0 mm per day. Sunshine duration is short (2.7 to 2.9 h per day) during the month of July to September, while the relative humidity ranges from 5.0 to 90% depending on the season (Owoyemi, 1997).

2. Material and methods

The geophysical data was acquired by carrying out the land Magnetic, Very Low Frequency Electromagnetic (VLF-EM) profiling and Electrical Resistivity Methods in the form of the Vertical Electrical Sounding (VES).

The land magnetic survey involves magnetic measurements at an interval of 10 m along the established traverse parallel to the proposed road. A base station was established outside the study

area. The base station readings were taken before commencement of measurement and immediately after the measured last station to do diurnal corrections.

The total field obtained from the land magnetic data can be considered to be the sum of a regional field and the anomaly due to the point source (Durrheim and Cooper, 1998). Consequently, correction is necessary to remove all causes of magnetic field variation from the observations other than those arising from the local magnetic effect of the subsurface. The corrections include drift correction and geomagnetic correction. The correction procedures are given below:

Drift correction due to diurnal variations:

$$\text{Drift Constant} = \frac{\text{Final Base Reading} - \text{Initial Base reading (nT)}}{\text{Final Base Time} - \text{Initial Base Time (second)}} \quad (1)$$

$$\text{Drift} = \text{Change in Time} - \text{Drift Constant} \quad (2)$$

$$\text{Drift Corrected Reading} = \text{Observed Magnetic Reading} - \text{Drift} \quad (3)$$

The drift value in Eq. (2) is then used to effect correction on the raw magnetic readings station for the individual station to obtain values (Eq. (3)) that truly represent the ambient magnetic field in the area. However, noise from local sources can also perturb the magnetic field such that spikes are observed on these drift corrected values. A three point moving average filter is applied in this case to iterate the spiky field so that the resulting values can be residualized using trend analysis on MS Office Excel 2007. Residualization of the magnetic field is done to remove the regional component of the field such that the net component is a representative of the local magnetic field of the area of study.

$$\text{Residual Magnetic Field} = \text{Drift Corrected Reading} - \text{Regional Magnetic Field} \quad (4)$$

(Regional Magnetic Field for each measuring station was obtained from the trend analysis). The resulting field is plotted in relation with the distance of measurement to yield profile that can be qualitatively interpreted to provide information on the sub-surface geology of the area. The inflection points are diagnostic of structural changes such as geological boundary, basement ridges and depressions, fractures and faults in the subsurface.

Similarly, the very low frequency electromagnetic method (VLF-EM) survey was conducted along the proposed road at an interval of 10 meters using ABEM WADI VLF equipment. Although both the real and quadrature components of the VLF-EM were measured, the real component data, which are usually more diagnostic of linear features, were processed for qualitative interpretation. The raw real VLF data were converted (with the aid of an in-built filtering program provided in the ABEM WADI equipment and a software known as KH Filt version 1.0 (Pirttijärvi, 2004)), into filtered real data in which anomaly inflections appear as peak positive anomalies and false VLF anomaly inflections as negative anomalies (Reynolds, 1997) of the profiles.

The electrical resistivity survey in the form of the Vertical Electrical Sounding was acquired using Schlumberger array. A total of twenty-two (22) stations were measured across the study area. The distance between each station is 50 m (Fig. 3). The electrode spacing was varied between 1 and 65 m. The Ohmega resistivity meter was used to acquire the field data. The resistivity data was presented as field curves (by plotting the apparent resistivity (ρ_a) against AB/2 or half the spread length on a bi-logarithmic paper. The data was interpreted qualitatively by visual inspection of the field curves and further interpreted quantitatively by partial curve matching (Koefoed, 1979) with the help of master curves (Orellana and Mooney, 1966) and auxiliary point charts (Zohdy, 1965; Keller and Frischnecht, 1966) to obtain initial estimates of resistivity and thickness of the various geoelectric layers at each VES location. These geoelectric parameters were used as starting model for a fast computer-assisted interpretation (Vander-Velpen, 1989). The program took the manually derived parameter as a starting geoelectric model, successively improved on it until the error is minimized to an acceptable level. The improved geoelectric parameters were used to generate geoelectric cross section.

Nine soil samples were collected from the study area for geotechnical analysis (Fig. 3). The sampling sites were based on the interpretation results of the Vertical Electrical Sounding. The depth at which all Geotechnical Investigation procedures were conducted was determined by the depth of the undisturbed soil. Soil samples were collected through soil boring conducted using a 4-in. inner diameter hollow-stem auger. Each location was drilled

to a depth of about 1 m and samples are taken at sampling depths of 0–0.3 m, 0.3–0.6 m and 0.6–1.0 m from each pit. The analyses carried out on the samples include sieve analysis, atterberg limits, natural moisture content, compaction and California bearing ratio (CBR) tests.

Mechanical sieving assisted in determining particle size distribution of gravel and sand proportions of dried coarse fraction. Consistency Limit Tests generally known as the Atterberg limits gave the plasticity characteristics of the cohesive fraction of the sieved samples. The consistency limit test includes; liquid limit, plastic limit and linear shrinkage test. The difference between the liquid and plastic limits gave the plasticity index, which is the range of moisture contents over which the soil remains plastic.

California Bearing Ratio (CBR) test, widely used to characterize and select sub-grade materials for use in road construction was carried out. The test was devised by the California Highway Association and it is simply the ratio of the load that cause a penetration of 2.5 mm or 5.0 mm material to a standard load that causes similar penetration on a standard California sample, notably 13.24 kN and 19.96 kN respectively. CBR tests were carried out and swelling of samples was carefully monitored during the 96 h of soaking period to assess the likely effect of water ingress on the swelling of base material. The samples were compacted at the modified American Association of State Highway and Transportation Official (AASHTO) level as described under procedure for compaction test in a standard CBR mold (Osinowo et al., 2011).

3. Results and discussions

The plot of the residual magnetic field against the distance along the investigated traverse of the investigated road is as shown in Fig. 4. The residual magnetic field is characterized by field intensities ranging between –549 and 557 nT which culminates into conspicuous changes in gradient consisting series of magnetic highs and lows observed across the entire profile. However, several anomalies with considerable variations in magnetic field intensities have been identified at varying positions along the profile. These anomalies are essentially characterized by peaks and troughs that are suspected to indicate magnetic sources in the subsurface (Reynolds, 1997). These magnetic sources could be related to fractures/faults and other weak zones that are capable of precipitating failure of overlying road structure.

Fig. 5 shows the quantitative interpretation of the magnetic profile using 2D Euler deconvolution which calculates the depth and location of magnetic sources by solving homogeneous equation of the Euler deconvolution. The horizontal and vertical gradients of the field data were calculated and plotted with the original data in order to accentuate the shallow anomaly sources and their edges. These in all provide a means of unraveling the structural disposition and the basement topography beneath the investigated road. Good point solutions were derived from the structural analysis using structural index of 1, which indicates possible presence of fractures/faults beneath the investigated road (Fig. 5c). Other structural indices (2, 2.5 and 3) applied for the interpretation could not provide reasonable clusters of solutions that can confidently be related to an idealized target.

The corresponding geo-magnetic section beneath the proposed road was generated by connecting the data to their individual sources and was presented in Fig. 5d. The section depicts the undulating nature of the basement topography which is characterized by depth to basement ranging between 5.4 and 11.6 m. The section equally reveals five suspected fractures/faults located at 160, 220, 370, 410 and 800 m respectively. The location of these suspected fractures/faults is consistent with the location of anomalies that

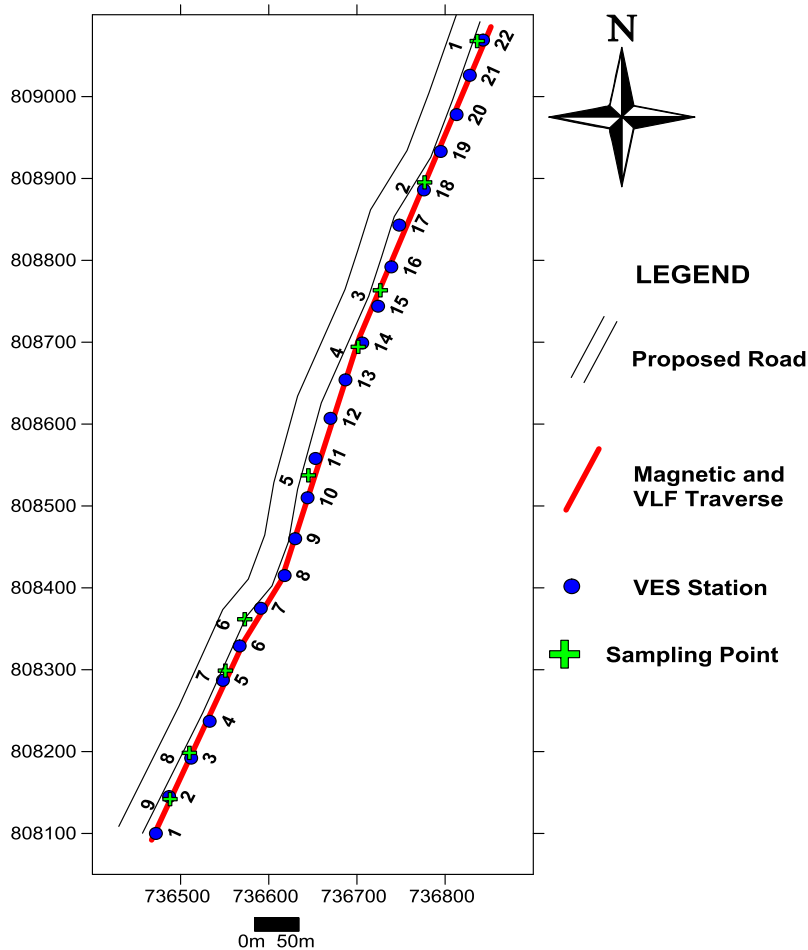


Fig. 3. Data acquisition map of the study area showing the magnetic measurements, VLF-EM traverse, vertical electrical sounding station and soil sampling points.

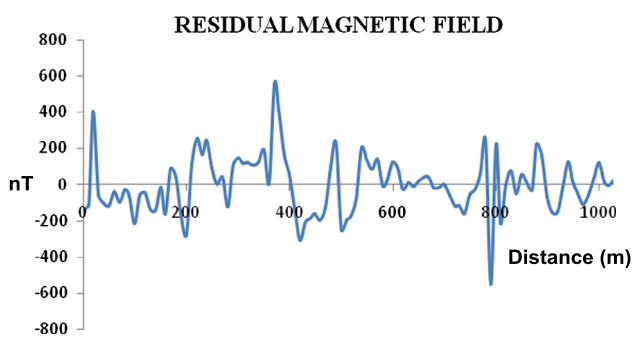


Fig. 4. Residual magnetic profile along the proposed road segment.

were qualitatively suspected on the profile. It is important to note that the symmetry of the anomalous field inform the orientation of the suspected structures (Reynolds, 1997).

The composite plots of the raw real and Q-factor (i.e. filtered real) are presented in Fig. 6a. The profile is qualitatively interpreted to provide location of conductive zones that are indicative of fractures within the subsurface. The coincidence of the inflection points of the raw real with the positive peaks of the filtered real gives indication of these conductive zones (Nabighian, 1982; Adiat et al., 2009). These conductive zones (indicated by vertically

downward arrows) are probably indicative of fractures/faults or other weak zones in form of clayey overburden were delineated along the profile as shown in Fig. 6a. These fractures are weak zones that can serve as conduits for the passage of underground water and thus facilitate the failure of the proposed road if not properly handled during construction.

It is obvious that there is a similarity in the results obtained from both the magnetic and electromagnetic methods; it is however important to add that little or no magnetic susceptibility contrast between the causative bodies and host rocks might account for the reason why the features observable on the VLF-EM profile at stations 30 and 110 were not observable on the magnetic profile at these stations. Furthermore, lateral displacement of the causative bodies occasioned by filtering of the VLF-EM raw data also account for the little variation in the position of occurrence of the features observable on the profiles.

Fig. 6b shows the Karous-Hjelt filter 2-D inversion current density plots for the VLF-EM profile which provides a pictorial indication of various current concentrations and the spatial distribution of subsurface geologic features. The conductors are indicated by the positive current density distribution (green to red colour) and are interpreted as possible fractures beneath the subsurface. These suspected fractures are observed to be dipping in both northeast-southwest and northwest-southeast directions (shown as red coloured lines in Fig. 6b). These fractures coincide with the suspected fractures qualitatively interpreted on the VLF-EM profiles above. The presence of the features characterized by negative current density (blue colour) could not necessarily mean a resistive

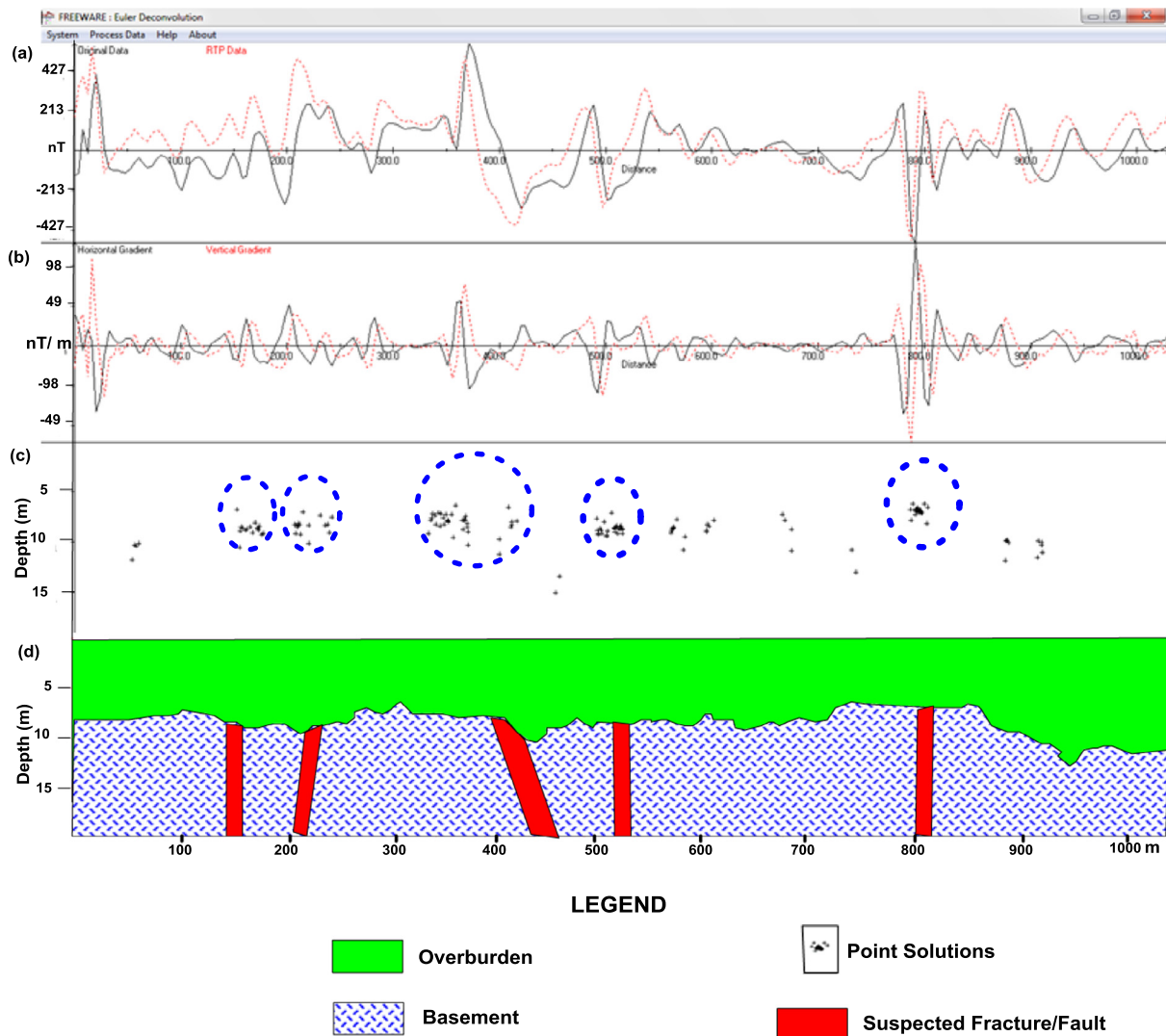


Fig. 5. Euler deconvolution interpretation of the ground magnetic profile along the proposed road traverse.

structure but might be due to the length of the filter or by a decrease of current density due to current gathering which is not present in 2D structures (Nabighian, 1982).

It is however important to add that the limitation of the software used to process the VLF EM data is the exaggeration of depth of probe particularly when the profile is long. (The longer the length of the profile, the more the depth is exaggerated). Consequently, the estimated depth as obtained from the VLF EM interpretation will not be used in the discussion of results. The VLF EM was merely used to delineate the presence of near surface linear features

Table 1 shows the summary of the interpreted VES results in the study area. The interpreted VES results were used to generate the geoelectric section for the area. Three curve types were obtained from the area and these were the A, H and KH curves types (Fig. 7). This suggests, among other things, three possible scenarios. The first scenario is that the study area is characterized by the occurrence of fresh basement at a very shallow depth as observed in the third geoelectric layer of Fig. 7a. Secondly, some parts of the investigated area are underlain by three geoelectric layers with the second layer being the weathered basement layer. This can also increase the vulnerability of the road to failure particularly if the depth to the weathered basement layer is shallow

with the evidence of water saturation in the layer as obviously shown in Fig. 7b. The third scenario represents the occurrence of fractured basement as seen in the third geoelectric layer of Fig. 7c. The presence of fractured basement can also undermine the integrity of the proposed road if not properly handled during construction.

The geoelectric section shows the variations of resistivity and thickness values of the subsurface layers and this would provide information on the geoelectric sequence with the penetrated depth in the study area. Generally, the constructed sections revealed the presence of four geoelectric layers. These layers are: the topsoil, the weathered layer, partly weathered/fractured basement and the fresh basement (Fig. 8).

The topsoil has resistivity values ranging between 23 and 540 Ωm and its thickness vary from 0.9 to 2.5 m. These resistivity values correspond to clayey sand, sandy clay to laterite. The major part of the topsoil is characterized by relatively low resistivity values (<100 Ωm) suggestive of weak zones that are capable of undermining the stability of the proposed road. The weathered layer beneath the topsoil is characterized by resistivity values that range between 37 and 422 Ωm and its thickness varies from 1.2 to 15.7 m. The low resistivity values of this geoelectric layer correspond to clay, clayey sand and sandy clay where the clay is predominant

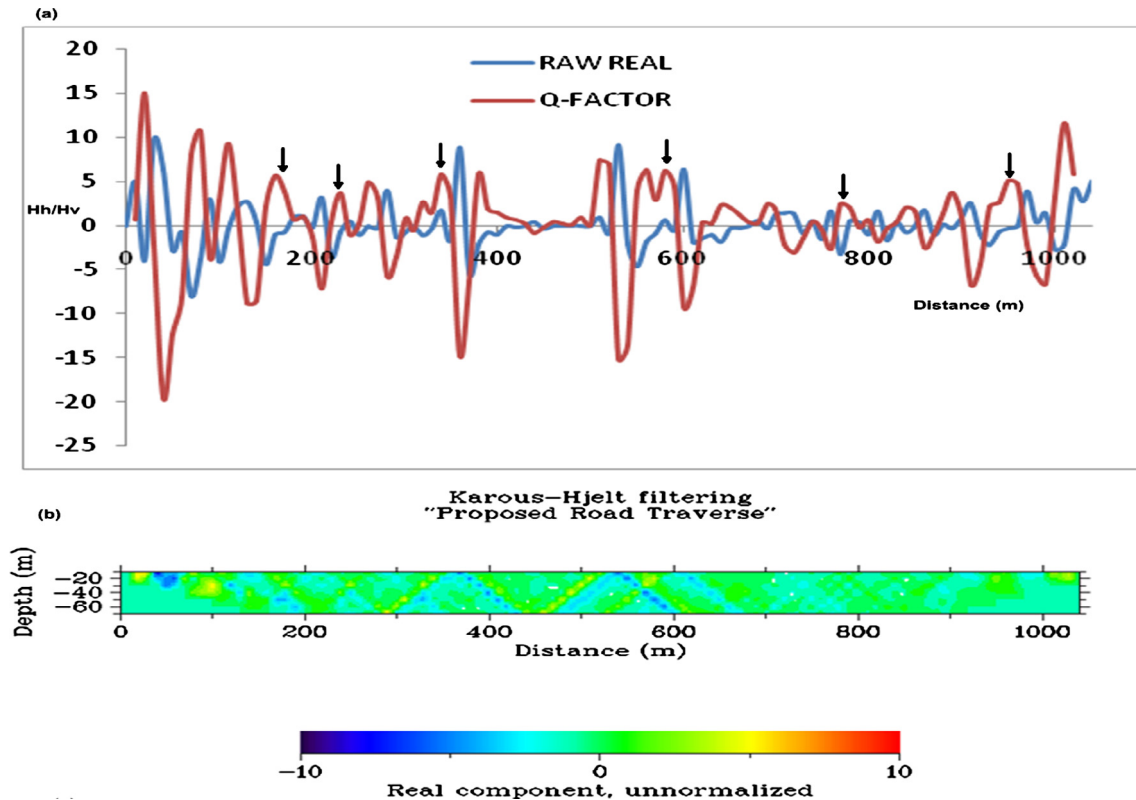


Fig. 6. VLF-EM profiles along failed road traverse (a) Raw Real Vs Q-Factor, (b) 2D Inverted model.

Table 1
Summary of VES interpretation results.

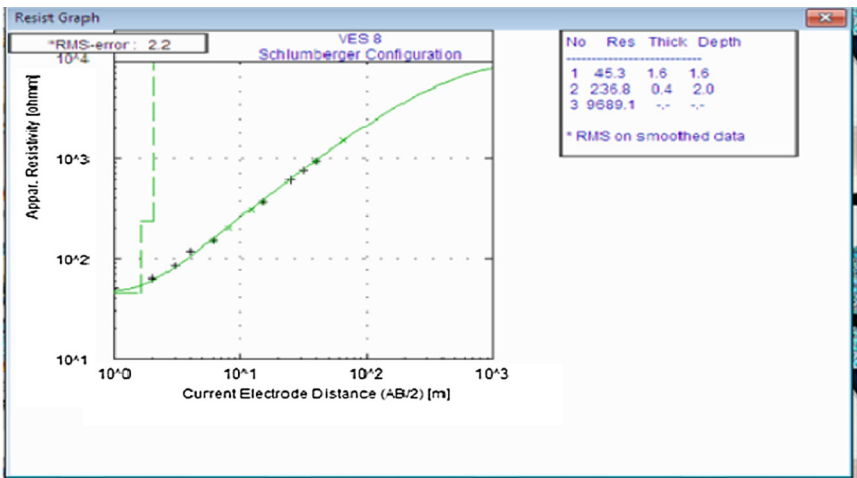
VES	Layer thickness (m)			Layer resistivity (Ω -m)			
	h_1	h_2	h_3	ρ_1	ρ_2	ρ_3	ρ_4
1	0.7	1.1	7.6	23	386	38	1239
2	1.2	10.9		54	126	∞	
3	0.9	1.1	3.8	76	329	37	352
4	2.1	9.1		52	114	384	
5	0.8	0.8	5.2	47	151	56	∞
6	1.7	15.7		88	422	7260	
7	1	5.3		73	137	5072	
8	1.6	0.4		45	237	∞	
9	0.9	1.2		52	201	1132	
10	0.7	1.2	9.4	79	540	85	∞
11	1	11.9		89	302	∞	
12	1.3			110	2200		
13	1.1	2.8		42	79	3141	
14	0.8	8.2		96	216	∞	
15	2.2	4.3		73	379	∞	
16	2.5	3.7		92	402	∞	
17	1	0.9	6.1	112	5614	268	∞
18	0.9	1.3		94	45	∞	
19	1.3	3.2		174	132	2013	
20	0.9	4.2		49	93	1169	
21	1	2.1		71	44	388	
22	1.4	7.9		103	182	614	

along the section. This clayey layer is a poor engineering material (characterized by low resistivity value $<100 \Omega\text{m}$) and is potentially inimical to the stability of the road structure. On the other hand, these low resistivity values may be attributed to the water saturation of these weathered zones. However, the last observed geoelectric layer of fresh basement. This basement sometimes has fractures in its upper part at some locations. The resistivity values of these fractured parts vary from 352 to 514 Ωm . These resistivity values correspond to water-bearing fractured basement. The presence of

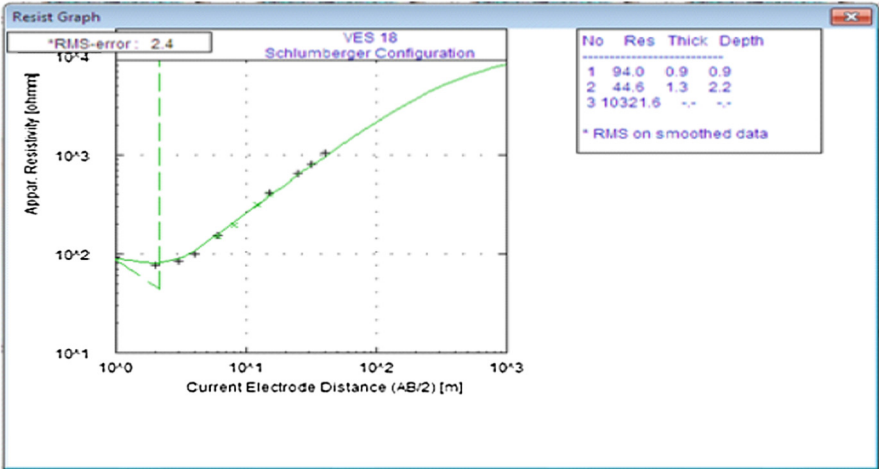
this layer constitutes weak zones and brings the bearing capacity of the bedrock under question. Meanwhile the depth to the basement is more than 10 m in some places in the southern parts of the section while, it is generally shallower at the northern part of the section ($<5 \text{ m}$). Characteristic depressions observed in the northern part of the section should be taken into cognizance during the design of the road structure.

Table 2 shows the summary of the geotechnical results. The natural moisture content for the nine (9) samples ranges between 11.1

(a) A Curve Type



(b) H Curve Type



(c) KH Curve Type

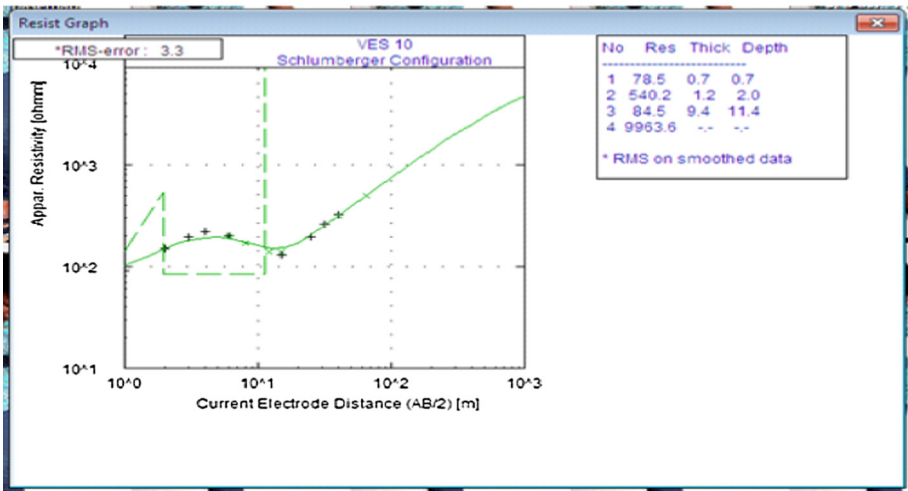


Fig. 7. Typical curves types obtained from the study area.

and 19.6%. These values show that the moisture content of the soils in the area is moderate at its natural state (Oni, 2009). The variation in the natural moisture content can be attributed to the varying soil texture, rainfall intensity and the depth at which the samples were collected. The Atterberg limits (liquid limits, plastic limits and plastic index) tests were carried out along this study

to establish and describe the consistency of the cohesive soil in the area thereby providing useful information regarding the soil strength, behaviour, stability and type and state of consolidation (Mallo and Akuboh, 2012). The results of the liquid limit (LL), plastic limit (PL) and Plasticity Index (PI) for the soil samples investigated as shown on the table show that the liquid limit ranges

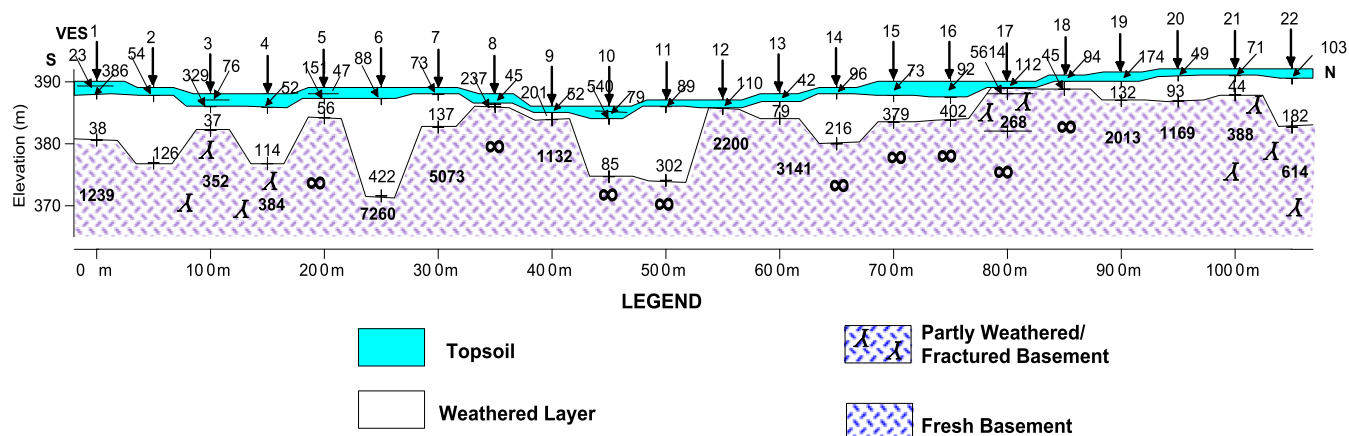


Fig. 8. Geoelectric cross section beneath the proposed road traverse along north-south direction.

Table 2

Summary of the moisture content, consistency and grain size analysis test results.

Sample Code	Moisture content, W (%)	Liquid Limit W_L (%)	Plastic Limit W_p (%)	Plastic Index PI (%)	% of Soil Passing No 10 sieve	% of Soil Passing No 40 sieve	% of Soil Passing No 200 sieve	Group Index GI	AASHTO Classification	USCS Classification code
L1	12.4	33.3	28.2	5.1	49.8	39.1	17.7	0	A-1-b	GCL
L2	11.1	26.9	21.9	5	85	69	30.2	0	A-2-4	SCL
L3	17.3	41.6	22.4	19.2	98.7	85.6	43.1	4.3	A-7-6	CL
L4	14.4	28.8	21.4	7.4	96.8	78.5	23	0	A-2-4	SCL
L5	16.1	44.5	23.9	20.6	97.6	82.7	45.8	5.7	A-7-6	CL
L6	14.4	38.9	19.1	19.8	97.4	81.6	39.5	3.3	A-2-6	CL
L7	19.6	43.8	20.2	23	98.7	87.1	47.6	7.2	A-7-6	CL
L8	16.3	41.9	20.4	21.5	100	89.6	43.6	5.1	A-7-6	CL
L9	18.6	52.4	21.3	31.1	98.8	89.2	56.4	14.3	A-7-6	CH

GCL-Gravelly clay of low Plasticity.

SCL-Sandy Clay of Low Plasticity.

CL- Clay of Low Plasticity.

CH-Clay of High Plasticity.

between 26.9 and 52.4, while the plastic limit and plasticity index range from 19.1–28.2% and 5.0–31.1% respectively. The values of the liquid and plastic limits are generally high and indicate the clayey nature of the soil samples. However, according to the guideline of [Nigerian Federal Ministry of Works and Housing \(1997\)](#), the liquid limit should not exceed 35% to be suitable for use as sub-grade and sub-base or base course materials. Hence samples 1, 2 and 4 are the only samples that can be regarded as fairly good for sub-base or base course materials. Generally, soils with high liquid limit (LL) are clays with poor engineering properties too weak in strength. Soils with intermediate plasticity index (0–20%) would make better engineering properties and thus samples 1–3 and 5 from the study area would make fair to good engineering materials.

The results of the grain size analysis and the grading curves for all the nine (9) samples as presented in [Table 2](#) show that the percentage of soil passings for sieves 10, 40 and 200 ranges from 49.8–100%, 39.1–86.6% and 17.7–56.4% respectively. It could be observed that most samples demonstrate more than 35% finer passing (sieve 200) which indicates that they are clayey in nature. According to the American Association of State Highway and Transportation Official (AASHTO) classification system, samples 1, 2 and 4 which shows less than 35% finer passing are categorized under A-1-b and A-1-4 ([Table 2](#)) and are considered fairly good engineering material.

[Fig. 9](#) shows the integration of the results obtained from the study area. There is high level of correlation among the subsurface models depicted by individual methods with regards to the

basement topography, structural disposition and inferred overburden materials. The magnetic subsurface model depicts that the basement topography is undulating in nature, recording a maximum depth to bedrock of 13 m and subtly characterized by ridges and depressions. This is equally reflected on the geo-electric section which puts the maximum depth to bedrock at 15.1 m. Similarly, structural disposition of the subsurface modeled by the three methods show good correlations. The suspected fault/fractures depicted by the geomagnetic section at about 150, 220, 400, 520 and 800 m respectively can be compared to the geometry of linear features delineated on the K-H pseudo-section at about the same locations. The same structures could also be related with partly weathered/fractured delineated on the geo-electric section most especially beneath VESs 3 and 17. These structures are potential weak zones that are capable of compromising the stability of the proposed pavement structure. Furthermore, the clayey nature of the overburden could be correlated with the conductors that pervade through the K-H pseudo-section. This correlation could equally be more corroborated by the fact that the geotechnical results reflect that most of the soil samples investigated are clayey materials and thus are weak engineering materials. However, samples 1, 2 and 4 which reflects fairly good subgrade materials can be correlated with the resistivity values (generally >90 Ω m) of the topsoil of the associated VES stations (VESs 21, 16 and 14 respectively). This follows that the topsoil resistivity values of the associated VES stations of the net soil samples are less than 80 Ω m, suggesting clayey materials which in turn corroborate the geotechnical results.

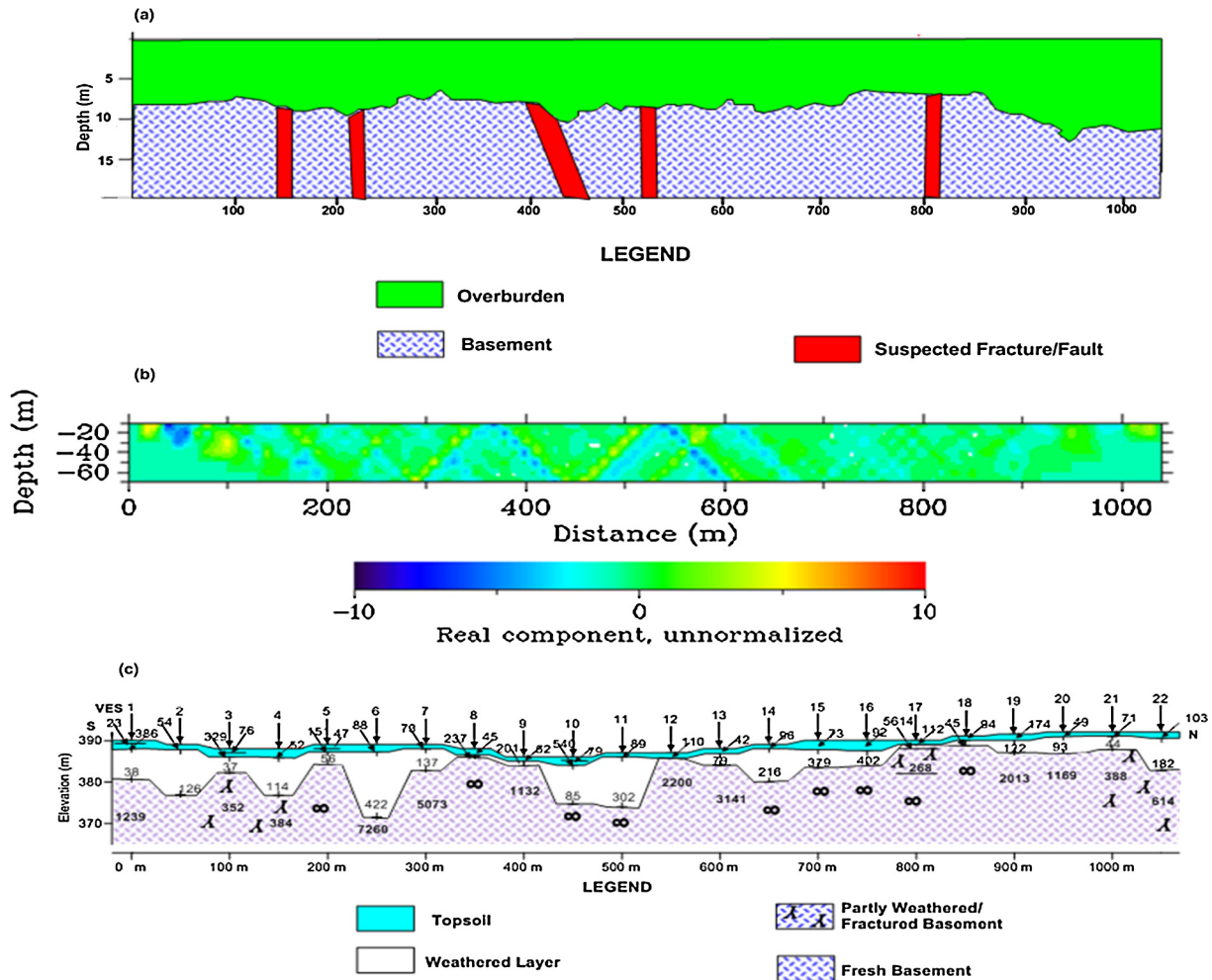


Fig. 9. Correlation of the (a) geomagnetic Section, (b) K-H pseudosection and (c) geo electric section along the proposed road.

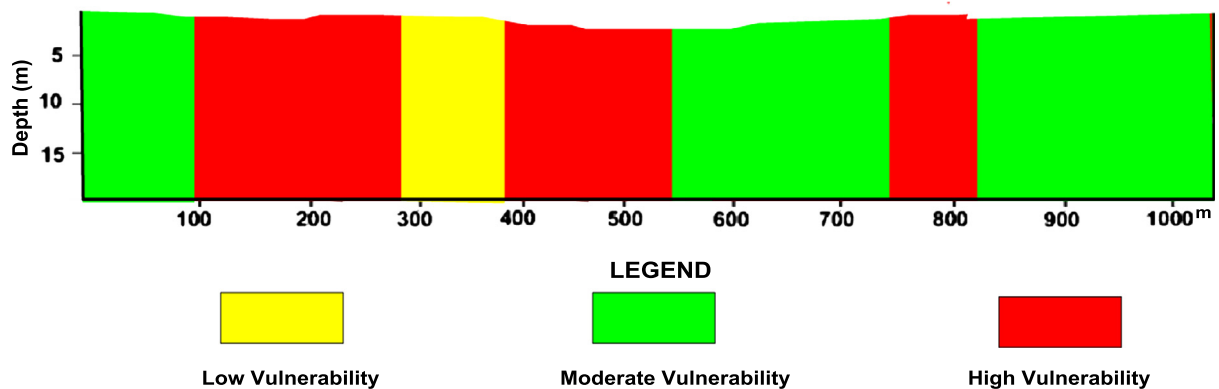


Fig. 10. Road failure vulnerability section for the investigated road.

Finally, the integrated results of geophysical and geotechnical investigations have enabled the development of the road failure vulnerability section of the studied road. The road segments are categorized into three zones of vulnerability to failure. These zones are high, moderate and low vulnerability zones (Fig. 10). It is estimated that about 60% of the road segments is rated to be of moderate vulnerability while 30% and 10% of the segments are rated to be of high and low vulnerability respectively.

4. Conclusion

Integrated geophysical methods involving Land Magnetic, Very Low Frequency Electromagnetic (VLF-EM) and Electrical Resistivity (Vertical Electrical Soundings) and geotechnical methods have been undertaken to investigate the competence of the proposed road for pavement stability along Akure-Ipinsa road Southwestern Nigeria. This was with a view to determining the nature of soils

and the near-surface geologic sequence underlain the proposed road segment as well as identifying the presence of geologic structures that can make the road vulnerable to failure after construction. In addition, determination of the geotechnical properties of the soil underlain the proposed road with their attendant implications on the integrity/stability of the proposed road and development of Road Failure Vulnerability Section (RFVS) through the integration of the geophysical and geotechnical results were also parts of the aim of the study.

Qualitative and quantitative interpretation of the land magnetic profile along the investigated road yielded geo-magnetic section which reveals the undulating basement topography characterized by ridges and depression as well as the presence of suspected fractures/faults. Such suspected fractures were equally delineated on the VLF-EM profiles and the Karous-Hjelt pseudo-section.

Twenty Two (22) VES were acquired along the investigated road segment using Schlumberger array with half current electrode separation varied between 1 and 65 m. The geoelectric parameters obtained from the quantitative interpretation of VES results were used to generate the geoelectric section for the area. The geoelectric section reveals that the study area is underlain by four geoelectric layers namely; topsoil, weathered layer, partly weathered/fractured basement and fresh basement. The major part of the topsoil is characterized by relatively low resistivity values suggestive of weak zones that are capable of undermining the stability of the proposed road. The weathered layer beneath the topsoil is characterized by resistivity values suggestive poor engineering material and thus poses danger to the stability of the road structure. This basement sometimes has fractures thereby making the layer constituting weak zones capable of bringing the bearing capacity of the bedrock under question. The geotechnical results reveal that most of the investigated soil samples are clayey in nature.

A vulnerability assessment of the proposed road segment was done to rate the road segment into three vulnerability zones namely; high, moderate and low vulnerability zones. A vulnerability section was developed from the integration of the techniques adopted for the study. It was established that more than 60% of the road segment is of moderate vulnerability while 30% and 10% of the segments respectively constitute high and low degree of vulnerability.

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