

A Multi-Dimensional Approach to Revealing Causes of Pavement Failures: Case Study of Minna – Suleja Highway, North-Central Nigeria

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Abstract: Remote sensing, geotechnical studies and geophysical data have been applied to determine the causes of the continuous pavement failure of the Minna – Suleja highway in a part of North-Central Nigeria. In this study, remotely sensed data in the form of Landsat 8 OLI and SRTM DEM were processed to extract structural lineaments and drainage pattern of the area. Geotechnical evaluation of soil samples such as grain size analyses, Compaction Test, Atterberg Limits and California Bearing Ratio (CBR) determination were also conducted. Geophysical data acquired were in the form of lateral resistivity profiling data at 500 m intervals and twenty-one Vertical Electrical Sounding (VES) spread across the selected sections of the road. Lineament analysis revealed predominant NNE-SSW trending structures. A notable percentage of the Lineaments trend NW- SE. Both sets of lineaments constitute a conjugate fracture system. CBR values in both portions range from 5 – 15% in soaked condition and unsoaked condition at OMC. Plasticity index range from 14 – 30 and 19 – 45 in both portions. Quantitative interpretation of the VES results established the presence of mostly three geologic layers which are: Clayey top soil, sand/lateritic sand and weathered basement. Resistivity values range from 20 Ω m to 300 Ω m for the top soil layer. The depths of this layer were generally less than 3 m. Preponderance of intersections of lineaments along failed portions account for near surface fractures, making these zones weak. This can be linked to low resistivity of the near surface materials and shallowness of the water bearing zones especially on the failed portions on which the road pavement foundation was laid. A distinction could not be made on the results of the geotechnical properties in both the failed and stable portions of the road. Hence, failure factors are not linked to the geotechnical properties of the soils.

Keywords: Remote Sensing, Lineaments, Geophysics, Geotechnical Investigation, Pavement Failure

1. Introduction

With increasing civilisation, it has become the norm for people to move from one place to another using various means of communication. Urbanisation is one of the chief

factors that contribute to increasing road usage. Vehicular transportation is one of the commonest means by which goods and services are transported and rendered. Because of its significant role in achieving national economic development and contribute to the overall performance and

social functioning of the community, the quality of a country's road network should be constructed in an efficient way in order to maximize economic and social benefits [1]. Several factors have been alluded to deterioration of roads. These include road usage, inadequate supervision, poor construction materials, non-compliance to specifications/design problems, inadequate knowledge of the characteristics and more importantly, the behaviour of residual soils on which the roads are constructed [2]. Non incorporation of geological studies during design and construction of roads have been identified to be the major factor causing incessant road failure in Nigeria [3, 4]. Geological factors such as the nature of topsoil (subgrade) and the near surface geologic sequence, existing geological structures such as fractures and faults and hydrogeology of that area can impair stability of any road structure. Hence, it is imperative that these factors are properly investigated prior to any road construction. Therefore, this research was conceptualised to investigate the causes of the continuous pavement failure of the Minna – Suleja highway in a part of North-Central Nigeria using Remote sensing, geotechnical studies and geophysical data.

This work is aimed at determining the nature of soils and the near-surface geologic sequence that characterize the road segment and identify the presence of geologic structures that has probably made the road vulnerable to failure after construction, the geotechnical properties of the subsurface geologic materials soil and their implications on the stability of the road using geologic, ground based structural mapping, extract lineaments, conduct ground resistivity survey utilising

VES at selected sites using Schlumberger configuration ($AB/2=50$ m) and correlate results from all methods applied in the study and infer the implication to road failures.

2. Study Area

The area of study form part of the south-western portion of Minna Sheet 164 which falls within Chanchaga Local Government Area of Niger State, north-central Nigeria. The area is delimited within Latitudes $9^{\circ} 32' 00''$ N and $9^{\circ} 34' 00''$ N and Longitudes $6^{\circ} 34' 00''$ E and $6^{\circ} 34' 00''$ E. with a total area of about 14 km^2 covered (Figure 1). Geologically, the area consist of rocks of the Basement Complex category of the Nigerian geology. Lithologically, the area is made up of the Granite, Quartzite, Schist and Gneiss with insignificant alluvial deposits. The area has a dentritic drainage configuration with River Gurara as the major River that drain the area which is characterized by tributaries of rivers Kudan, Jatau, Gudna, Jedna and Jednadalaso which are lithologically and structurally controlled [5]. Annual rainfall of the study area averages about 1300 and stretches from the month of April to October. The peak of rainfall is recorded between the months of August and September. The maximum day time temperature is about 35°C in the months of March and April, while a minimum temperature of about 24°C is recorded in the months of December and January.

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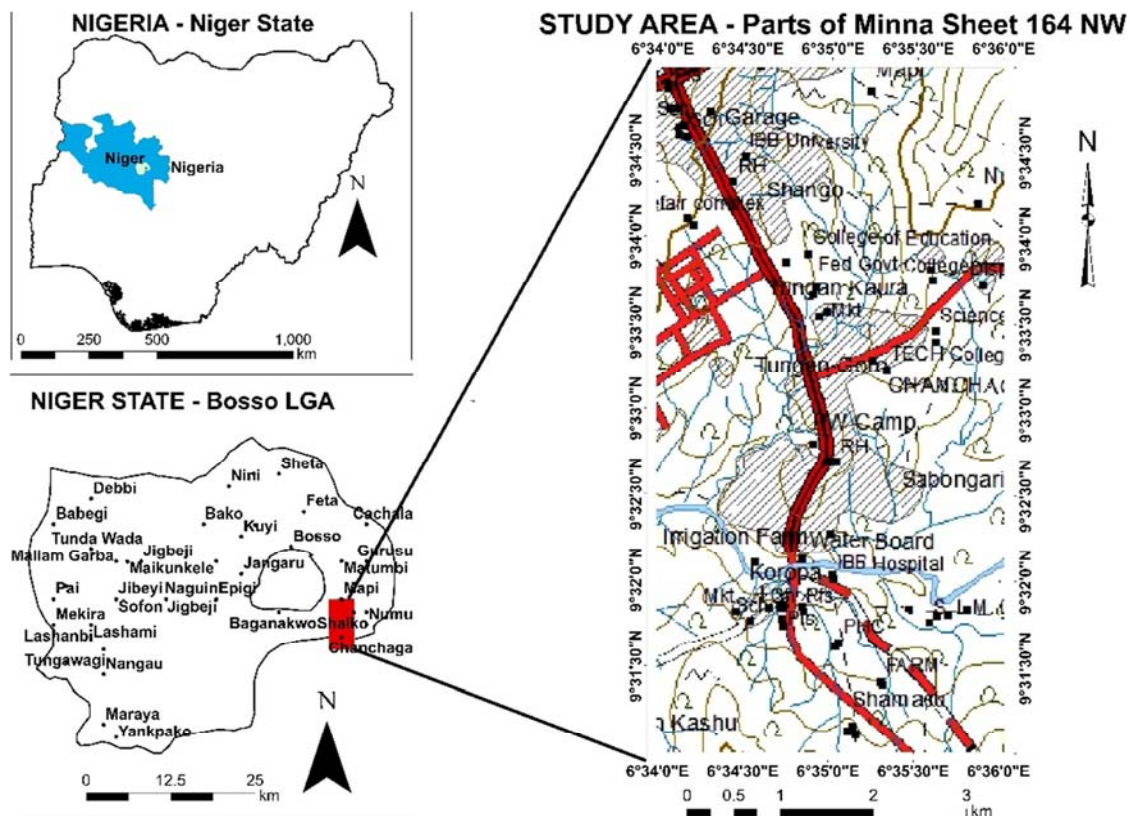


Figure 1. Location map of the study area.

3. Method of Study

Lithological and structural field mapping was carried out on a scale of 1:12,500 where joints and fractures orientations (azimuthal reading) were taken where possible. Hydrogeological conditions of the area was determined by observing the conditions of some selected hand dug wells. Factors such as topography, geographic location, weathering, rock type and structure were considered. Rose diagram showing the predominant joint directions were constructed from these measurements.

3.1. Remote Sensing/Lineament Analysis

A combined version of 5.3 Exelis visual information solutions and ArcGIS softwares (Boulder CO USA and Environmental Systems Research institute CA, USA respectively) were used to perform image processing for both Landsat OLI and SRTM DEM. SRTM shaded relief representations were achieved using sun elevation angle of 25° and 0°, 45°, 90°, 270° and 135° sun illuminations directions, which was oriented perpendicularly to the prominent structural directions. This was done in selected regions so as to enhance the linear structures. Directional and normalised derivatives were also calculated to accentuate near surface structures from which lineaments were identified and delineated. Using ArcGIS software, lineaments were digitized separately from SRTM DEM and Landsat maps and subsequently combined to form a composite of lineaments extracted from remote sensing imagery. These were achieved using the methods of [7-11].

3.2. Electrical Resistivity Survey

The electrical resistivity survey in the form of the Vertical Electrical Sounding was acquired using Schlumberger array. A total of twenty-one (21) stations were occupied across the study area at an inter-station distance of 100 m (Figure 2). The maximum AB/2 electrode spacing was pegged at 200 m. A locally fabricated but calibrated Resistivity meter was used to acquire the 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 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 using IPI2WIN [12]. The software was also used to generate geoelectric cross section of the surveyed areas.

In most geologic materials, ionic strength and control amount of pore water present majorly control the resistivity of the substratum since current is conveyed mostly by flowing ions in the pore water. High water content high ionic strength lead to lower the resistivity. Clay minerals, with their charged surfaces and associated boundary layers of attracted ions, also contribute to low resistivity [13]. Rocks conduct current by means of electrolytic and electronic

conduction. The resistivity of rocks and minerals varies between 10^{-6} and 10^{+14} ohm-m (a range of 10^{20}) when measured through its electrolytic conduction. While electronic conductivity is mainly encountered in minerals, in groundwater studies, electrolytic conductivity is most important. The conductivity is largely controlled by porosity, water content, and water quality [14].

In the VES method, the positions of the electrodes are changed with respect to a fixed point (known as the sounding point). In this way, the measured resistance values at the surface reflect the vertical distribution of resistivity values in a geological section. The VES procedure consists of passing a known amount of current (I) into the ground through two current electrodes, C_1 and C_2 , and measuring the potential difference (V) developed between the potential electrodes P_1 and P_2 . The spacing between the current electrodes is gradually increased while the distance between potential electrodes is increased only when the observed potential difference across P_1 and P_2 becomes quite low [15]. The electrodes C_1 P_1 P_2 C_2 are placed on straight line with C_1 $C_2 \geq 1/5$ P_1 P_2 the apparent resistivity for this array is given by [15].

$$\rho_a = \frac{(C_1 C_2)^2 - (P_1 P_2)^2}{4 P_1 P_2} \left(\frac{\Delta V}{I} \right) \quad (1)$$

Where ρ_a is the apparent resistivity in ohm-m, C_1 C_2 is the current electrode spacing in m, P_1 P_2 is the potential electrode spacing in m, ΔV is the measured potential difference in Volt, and I is the injected current in Ampere.

Schlumberger electrode configuration arrays with a maximum current electrode separation (C_1 C_2) ranging between 80 and 100 m were used. At every VES station, current electrodes were spread out step by step. Apparent resistivity data were calculated and manually plotted in the field for checking the data quality. If distortions or errors appeared in data, measurements were repeated or the current electrode locations were changed to improve data quality. The VES data were plotted on a log-log graph with the electrode separation (C_1 $C_2/2$ or AB/2) on the abscissa and the apparent resistivity (ρ_a) values on the ordinate. The advantages of using a log-log plot are that it emphasizes near surface resistivity variations and suppresses variations at greater depths, simply because interpretation of the results depends largely on the small variations in resistivity occurring at shallow depths.

3.3. Geotechnical Analysis

Nine soil samples were collected from preselected sites based on the interpretation results of the Vertical Electrical Sounding. Sampling depths were determined by the depth of the undisturbed soil using a hand auger to a maximum of 1.5 m. samples were taken at 30 cm intervals. These samples were subjected to 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 [16].

The particular state of consistency of any particular soil depends primarily upon the amount of water present in the soil-water system thereby making the behaviour of soil directly related to the amount of water present. The Atterberg limit represents a water content at which the soil changes from one state to another. The values of the Atterberg limits of the soil samples are shown in Table 1.

Table 1. The values of the Atterberg limits of the soil samples.

Boreholes Label	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Liquidity Index	Soil classification based on the Plasticity Index
BH1	12.5	7	5.5	2.60	Low Plastic
BH2	12.5	13	-0.5	-19.06	Non-Plastic
BH3	11	12	-1.0	-78.41	Non-Plastic
BH4	14.01	9	5.01	19.91	Low Plastic
BH5	15	14	1.0	98.98	Low Plastic

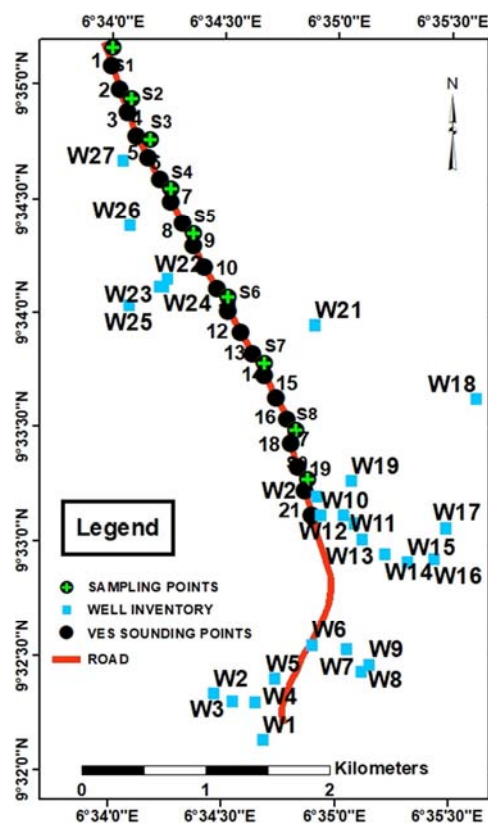


Figure 2. Map showing locations that were occupied for the Vertical Electrical Sounding (VES), soil sample collection and well inventory.

4. Results and Discussions

Linear structures such as fractures and shear zones that characterize the study area have different orientations. Present are the minor N–S fractures which are attributed to

brittle deformation and the twin conjugate sets of NE–SW and NW–SE trends, produced by transcurrent movements [17]. The structural framework of the Nigerian Basement Complex is dominated by the NE–SW lineaments (Figure 3).

The summary of the interpreted VES results in the study area is shown in Table 2. These data were used to produce both the resistivity and pseudo sections for the area. Four major curve types were produced from the area and these are the H, K, KH and HA curves.

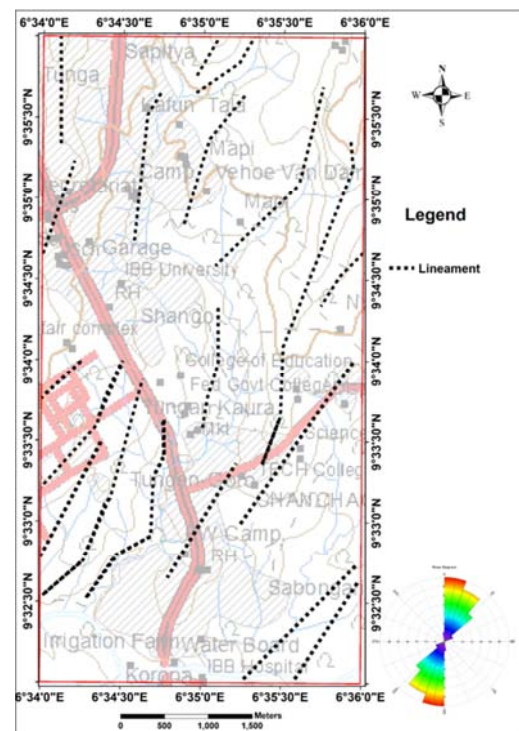


Figure 3. Lineaments extracted from Landsat 8 OLI and SRTM DEM.

Table 2. Summary of VES data interpretation.

S/NO.	VES	LAYER THICKNESS (m)				Layer Resistivity (Ωm)						Curve Type
		d1	d2	d3	d4	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	
1	1	1	2	3		143	8	1451	196			HK
2	2	1	5			84	26	114				H
3	1	2	3	50		32	56	8	59	818		KH
4	1	2	4			276	13	4000	270			HK
5	1	2	3	12	25	28	45	12	140	34	2600	HKH
6	1	7				1000	220	612				H
7	2	3	9	18		260	43	890	91	10000		HKH
8	1	2				183	3	120				H
9	1	2				10	5000	114				K
10	1	2	4			609	989	50	391			KH
11	1	4	11			231	31	15	41			HA
12	1	2	3	13	26	36	222	21	301	67	4000	KHA
13	1	3	15			318	126	58	114			KH
14	2	4				15	717	182				K
15	1	3	47			173	53	290	3200			HA
16	1	2	3			2000	6	4000	60			HA
17	1	2	4			426	1080	26	208			KH
18	1	2	3			15	2000	39	387			KH
19	1	2				5	1000	30				K
20	1	2	3			139	292	17	187			HA
21	1	2	3			150	312	15	220			HA

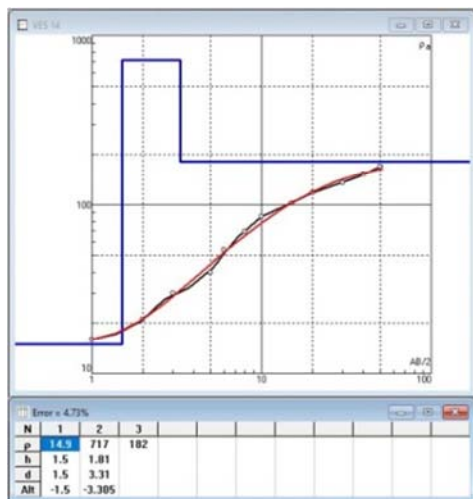


Figure 4. A K-Type curve.

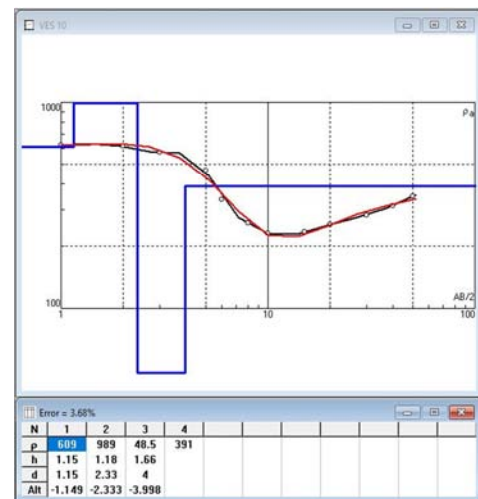


Figure 6. A KH-Type curve.

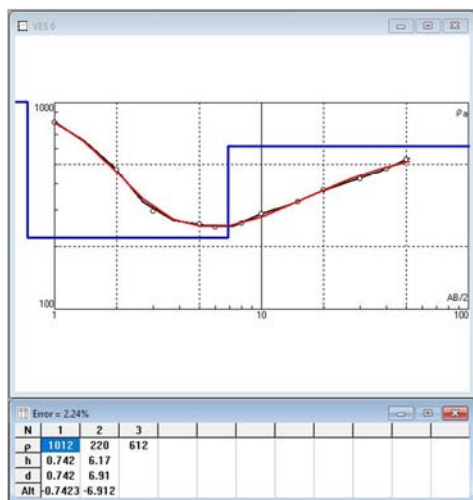


Figure 5. An H-Type curve.

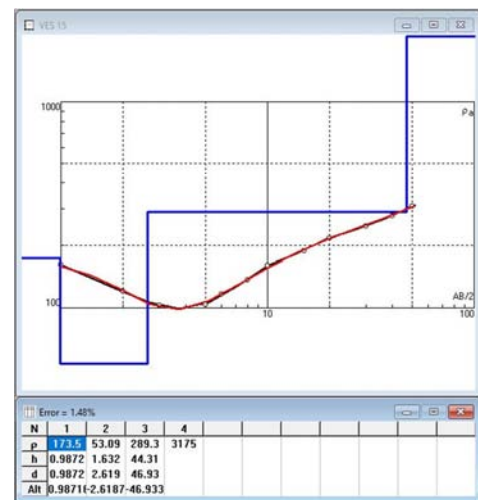


Figure 7. An HA-Type curve.

Several inferences can be made from this. Firstly, three geoelectric layers can be observed in some places as evidenced by the H type curves. This means that parts of the study area is characterized by the occurrence of fresh basement at a very shallow depth as observed in the third geoelectric layer (K type curve) (Figure 4) and some parts of the investigated area have the second layer being the weathered basement layer. This scenario may 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 (H) as obviously shown in Figure 5. The second inference that can be made is that the KH curve type, wherever they occur, represents the occurrence of fractured basement as seen in the third geoelectric layer of Figure 6. The presence of fractured basement may be responsible for the failure of the road if this was not properly handled during construction. The HA curve types (Figure 7) seem ideal in these circumstances. However, it is important to take into consideration the peculiarities of the different curve types and make provision for how it may be tackled during and after the construction of the road.

The resistivity cross section shows the variations of resistivity and depth values of the subsurface layers and this would provide information on the geoelectric sequence with the penetrated depth in the study area (Figure 8). Generally, the constructed sections revealed the presence of three to four geoelectric layers. These layers are: the topsoil, the weathered layer, partly weathered/fractured basement and the fresh basement. The range of the resistivities of the top soil is highly varied with values between 5 Ωm to 2000 Ωm . Thickness varies from 1 m to 7 m. These resistivity values

correspond to clayey sand, sandy clay, laterite to fresh rock outcropping at the surface. Top soil layers having low resistivity values ($<100 \Omega\text{m}$) have the capability of undermining the stability of the road. The weathered layer beneath the topsoil is characterized by resistivity values that range between 37 and 4000 Ωm and their various depths vary from 1 to 47 m. very low resistivities at such shallow depths has the potential of yielding the constructed road to failure. 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 presence of fractures in this layer constitutes weak zones and brings the bearing capacity of the bedrock under question. These factors are to be seriously considered during road maintenance and rehabilitation.

Table 3 shows the summary of the geotechnical results. The Atterberg limits (liquid limits, plastic limits and plastic index) tests sought to establish and describe the consistency of the sampled soils in order to provide useful information regarding the soil strength, behaviour, stability and type and state of consolidation [18]. Liquid Limit (LL) range from 22% to 42% while Plastic Limit range from 2% to 7%. Since the recommended LL for materials to be used as sub-grade and sub-base or base course materials is $\leq 35\%$ [19], samples 7, 8 and 9 failed to meet the standards. 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 and 4 from the study area would make fair to good engineering materials suitable for road construction.

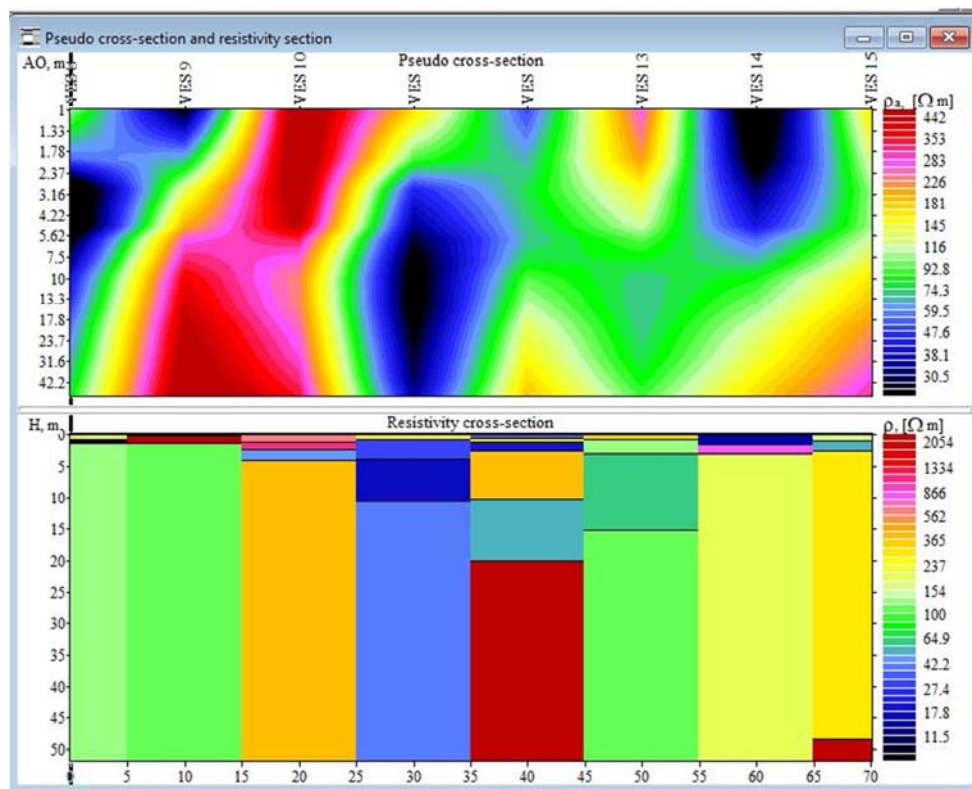


Figure 8. Pseudo and resistivity cross section of the study area.

Table 3. Summary of Geotechnical results from the study area.

Sample	LL (%)	PL (%)	PI	USSC classification	% of Soil Passing	GI
1	28.5	7.3	21.2	CL	18.5	0.392
2	31	6.5	24.5	CL	29.8	2.146
3	23	4.6	18.4	CL-ML	42.9	4.7636
4	22.5	1.8	20.7	CL	25	3.07
5	28	3	25	CL	43.6	6.01
6	35	4	31	CH	38.8	0.76
7	48	2.6	45.4	CH	45.5	2.52
8	45	3.6	41.4	CH	42.2	1.62
9	39.5	5	34.5	CH	55.5	4.1

CL- Clay of Low Plasticity.

CH-Clay of High Plasticity.

Correlation of the results of this study has been able to establish that the constructed road has weak zones that have relatively high water table. This is likely the reason why the sampled soils have poor engineering qualities. Also, the structural attributes of the area indicate the preponderance of shallow fractures along the pavement. This also has been attributed to compound the problem at the failed sections of the road. The degree of vulnerability along different sections of the road depends on the geophysical and geotechnical characteristics.

5. Conclusions

A Multi-dimensional approach to revealing causes of pavement failures in a part of North-Central Nigeria has been undertaken using Remote sensing, geotechnical studies and geophysical data. These were carried out to reveal geologic structures that may be a contributing factor to the continuous failure of the road. Also, the nature of the soils, near surface geologic sequence and their geotechnical properties were investigated to deduce the factors that have been inimical to the integrity/stability of the road.

Twenty-one (21) VES were acquired along the investigated road segment using Schlumberger array with maximum AB/2 separation at 50 m. The geoelectric parameters obtained from the quantitative interpretation of VES results were used to produce the VES curves, resistivity and pseudo sections for the area. Interpreted VES curves revealed several curve types while interpreted geoelectric layers were delineated as topsoil, weathered layer, partly weathered/fractured basement and fresh basement. Most of the topsoil layers are 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. Some portions of the basement are laden with fractures that constitute 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. Integrating the results of the study has enabled the categorization of the road segment into three vulnerability zones: high, moderate and low vulnerability

zones. Most of the road segment fall within the moderate vulnerability zone.

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