

Integration of VLF-EM and VES data for pavement failure investigation in a typical basement complex terrain of southwestern Nigeria

Kombinacija VLF-EM in VES podatkov pri preiskavi poškodb cestišča na magmatsko-metamorfni podlagi jugozahodne Nigerije

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Abstract

Geophysical investigations involving very low frequency electromagnetic (VLF-EM) and vertical electrical sounding (VES) techniques were deployed to study the pavement failure along a major road in a typical basement complex terrain of southwestern Nigeria. This study was designed to assess the failure and provide a basis for ultimate engineering design. The study delineated a 3- to 4-layer geoelectric sequence: a topsoil of thickness varying from 0.4 to 1.2 m, a spectrum of clayey materials of thickness varying from 1.9 to 14.5 m and a weathered/fractured basement occurring at depths of between 3.6 and 15.0 m. The shallow basement indicated low bearing capacity, with resistivity values ranging from 62.1 to 377.9 Ωm . The presence of clay/clayey materials, linear features and the effect of rising water table within the influence zone underlined the pavement failure. This information will facilitate appropriate designing, soil improvements and selection of materials for road construction that can stand the test of time.

Keywords: basement, fractures, pavement failure, stability, subsoil characterization

Povzetek

Za določitev vzroka poškodb cestišča na magmatsko-metamorfni podlagi jugozahodne Nigerije smo uporabili zelo nizkofrekvenčno elektromagnetno metodo (VLF-EM) in vertikalno električno sondiranje (VES). Namen raziskave je bila ocena poškodb cestišča in pridobitev podatkov za ustreznejšo izvedbo cestišča, ki bo dolgoročno obstojno. Z omenjenima metodama smo ločili tri do štiri plastno geoelektrično zaporedje. Zgornji horizont tal je debel 0,4 do 1,2 m, sledi nabor zaglinjenih tal debeline 1,9 do 14,5 m ter preperela/razpokana podlaga na globini 3,6 do 15,0 m. Plitva podlaga kaže nizko nosilnost z upornostjo med 62,1 in 377,9 Ωm . Poškodbe cestišča lahko pripišemo prisotnosti gline/glinenih mineralov, linearnim strukturam in nihanju gladine podzemne vode. Ti podatki bodo pripomogli k primernemu načrtovanju, izboljšanju lastnosti tal in primerno izbiro materialov za izdelavo cestišča, ki bo obstojno dlje časa.

Ključnebesede: podlaga, razpoke, porušitev cestišča, stabilnost, karakterizacija pod površja

Introduction

The incessant pavement failure along the Ado-Ikere road, a trunk “A” road in Southwestern Nigeria, has been a major concern to road users and relevant stakeholders. Reconstruction and rehabilitation works have not produced desired utility as the road slipped into failure shortly afterwards [1]. The huge financial and human resources committed to road construction demand that 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 an accompanying colossal financial burden [2, 3].

Road failures have been attributed to poor visco-elastic properties of asphalt binder [4], inadequacies in pavement structural design [5] and poor sub-grade soil properties [6]. Adeyemo & Omosuyi, Akintorinwe et al., Layede et al. [7–9] and similar works hinged most problems of road failure on inadequate knowledge of the subsurface and associated geologic features governing the competency of the subsoil materials which bear the pavement.

The Ado-Ikere road is underlain by the basement complex terrain of southwestern Nigeria. Basically, the rocks weather to produce residual soils of varying geotechnical properties. The heterogeneous nature of the subsurface demands investigation in considerable detail [9, 10]. Adequate knowledge of the subsoil has become imperative for design and construction of civil engineering structures to mitigate failure.

The need for geophysical characterization of the subsurface and appraisal of the nature and integrity of the subsoil supporting pavement structure has been recognized. Geophysical studies provide a relatively rapid and cost-effective means of deriving aerially distributed information on subsurface geology. The methods offer characteristic bedrock delineation, lithological boundary differentiation and determination of structural trends. Geophysical methods are capable of detecting and delineating local features of potential interest that couldn't have been discovered by any realistic drilling programme [11, 12].

Road failures are associated with losses in terms of capital, labour and human misery. Often, road accidents are traceable to the

deplorable conditions of roads, many a time resulting in severe injuries and loss of lives. The Ado-Ikere road often slips into failure not long after rehabilitation works. The road has been decimated by recurrent pavement failures.

The Ado-Ikere road is the main link between Akure and Ado-Ekiti, capital towns of Ondo and Ekiti States, Nigeria, respectively (Figure 1). The area lies in the tropical rain forest with mean annual rainfall of about 1300 mm and annual mean temperature of between 18 °C and 33 °C. The study area is underlain by the Precambrian basement complex of southwestern Nigeria (Figure 2).

The coarse-grained charnockitic rocks occupy the central portion of the study area. The coarse-grained type is the most prominent and is found in association with coarse-grained porphyritic granites. The fine-grained type occurs between the coarse-grained and gneissic fine-grained charnockitic rocks. The quartzite occurs as elongated bodies within the charnockitic, granitic, gneissic and migmatitic rocks. They are prominent as narrow ridges. The associated rock units include coarse-grained biotite and biotite hornblende granite and coarse-grained charnockitic rocks [1, 13, 14].

The thrust of this paper is to assess the pavement failure along the Ado-Ikere road using non-invasive VLF-EM and VES geophysical surveying. This information will provide a basis for ultimate engineering design and forestall the recurrent pavement failures.

Materials and methods

Very low frequency electromagnetic (VLF-EM) and vertical electrical sounding (VES) techniques were employed for the study. The theory and principles of the methods abound in the literature [12, 15, 16]. The methods being non-invasive enabled in-situ measurements and ensured preservation of the subsoil in its natural state. This combination has been widely used in engineering site investigations, given the existing good correlation of attributes such as electrical properties, geological composition and fluid content [7, 9, 17].

VLF-EM is an effective tool in mapping conductive materials and geologic structures in the

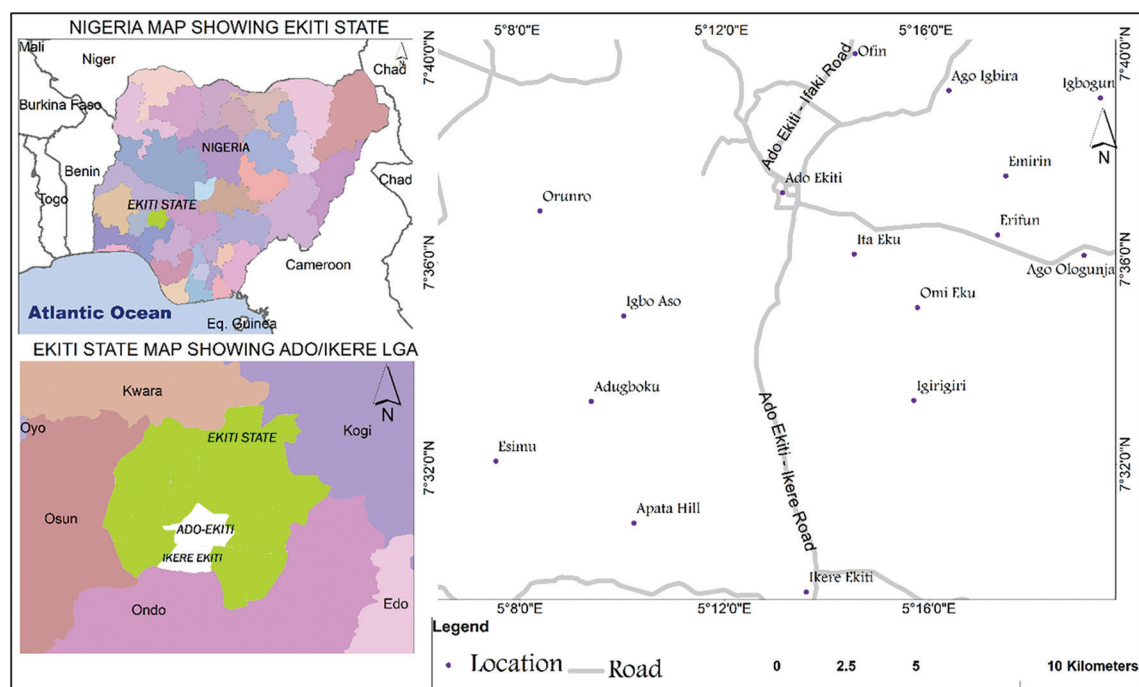


Figure 1: Location Map of The Study Area.

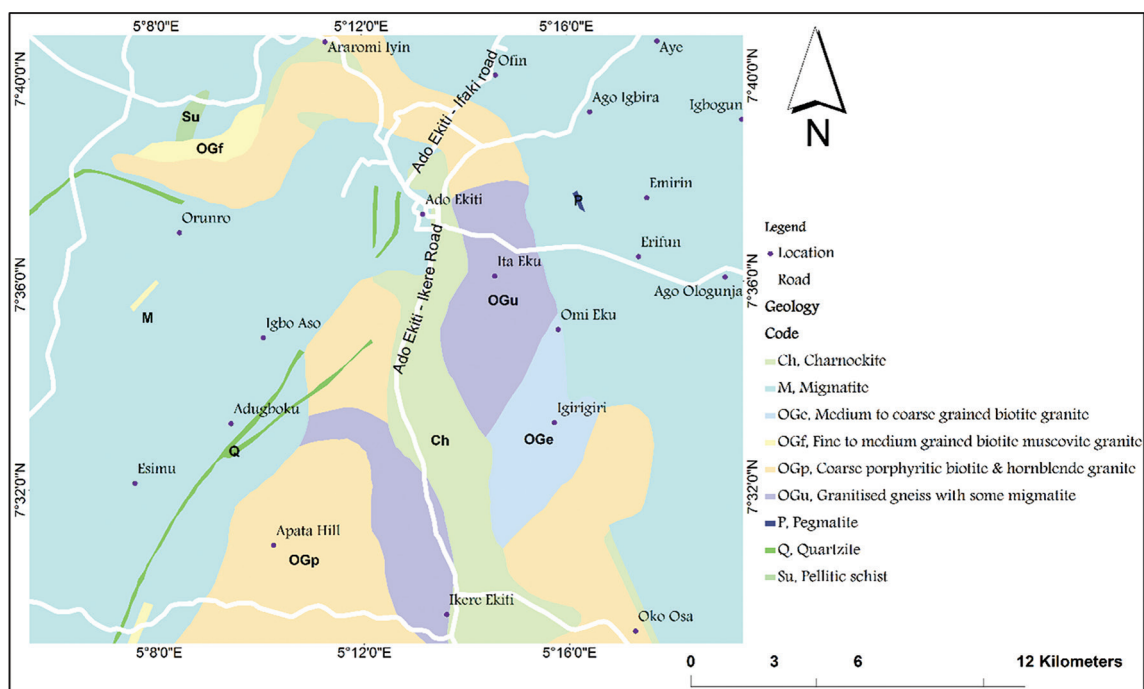


Figure 2: Geological Map of Ado-Ekiti /Ikere-Ekiti Area, SW Nigeria.

subsurface. The method detects electrical conductors, such as moderate to steeply dipping water-filled fractures or faults, by utilizing radio signals in the 15 to 30 kHz range. The method

gives recognizable signatures over conductive bodies [15, 16]. The VES technique provides 1-D layering information in terms of resistivity variation with depth in site investigation.

The electrical resistivity method is well suited for structural mapping and lithology differentiation [17, 18].

The VLF-EM data were acquired along a profile parallel to the road, covering a distance of 1710 m at a 10 m station interval. ABEM WADI electromagnetic receiver unit synchronized with the radio signal from the GBR station located in Rugby (England) operating at a frequency of 18.8 kHz was used for the survey. The equipment measured the raw real/in-phase and imaginary/quadrature components of the vertical to horizontal magnetic field ratio on the field. An in-built filtering program provided by the equipment and a software package KHFilt Version 1.0 enabled the conversion of the raw real 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. VLF-EM 2D Inversion model was prepared following the application of Fraser Filtering and Karous-Hjelt Filtering [19]. The VLF-EM mapping was particularly deployed to isolate subsoil conductive zones and linear structures of geological importance.

Subsequently, 12 VES stations were occupied along the profile. Measurements of ground resistance were made with a unit of Resistivity Meter. Schlumberger configuration with the half-current electrode separations ranging from 1 to 100 m was adopted for the survey.

The current electrodes were moved more often during measurements until the measurable signal became very small. The potential electrodes were then expanded symmetrically around the point of investigation. The terrameter gave the apparent resistivity values digitally as computed fundamentally from Ohm's law. The VES data were plotted as depth sounding curves and interpreted qualitatively and quantitatively. The quantitative interpretation entailed partial curve matching and computer iteration technique with the aid of RESIST computer software. The subsurface 2D geoelectric sections were generated using the resulting layer resistivities and thicknesses [8, 9].

Results and discussion

The VLF-EM profile

The VLF-EM measurements and the filtered graphs are presented in Figures 3–6. The in-phase profile shows positive peaks of different intensities, suggesting the presence of shallow and deep conductors [16, 17]. The 2D inversion model shows the variation of equivalent current density and change in conductivity with depth. It discriminates between conductive and resistive structures. Higher values of relative current density are indicative of conductive subsurface structures with varying low values of resistivity while

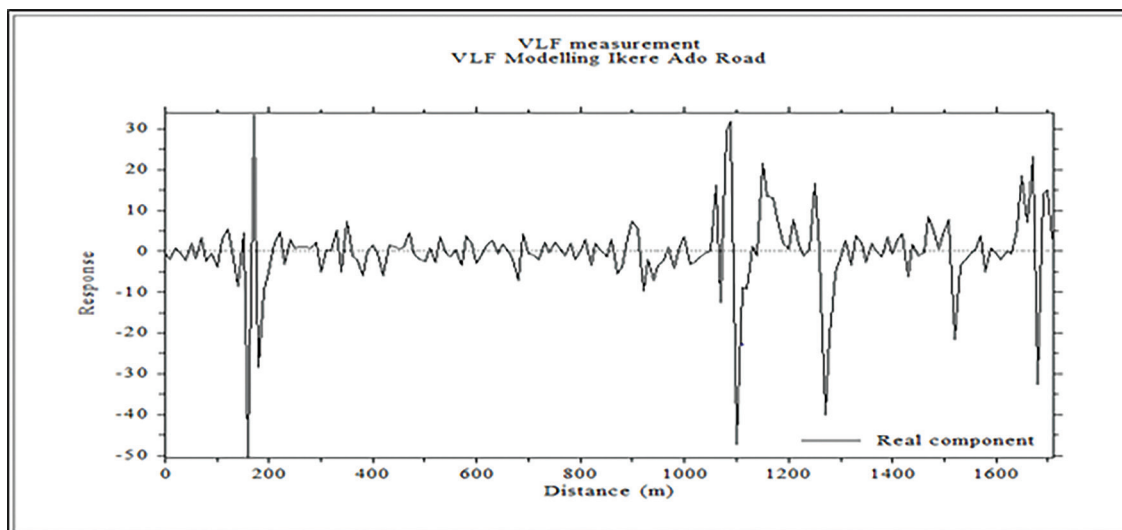


Figure 3: VLF-EM measurement of the study area.

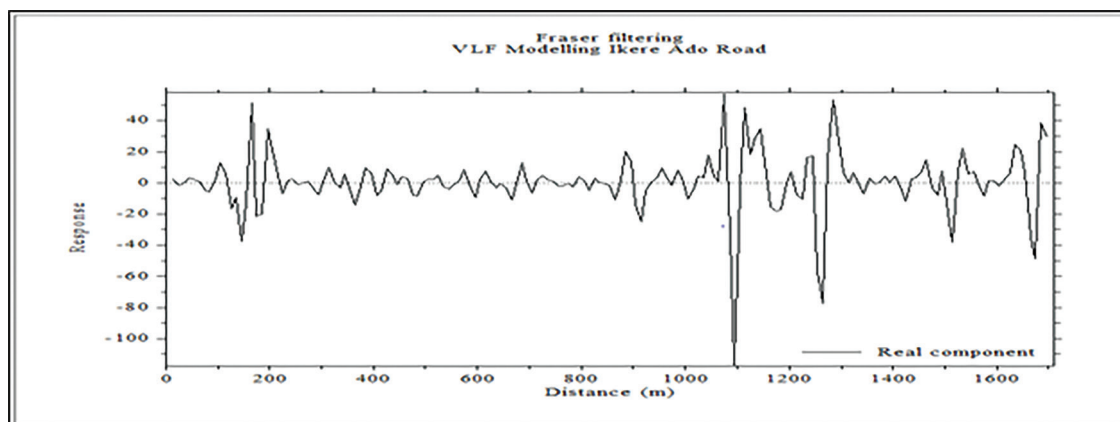


Figure 4: VLF-EM Fraser Filtering Graph of the study area.

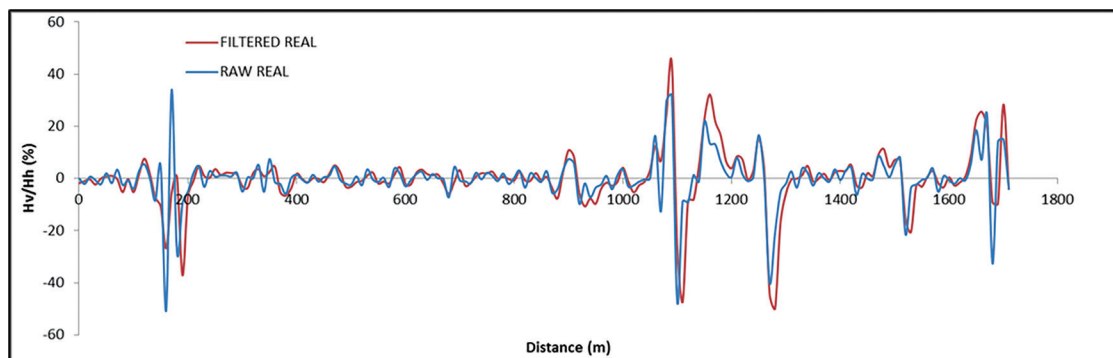


Figure 5: VLF-EM data (raw real and filtered real) of the study area.

lower values correspond to zones of low conductivity characterized by higher values of resistivity.

The 2D pseudosection indicates stable, partly failed, unstable and very unstable portions along the profile (Figure 6). The highly conductive zones, delineated as very unstable portions (distances of 150–260 m, 990–1200 m and 1600–1710 m) are underlain by conductive subsurface structures. These include linear geological structures (trending in different directions) which are indicative of major subsurface fractured/faulted zones with varying degrees of saturation and other conductive zones with lower positive amplitude suggesting the presence of clayey soil materials and/or fractures at varying depths. Partly unstable zones (distances of 0–100 m and 260–820 m) are characterized by moderately low conductivity values.

Distances of 100–150 m and 1200–1260 m correspond to the stable zones and are composed of highly resistive materials. These portions are characterized by lower values of relative current density. The stable segments of the road are generally devoid of geological features [7, 9, 18].

Geoelectric sequence and characteristics

A summary of the VES interpretation results is presented in Table 1. The curve types are H, A, Q, KQ, KH and QH; these are curves with occurrence of 33%, 17%, 8%, 8%, 17% and 17% respectively. They reflect the degree of weathering, fracturing and geoelectric complexity in the study area [8, 13, 14]. Figure 7 shows typical resistivity type curves in the study area.

The H-type curve predominates the area of study. A stratigraphic sequence comprising the topsoil whose composition is variable alluvium,

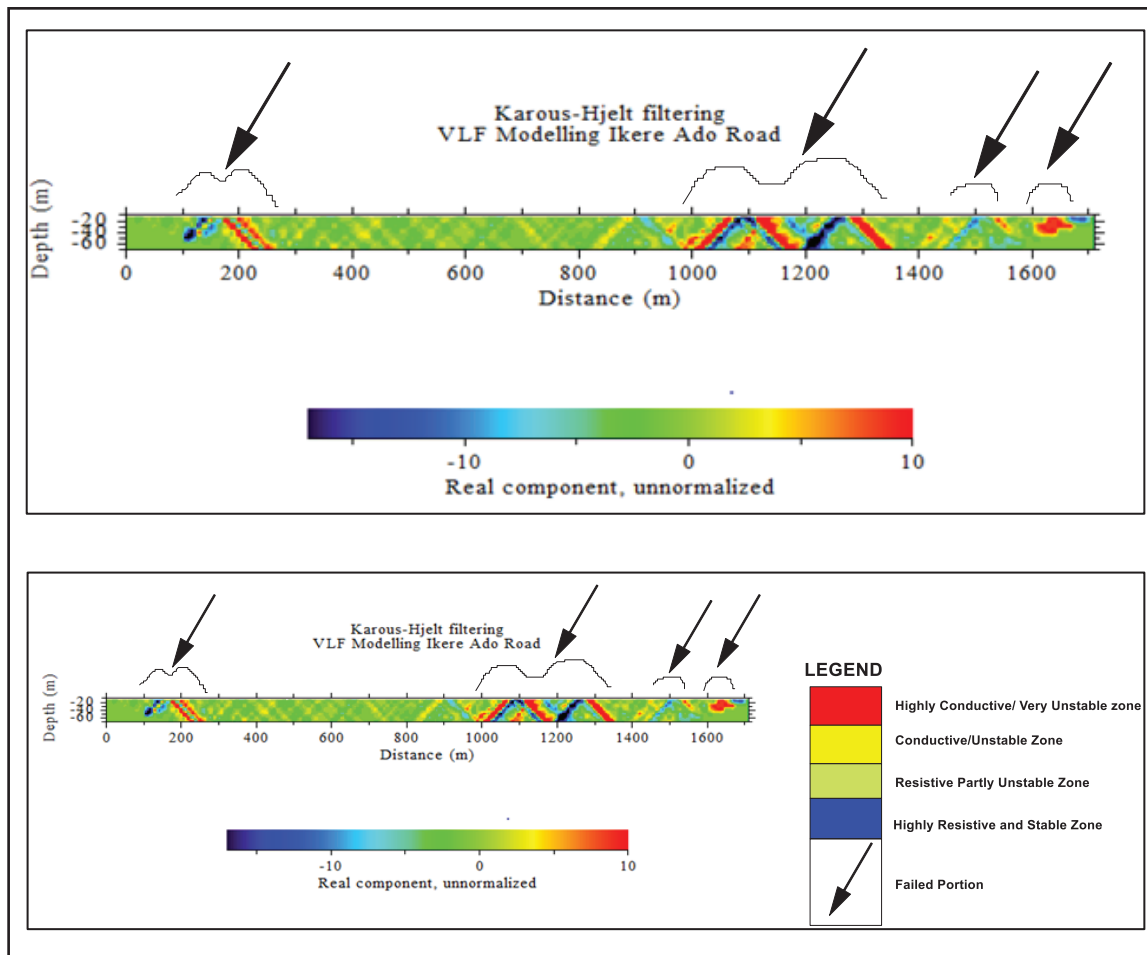


Figure 6: VLF-EM 2D Inversion model of the study area.

sand, lateritic clay or clay followed by clay/sandy clay and the bedrock corresponds to the H-type curve. The bedrock could be weathered or possibly fractured basement. The intermediate layer is characterized by low resistivity. It is commonly water-saturated. The A-type curve presents subsurface conditions in which there is a persistent increase in the layer resistivity values from the topsoil to the basement rock ($\rho_1 < \rho_2 < \rho_3$). It suggests increasing subsoil strength and integrity [3, 9, 11].

The underlying geoelectrical units in QH-type curves consist of clay and clayey sand/sand, respectively. The clayey sand and the weathered/fractured basement may jeopardize the stability of the pavement with varying degree of saturation. The KH-type curve has a succession of sand/sandy clay topsoil, lateritic clay, weathered basement and the fresh bedrock. The third layer is essentially clayey [7, 8].

The geoelectric sections

The 2D geoelectric sections, Figures 8–10, reveal the subsurface geology and structural disposition of the study area. Figure 8 shows the 2D section beneath VES 1 to 4 (segment I). The first layer constitutes the topsoil with layer resistivity values ranging from 57.4 to 288.4 Ωm indicating materials of varying clay contents. The thin layer has an average thickness of 0.65 m except at VES 3 where composite clayey material with resistivity of 57.4 Ωm extends to a thickness of up to 6 m. This suggests lateral inhomogeneity and varying level of competence/stability [2, 8].

The topsoil is underlaid by a clayey horizon of resistivity values ranging from 36.2 to 119.3 Ωm . The clayey substratum of about 14 m thickness delineated at VES 1 is inimical to the stability of the pavement as it is subject to flowing under traction. A clay fraction in a

Table 1. The layer parameters and geoelectric characteristics.

VES No.	Layer resistivity (Ωm)	Layer thickness (m)	Depth (m)	Curve types	Lithology
1	288.4	0.5	0.5	H	Topsoil/Laterite Clay
	76.6	14.5	15		Weathered layer
	182.6	-	-		
2	138.4	0.9	0.9	H	Topsoil/Laterite Clay
	36.2	3.1	4.0		Weathered layer
	113.6	-	-		
3	57.1	6.0	6.0	A	Topsoil/Laterite Clay
	119.3	2.1	8.2		Weathered layer
	157.7	-	-		
4	208.3	0.5	0.5	KQ	Topsoil
	307.2	1.1	1.6		Lateritic clay
	102.8	2.0	3.6		Clay
	100.8	-	-		Weathered layer
5	153.6	1.2	1.2	QH	Topsoil
	121.6	2.6	3.8		Lateritic clay
	64.7	8.4	12.2		Clay
	208.2	-	-		Weathered layer
6	170.2	1.0	1.0	QH	Topsoil
	151.8	3.2	4.2		Lateritic clay
	57.0	4.0	8.2		Clay
	126.5	-	-		Weathered layer
7	177.8	1.1	1.1	KH	Topsoil
	277.9	2.1	3.2		Lateritic clay
	48.0	4.2	7.4		Clay
	170.0	-	-		Weathered layer
8	88.7	0.8	0.8	KH	Topsoil
	180.1	4.0	4.8		Lateritic clay
	26.5	5.0	9.8		Clay
	113.9	-	-		Weathered layer
9	289.0	0.4	0.4	Q	Topsoil/Laterite Clay
	66.4	1.9	2.3		Weathered layer
	62.1	-	-		
10	94.9	9.9	9.9	A	Topsoil/Laterite Clay
	146.0	2.4	12.3		Weathered layer
	229.6	-	-		
11	105.7	0.9	0.3	H	Topsoil/Laterite Clay
	33.4	2.1	3.0		Weathered layer
	149.8	-	-		
12	131.5	0.5	0.5	H	Topsoil/Laterite Clay
	38.2	6.8	7.3		Weathered layer
	377.9	-	-		

soil is generally expandable and compressible thereby promoting swelling and shrinkage. High clay contents thus impact weaknesses to the pavement structure [10, 20]. A lateritic cap with resistivity of 307.2 Ωm and average thickness of 1.2 m, observed at VES 4 may support stability at that zone.

The weathered/fractured basement is revealed at varying depths ranging from 4.0 to 15.0 m with a resistivity spectrum of 100.8 to 182.6 Ωm . This affirms a system of linear geological structures prescribed by the VLF-EM profile. The generally low resistivity values indicate low bearing capacity. Transmitting load

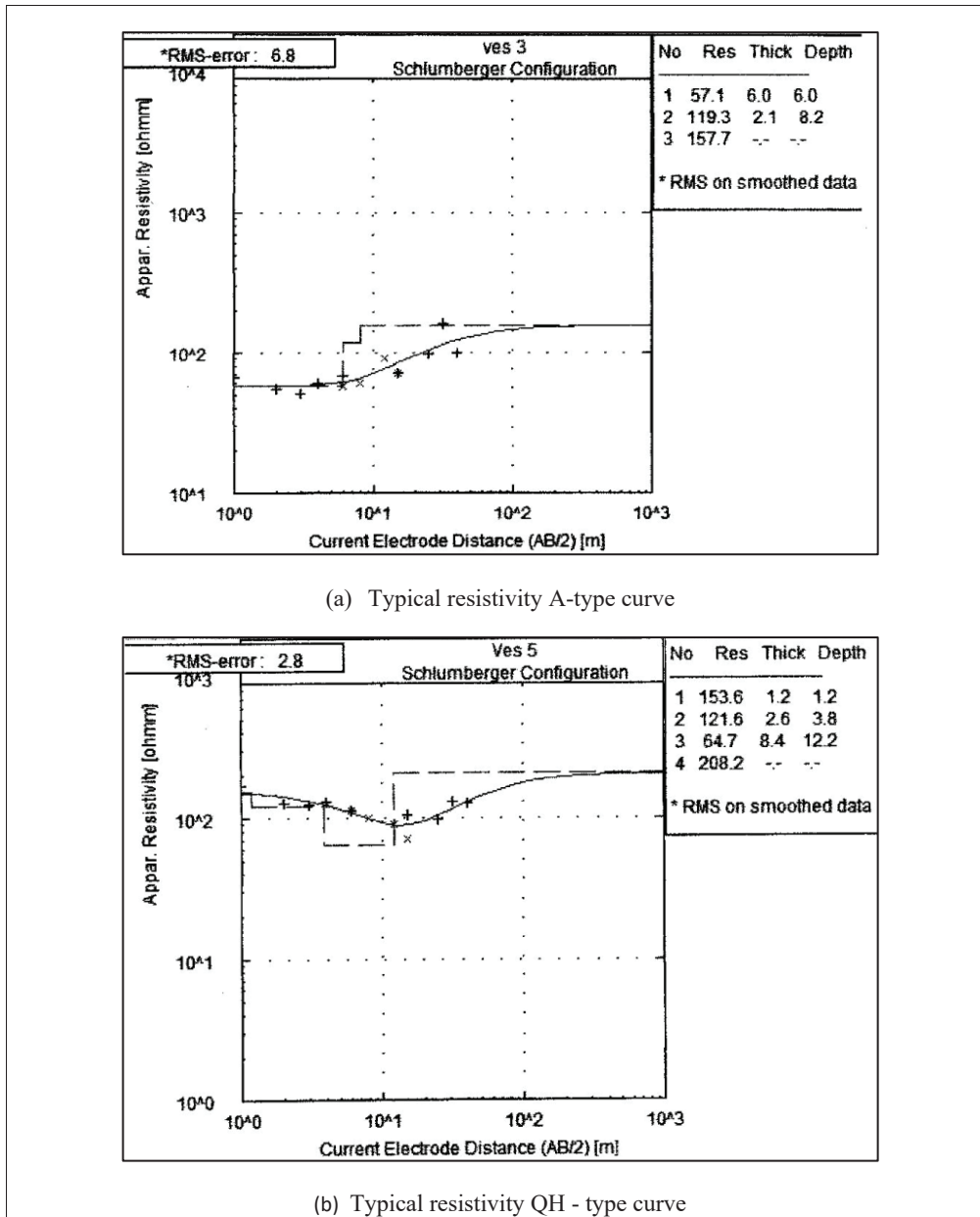


Figure 7: Typical resistivity type curves in the study area.

to this layer may induce differential settlement of the pavement structure and precipitate failure [3, 7, 9].

Figure 9 reveals a 4-layer geoelectric sequence below VES 5–8 (segment II). The topsoil is clayey with resistivity values ranging from 88.7 to 177.8 Ωm and its thickness varies from 0.8 to 1.2 m. A lateritic crust forms the second layer with resistivity values ranging from 121.8 to 277.9 Ωm and thickness ranging from 2.1 to 4.0 m. This suggests varying levels of competence/stability giving

rise to the partly unstable/stable zones along the profile. The average thickness of 2.98 m and varied composition may not absolutely fulfil the expected characteristics of a base course/sub-base course, particularly acting as the structural portion of the pavement and distributing the imposed stresses evenly [2, 9, 11].

The third geoelectric layer, a clay/clayey horizon extending to a depth of about 12.5 m at VES 5 is geotechnically significant. The layer resistivity values ranging from 26.5 to 64.7

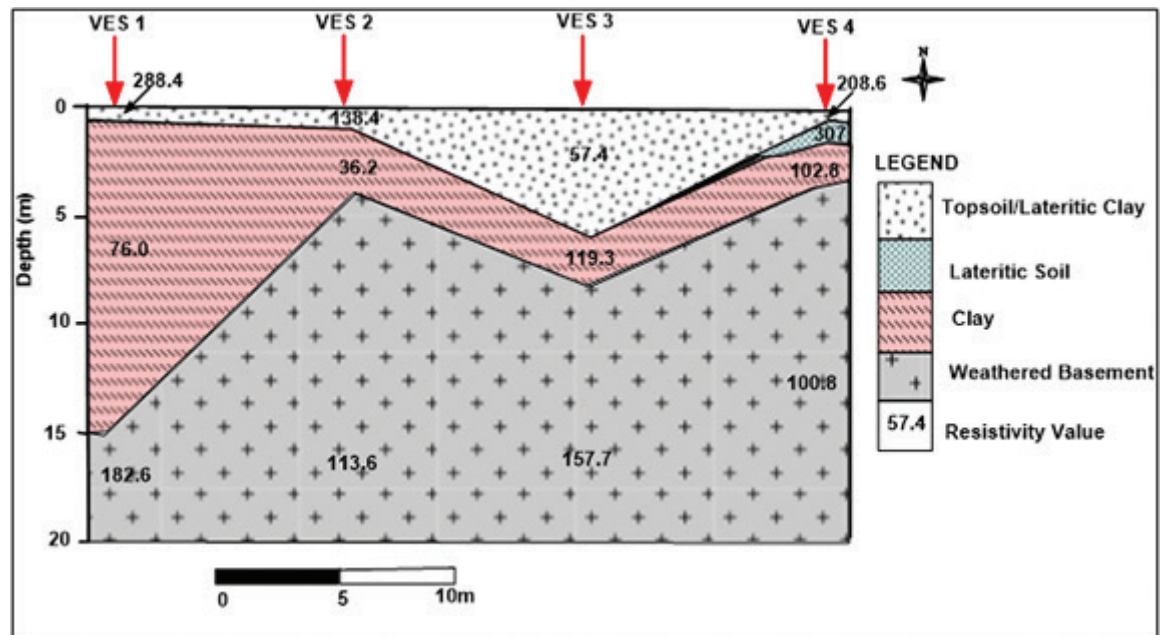


Figure 8: Goelectric section of segment I covering VES 1–4 along Ado-Ikere Road.

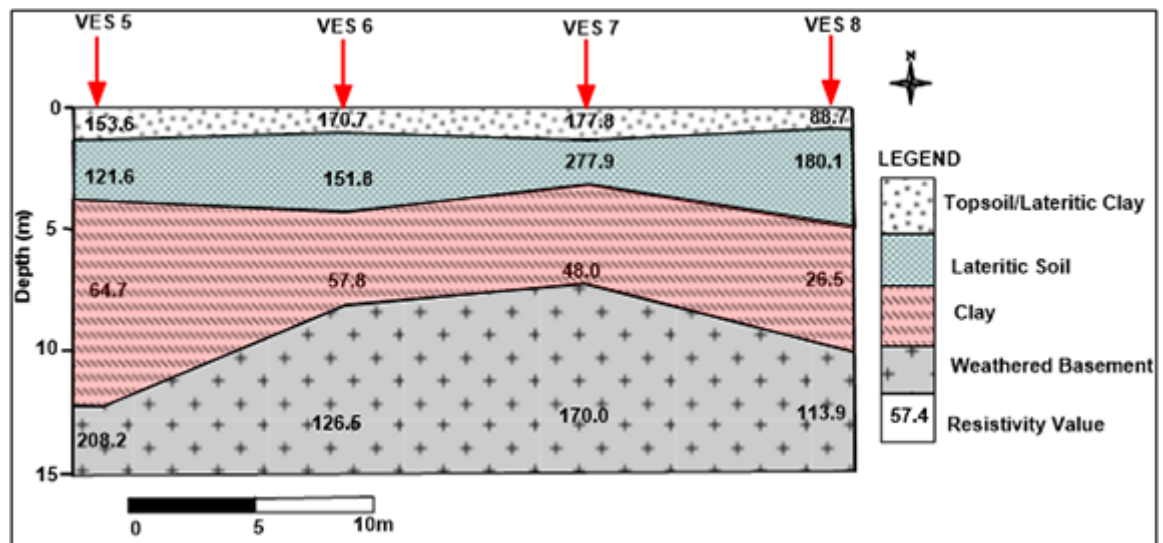


Figure 9: Goelectric section of segment II covering VES 5–8 along Ado-Ikere Road.

Ωm indicate varying degrees of saturation owing to capillary effect. The material in place lacks a basic requirement of sub-base course to facilitate the drainage of free water that may accumulate below the pavement. Clayey formations are prone to differential settlement under prolonged vehicular traffic/axle loading owing to high porosity and practically little or no permeability [5, 21]. This fragile layer is underlain by a weathered/fractured

basement with resistivity values ranging from 113.9 to 208.2 Ωm . The degree of weathering and fracturing permits groundwater accumulation and the effect of rising water table. The bearing capacity of the layer is corresponding low [3, 16, 20].

The goelectric section of segment III encompassing VES 9 to 12 presents a 3-layer goelectric succession (Figure 10). The resistivity of the topsoil ranges from 94.4 to 289

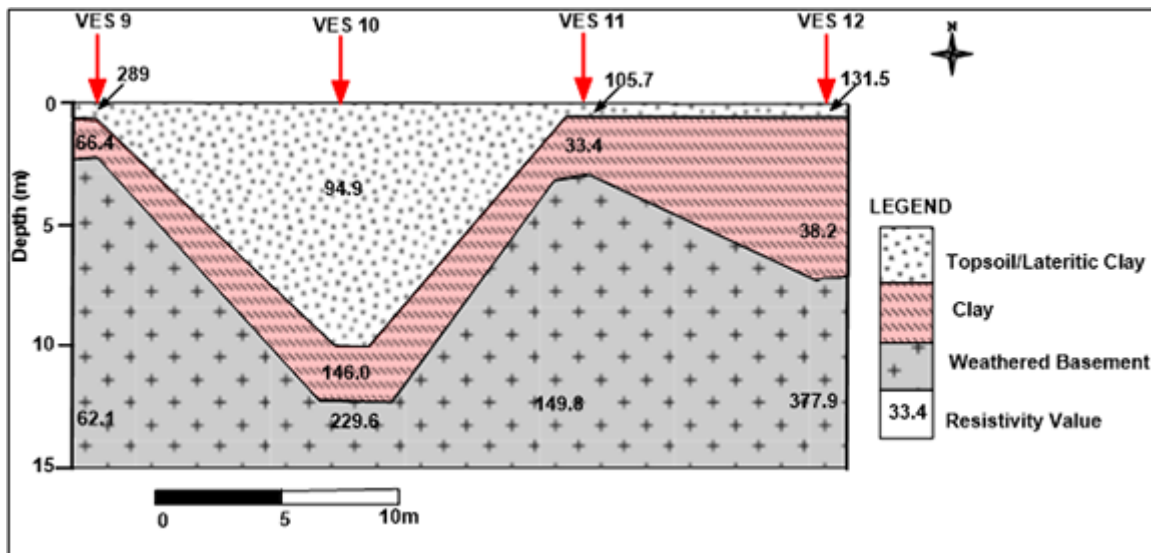


Figure 10: Geoelectric section of segment III covering VES 9–12 along Ado-Ikere Road.

Ωm ; indicating materials of varying clay contents, with thickness varying from 0.4 to 9.9 m. The generally thin layer is delimited by a massive clayey material (resistivity of $94.9 \Omega\text{m}$) stretching from VES 9 to VES 11 and extending to 9.9 m at VES 10. It is underlaid by a clayey substratum with resistivity value as low as $33.4 \Omega\text{m}$ at a depth of 0.9 m around VES 11.

A weathered/fractured basement forms the third layer with resistivity values ranging from 62.1 to $377.9 \Omega\text{m}$. The layer is closer to the surface at VES stations 9 and 11, being at 2.3 m and 3.0 m depth, with associated resistivity values of 62.1 and $149.0 \Omega\text{m}$, respectively. High contrasts of resistivity values confirm the presence of linear features, mainly fractures/faults, lithologic contacts and near-surface lateral inhomogeneity [9, 17].

Adverse effects of groundwater can be expected across the third layer as the features often store groundwater in the basement complex terrain [16, 20]. This geoelectric layer constitutes a layer of low bearing capacity. It is structurally weak and may not be able to support heavy wheel loading structures [6, 18, 22].

Subsoil Integrity Evaluation

The basic structure of a pavement represents four layers of surface: wearing course, base course, sub-base course and the subgrade. A

flexible pavement surface reflects the entire behaviour of the subgrade layer. The characteristics of the soil bed over which the entire pavement system rests are indicative of the geotechnical properties of the pavement [21, 22]. Engineering design should be in line with the anticipated traffic load and ultimate strength of the pavement layers to ensure the stability and durability of the pavement structure [2, 18, 23].

The crystalline basement terrain of southwestern Nigeria presents challenges in geotechnical investigations due to the heterogeneous nature of the subsurface and the existence of localized geologic features [13, 20]. In this study, the subsurface geology indicates substantially clayey subsoil with relatively low resistivity values and presence of geological features including fractures, faults and lateral inhomogeneity. The presence of the linear features in the area suggests lithological contacts and/or fault/fracture zones along the road alignment occurring within the coarse-grained biotite and biotite hornblende granite and coarse-grained charnockitic rocks associations [13, 14].

According to Akintorinwa & Oluwole [11] and Asif et al. [23], the electrical resistivity of subsoil increases with increase in compaction and decrease in porosity. Higher moisture content decreases the value of subsoil

resistivity. Compact subsoil is characterized by reduced porosity and moisture content with consequent increase in electrical resistivity. Diastrophic features and lithological contacts are associated with typically high porosity and permeability which enhance groundwater accumulation and transmission. The presence of these tectonic features readily permits the flow of water to the overlying clayey materials. The subgrade at some portions of the road might be wholly or partly immersed in the zone of saturation, particularly during the wet season of the tropics when groundwater table rises, leading to low resistivity and bearing capacity [16, 24]. This geological scenario ultimately promotes heaving, differential settlement and reduction in the load bearing capacity of the near surface subsoil [10, 22, 25].

The failure of the overlying pavement becomes apparent due to the plastic nature of the clayey soil and high moisture content [2, 7, 9]. Clays characterized by low resistivity (usually less than 100 Ωm) are regarded as incompetent materials as they tend to flow under stress. This result agrees with Akintoriwa & Oluwole [11] and Falowo [26], whose studies indicate an inverse relationship between apparent resistivity and moisture content, clay and silt content, liquid limit, plastic index, linear shrinkage, and unconfined compression shear strength. The specific gravity, maximum dry density and California Bearing Ratio (CBR) were shown to exhibit a direct relationship with apparent resistivity.

In an earlier study, Adams et al. [1] adopted conventional geotechnical methods to study the pavement indices influencing failure along the road under investigation, the Ado-Ikere Road, in southwestern Nigeria. The work provides a basis for comparison and validity of the present study. The study classified most of materials in place as clayey soil under group A-2-6 and A-7, rated as fair to poor material for road use according to the AASHTO classification system. The compaction and CBR tests indicated unsuitable base course materials. The soil has a high water retention capacity, with the natural moisture content ranging between 7.7 and 14.5% for base course, between 10.5 and 17.5% for sub-base and between 12 and 19% for sub-grade, for all failed segments considered. The

liquid limit showed that the majority of the failed section exceeded the allowable limit for base course materials.

The study of Adams et al. [1] significantly affirmed the presence of clayey formation underlying the pavement and effect of a rising water table, as reported in the present geophysical investigations. Application of the geophysical methods enabled delineation of linear geological structures including fractures, faults and lateral inhomogeneity beneath the pavement. The presence of these features renders geomaterials at such regions geotechnically weak with resultant pavement failures [9, 20, 26]. Incessant failure of the pavement under investigation has been promoted by the effect of the rising water table, heterogeneity of the subgrade materials, presence of expansive clays and linear features such as fractures, faults and geological contacts.

Conclusions

Pavement failures along Ado-Ikere Road have been investigated using the integration of data from VLF-EM and VES techniques. The study revealed the dominant presence of clay/clayey materials below the topsoil, the presence of linear features and contributory shallow water table. Aside from any unethical engineering practice, the presence of clayey subgrade, lateral inhomogeneity, near surface geological structures and fluctuations in the saturated zone largely accentuated the pavement failures along the road. Soil stabilization procedures should be deployed as appropriate. These should include excavation to requisite depths, replacement of excavated materials with competent materials, as well as construction of appropriate drainage systems.

The present study demonstrates the usefulness of geophysical techniques in civil engineering works, particularly the advantage of high spatial resolution, over results from boring and coring, which are known to provide information at discrete locations. Geophysical site investigations offer to reduce cost outlay by reducing the number of borings, sampling, and time-consuming tests required in the

geotechnical procedure. An all-inclusive and pragmatic approach is required for subsoil characterization and ultimate engineering design. This is a necessary prerequisite to achieve sustainable development and reduce investment losses through routine rehabilitation of failed segments of highways.

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