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Geoelectric Characterization of the Subsurface Road Pavement Failures Along Itapa-Ikole Highway, Southwestern, Nigeria

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ABSTRACT

A geophysical investigation using the electrical resistivity method was conducted at the Oloko section of the Itapa-Ikole highway, South-Western Nigeria, to identify the causes of persistent road pavement failure despite multiple rehabilitation efforts. The primary objective of the study was to determine the geoelectric parameters of the subsurface, delineate the lithological units, and assess whether there are underlying structures that could compromise the stability of the road pavement. The investigation employed both 1-D Vertical Electrical Sounding (VES) using the Schlumberger array and 2-D resistivity imaging using the Dipole-Dipole array. Two parallel traverses were surveyed with the 2-D dipole-dipole method, and the data were inverted into 2-D resistivity structures. A total of nine VES stations were occupied with a maximum AB/2 spacing of 65 m. The VES data were presented as sounding curves and interpreted through partial curve matching and 1-D computer-assisted forward modeling, leading to the generation of geoelectric sections. The geoelectric sections revealed four distinct subsurface geoelectric layers: topsoil, laterite, weathered layer, and fresh basement. The 2-D dipole-dipole images and geoelectric section indicated the absence of significant geological structures; however, they highlighted a relatively low-resistivity (< 100 Ω m) weathered zone and a thin lateritic subgrade (approximately 1.5 m thick). The study generally indicates that the road failures are primarily due to the insufficient thickness of the lateritic subgrade, which is inadequate to support the axle load, combined with the underlying clayey weathered layer that yields under heavy loads, ultimately leading to pavement instability.

Keywords: electrical resistivity, rehabilitation, topsoil, laterite, weathered layer

INTRODUCTION

Road failures have long been a significant concern for transportation authorities and road maintenance agencies worldwide. The repercussions of such failures extend far beyond simple inconveniences, often leading to severe economic losses, traffic disruptions, and even life-threatening safety hazards. The inability to maintain road infrastructure can strain a nation's economy, impede its logistical capabilities, and threaten the well-being of road users. Therefore, identifying and addressing the underlying causes of road pavement failures is critical to sustaining a nation's economic health, safety, and infrastructural integrity. One method that has emerged as highly effective for diagnosing road pavement conditions is the electrical resistivity method, which offers deep insights into the subsurface conditions of road structures.

Electrical resistivity measurements provide valuable data about the properties of road materials, including their composition, moisture content, and structural integrity (Akintorinwa *et al*., 2011). These factors play an integral role in road performance, as substandard materials or conditions can lead to rapid pavement deterioration. The resistivity method works by passing electrical currents through the subsurface, and the variations in resistivity can indicate different material properties. Low resistivity values, for instance, may signify high moisture content or the presence of weak subgrade materials, both of which are known precursors to road failure. By analyzing resistivity data, engineers and road maintenance teams can identify areas that are prone to failure due to issues such as poor compaction or water infiltration—common problems that undermine the integrity of road pavements.

The ability to anticipate road failures before they occur offers tremendous advantages. Rather than relying solely on visual inspections or waiting for physical signs of degradation, transportation authorities can use resistivity data to map out vulnerable sections of roadways, enabling them to target maintenance efforts precisely where they are needed most. Studies such as those by Smith *et al.* (2018) and Johnson *et al.* (2019)

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have shown that this technique is not only accurate but also proactive. This proactive approach allows for the timely intervention needed to extend the lifespan of road pavements and reduce the economic costs associated with frequent repairs and reconstructions. More importantly, it ensures safer travel for road users by mitigating the risk of accidents caused by unforeseen road collapses or pavement damage. In developing countries, where the financial burden of road maintenance is particularly acute, such technology offers a cost-effective solution to preserving road networks, which are crucial for national development.

Transportation is the lifeblood of any nation, supporting not only the movement of people but also the distribution of resources, integration of industries, and provision of essential services like healthcare and education. Among the various modes of transport—air, water, rail, and road—road transportation plays a particularly vital role. Its flexibility, accessibility, and ability to reach remote areas make it the most widely used mode of transport, especially in developing regions. However, the reliability of road networks is continually undermined by frequent road failures, particularly of flexible pavements. These failures lead to a wide range of negative outcomes, from fatal accidents and vehicle damage to the loss of agricultural produce and inflated prices for goods and services. In developing countries, such as Nigeria, these challenges are compounded by financial constraints and the immense costs involved in road rehabilitation and reconstruction (Mulei *et al*., 2002).

Flexible pavements are particularly vulnerable due to their susceptibility to wear and tear from environmental factors, traffic loads, and the underlying geology. Continual road failure in these regions has become a critical issue, leading to not only economic losses but also the degradation of public confidence in road safety. Poor road conditions force transportation companies and everyday drivers to incur extra costs due to vehicle damage, wasted time, and lost resources. Governments, in turn, face increasing pressure to invest in rehabilitation efforts, diverting funds from other crucial areas of development. The application of advanced technologies like the electrical resistivity method, however, provides a viable solution to these challenges. By using this technology to pinpoint problem areas before they lead to catastrophic failures, transportation authorities can optimize their maintenance schedules, minimize repair costs, and, most importantly, ensure the safety of road users.

MATERIALS AND METHODS

Description of the Study Area

The study highway is along Itapa-Ikole express road and it is within Ikole local government in Ekiti state, southwestern Nigeria. The study area lies within Northings: 0862645 m and 0862731 m and Eastings: 0754441 m and 0754878 m which are within the Universal Traverse Mercator (UTM) zone 31N (Minna Datum). Ikole local government is bounded by Irepodun/Ifelodun to the south, Ekiti East local government to the East and Oye local government to the West. This makes the entire study area accessible. The location and topographic map is shown in Figure 1 and Figure 2 respectively. The road is a major highway and it is accessible by mainly vehicles.

Brief Geology of the Study Area

The study area falls in the South-Western Basement Complex of Nigeria. It comprises migmatite, charnockites, and granite-gneiss (Figure 3). Ikole-Ekiti basement rocks also comprise the granite gneiss which covers 50% along Bolorunduro, Itapaji, Ipawo areas and a very small quantity of Charnokites of about 5% along the area of Itapaji. The migmatite which is located within Ire-Ekiti, Ijesha Isu, Ikole town is a widespread form of non-foliated rocks which includes the migmatite, granite-gneiss, charnokites and the basement rock have been concealed with variably thick overburden. The granite-gneiss and migmatite-gneiss are highly metamorphosed rocks that occur in light and dark bands which shows an alignment of minerals (Rahaman, 2003; Dada, 2006). The major mineralogical content of the Migmatite-gneiss rock includes quartz, felspar, muscovite, and plagioclase (Woakes *et al.,* 1987; Kogbe,1989.)

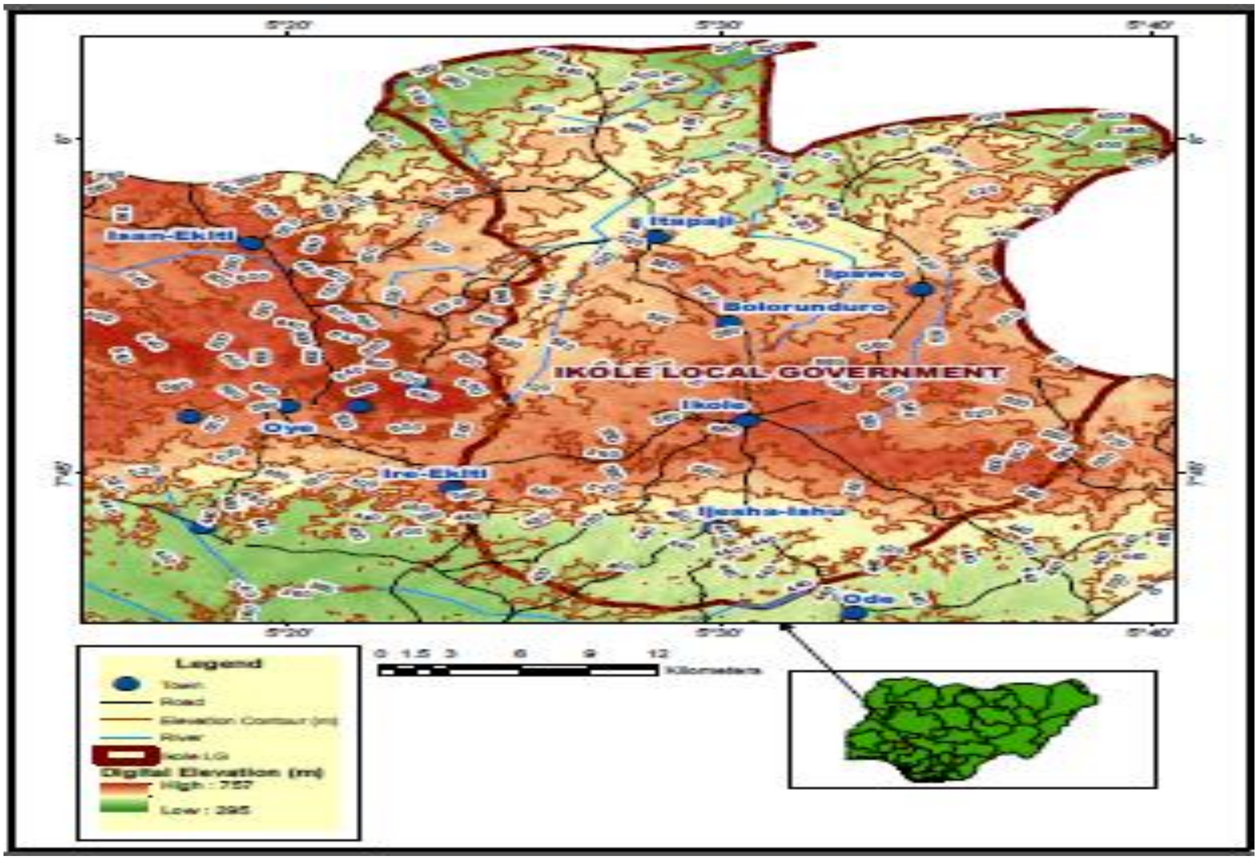

Figure 1: - The Location Map showing the Study Area

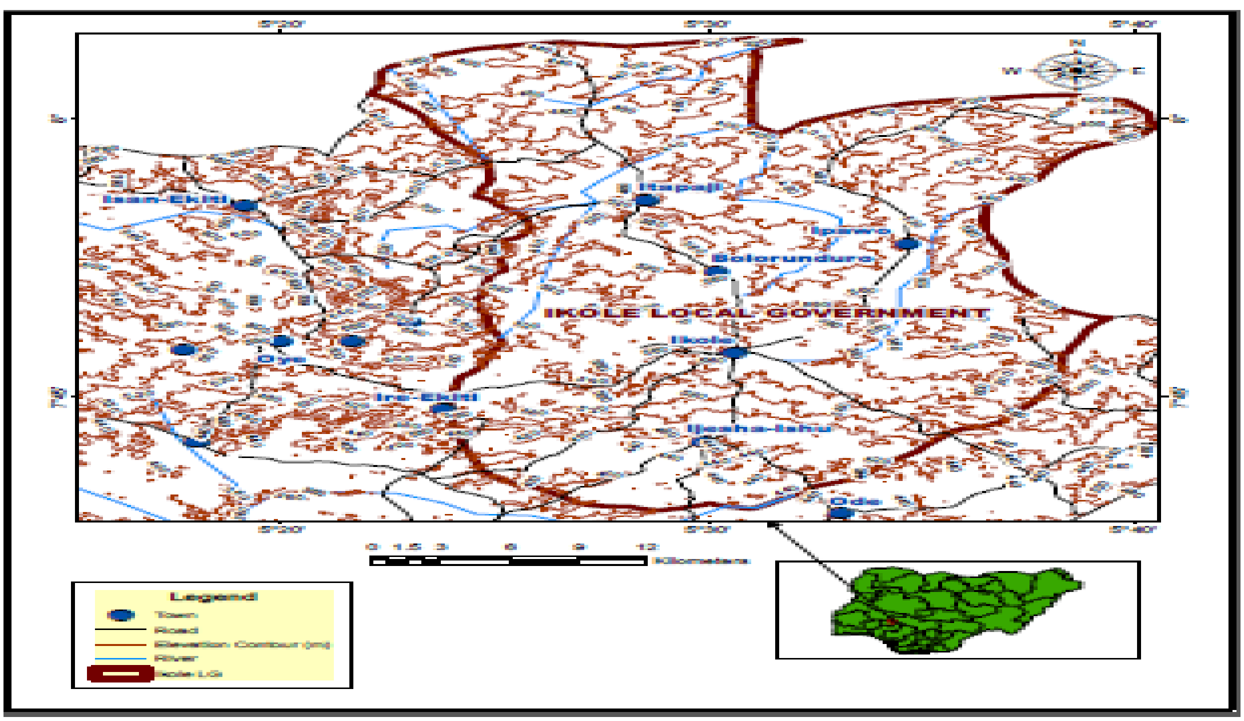

Figure 2: - The Topographic Map of the Study Area

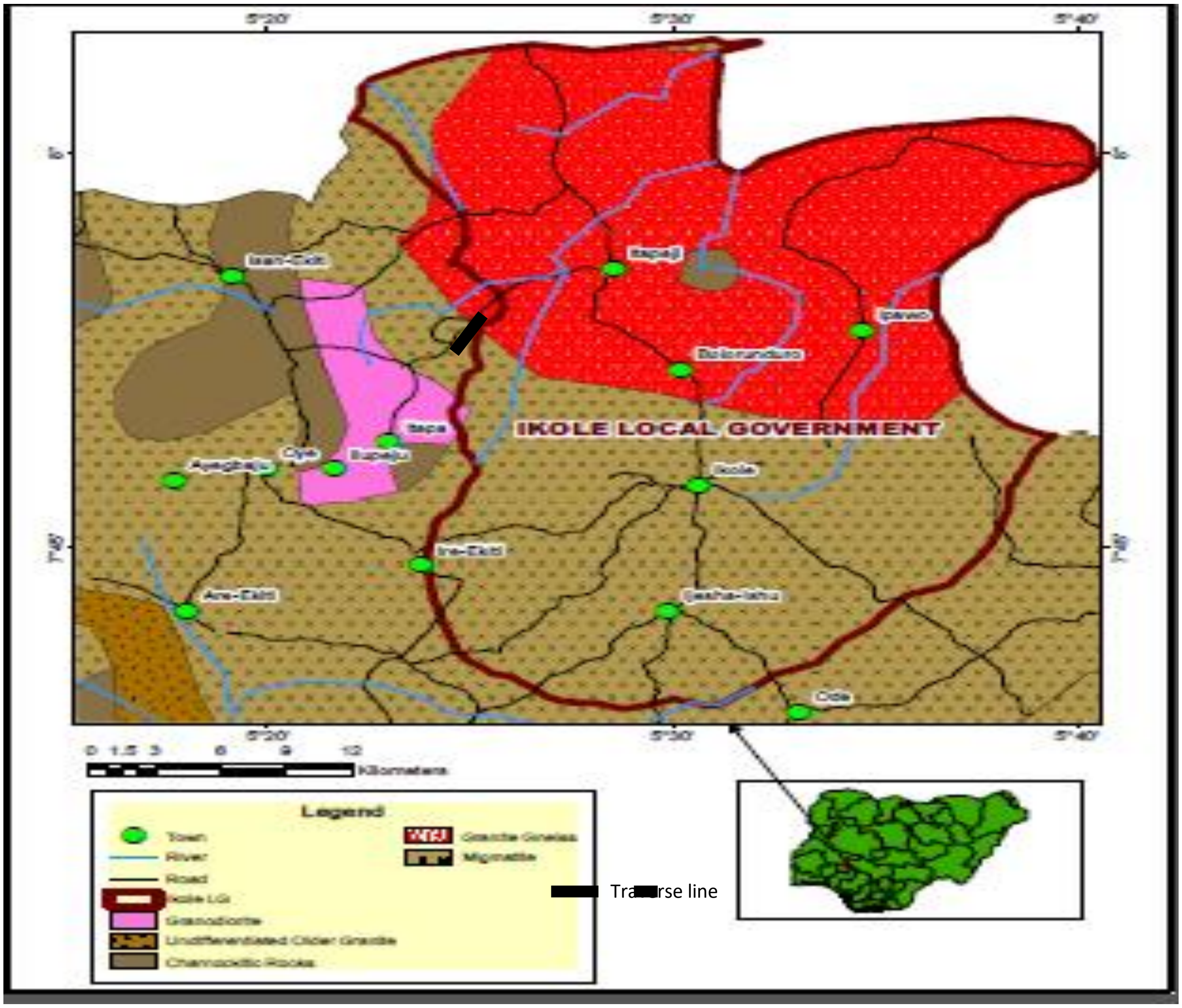

Figure 3: Geological Map of Ikole Ekiti and its Environs (after Obaje, 2009). The two traverse lines are indicated.

Data Collection
The preliminary investigation involved cutting two parallel traverses, each 100 m long, and acquiring the geographical coordinates of the study area using a GPS device. These coordinates were then utilized to generate a base map of the study location. A geophysical survey was conducted along the study highway, with a west-east trending traverse established as the main reference line. The electrical resistivity method was employed for this investigation, utilizing both the Dipole-Dipole array and Vertical Electrical Sounding (VES). The dipole-dipole electrode array and Schlumberger configuration for VES were chosen to assess the lateral and vertical variations in subsurface resistivity. For the dipole-dipole array, two current electrodes and two potential electrodes were inserted into the ground. The apparent resistivity values obtained from this setup were plotted at the intersection of lines drawn at 45 degrees from the midpoints of the potential and current dipoles. The inter-electrode spacing was set at 5.0 m, with the inter-dipole separation factor (n) varying from 1 to 5 m. A low-frequency direct current (DC) source powered the transmitting dipole, initially positioned at stations 1 and 2. The receiving dipole was first located at stations 3 and 4 (n=1) and then sequentially moved to stations 4 and 5 (n=2), stations 5 and 6 (n=3), stations 6 and 7 (n=4), and finally to stations 7 and 8 (n=5). The transmitting dipole was then relocated to stations 2 and 3, and the entire expansion procedure was repeated. The 2-D Dipole-Dipole data were processed using DIPROfWin software and were presented as 2-D pseudosections, which were subsequently inverted to generate 2-D resistivity images. For the vertical electrical sounding (VES) using the Schlumberger array, the vertical variation in the ground's apparent resistivity was measured, maintaining a fixed center for the electrode array. A total of nine VES locations

were surveyed along the two established traverses, with a maximum current electrode spacing (AB/2) of 65 m. The apparent resistivity values were plotted against their respective electrode spacings on a log-log scale and presented as VES curves. These curves were quantitatively interpreted through a combination of partial curve matching and 1-D forward modeling using the WinRESIST software (Vander Velper, 2004).

The interpretation results, consisting of layer resistivities and thicknesses, were used to generate geoelectric sections of the subsurface. Data interpretation involved both qualitative and quantitative methods. Qualitative analysis consisted of visual inspection of profiles, maps, and 2-D resistivity structures to identify anomalies, while quantitative analysis focused on the processing and interpreting the VES data. The 2-D resistivity structures and geoelectric sections provided a detailed picture of subsurface conditions, aiding in the identification of potential subsurface anomalies that could affect road stability.

RESULTS AND DISCUSSION

The results of the geophysical investigation carried out along Itapa- Ikole highway for road pavement investigation were presented as 2D resistivity structures, VES curves, and tables.

Traverse Line 1

Vertical Electrical Sounding (VES)

The VES interpretation results for traverse line 1 are displayed in Table 1 while the typical VES curves type characteristic of this traverse is shown in Figure 4. The VES curve type that was identified is KH types only, which signifies high resistivity second layer that usually form the subgrade materials for road pavement structures.

Table 1: Summary of the VES Interpretation Results across the Traverse Line 1

VES No	No. of Layers	Resistivity (Ω m)	Thickness (m)	Depth (m)	Lithological Equivalence	Type Curve
1	1	4401.4	0.65	0.65	Top Soil	KH
	2	671.6	0.54	1.19	Laterite	
	3	110.5	6.3	7.5	Weathered Layer (Clayey)	
	4	2386	____	____	Fresh Basement	
2	1	276.3	0.44	0.44	Top Soil	KH
	2	959.2	0.47	0.91	Laterite	
	3	105	8.31	9.2	Weathered Layer (Clayey)	
	4	4368	____	____	Fresh Basement	
3	1	193	0.52	0.52	Top Soil	KH
	2	638.1	2.31	2.83	Laterite	
	3	39.33	3.56	6.4	Weathered Layer (Clayey)	
	4	106623	____	____	Fresh Basement	
4	1	173.2	0.56	0.56	Top Soil	KH
	2	1805	0.70	1.26	Laterite	
	3	104.7	14.12	15.38	Weathered Layer (Clayey)	
	4	6027	____	____	Fresh Basement	
5	1	107.7	0.40	0.40	Top Soil	KH
	2	927.9	0.66	1.06	Laterite	
	3	78.7	11.23	12.3	Weathered Layer (Clayey)	
	4	29987	____	____	Fresh Basement	

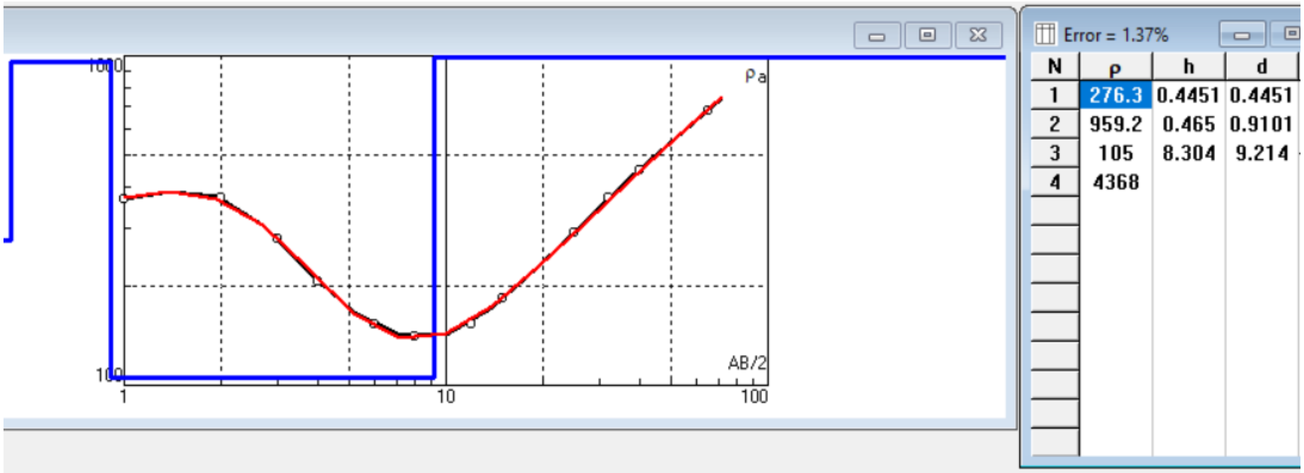

Figure 4: Typical KH-Curve Type of the Study Area along Traverse Line 1

Geoelectrical Section along Traverse Line 1
Figure 5 shows the geoelectric section relating VES 1, 2, 3, 4and 5. The section revealed four (4) geoelectric layers which are the topsoil, lateritic layer, weathered layer and the fresh basement. The topsoil is composed of sandy clay/clayey sand materials with resistivity values ranging between 138 Ω m to 405 Ω m and thickness value that varies from 0.5 m to 1.l m beneath surface layer. The underlying lateritic layer has resistivity values ranging between 502 Ω m and 1453 Ω m with thickness values between 0.6 m to 1.2 m, this layer forms the subgrade materials that directly underlie the road pavement structure. The weathered layer underlying the lateritic layer is predominantly clay. It has resistivity values that ranges from 80 Ω m to 103 Ω m and thickness between 5.3 m and 15.4 m. The fresh basement constitutes the last layer, its resistivity values ranged from 4371 Ω m to infinity (∞) while depth to the rock head ranges from 6.8 m-16.6 m The topsoil/laterite that constitutes the subgrade material on which the road pavement was founded is underlain by significantly thin lateritic subgrade (<1.5 m) and weathered layer with relatively tow resistivity values (<100 Ω m), which is presumed to be composed of clay materials that normally compress on imposing axle load, further resulting into adverse effects on the overlying subgrade materials. Consequently, has effect on the pavement which manifested as potholes, rutting and other forms of road pavement failures.

2-D Resistivity Structure
Figure 6 shows the 2-D resistivity structure along Traverse Line 1. The resistivity image delineated three distinct geoloelectric layers. The topmost layer, primarily consisting of topsoil and laterite, is represented by the color bands ranging from purple to yellow and red. This layer exhibits higher resistivity values, particularly between stations 10 m to 30 m and 60 m to 80 m. The resistivity values in these sections range between 386 Ω m and 1,846 Ω m, which indicate the presence of compacted lateritic materials. The thickness of this layer is approximately 2.3 m on average, which is favorable for road stability as laterite is known for its strength and resistance to deformation under load (Fatoba, 2012, Afolagboye *et al*., 2016).

The second layer, represented by the green color bands, corresponds to the weathered zone. This layer has lower resistivity values, ranging from 14 Ω m to around 424 Ω m, characteristic of clay-rich materials. The clayey nature of this weathered zone, particularly evident between stations 40 m to 60 m and 70 m to 90 m, suggests it is structurally weak and less capable of supporting heavy axle loads from vehicular traffic. The presence of a clayey weathered layer under a thin lateritic subgrade can lead to significant pavement failures, such as the potholes and cracking observed in these sections.

The lowest layer, marked by deep red and purple colors, represents the fresh basement rock, with resistivity values ranging from 2,323 Ω m to approximately 12,722 Ω m. The depth of this basement layer varies considerably, ranging from around 6 m to as much as 13 m in certain sections. A basement depression is suspected between stations 40 m and 65 m, as indicated by low resistivity values. This depression may cause instability in the overlying pavement due to uneven load distribution, which could lead to road failures in the long term.

The road appears to be more stable between stations 45 m to 65 m, attributed to the thicker lateritic subgrade layer, which exceeds 2.0 m in thickness. This thicker subgrade offers more robust support for the pavement, making this section more resistant to deformation. However, the road failures observed between stations 10 m to 30 m and 70 m to 90 m can be attributed to the combination of a thinner lateritic subgrade and a weaker clayey weathered layer beneath, which is insufficient to withstand the pressure from heavy traffic.

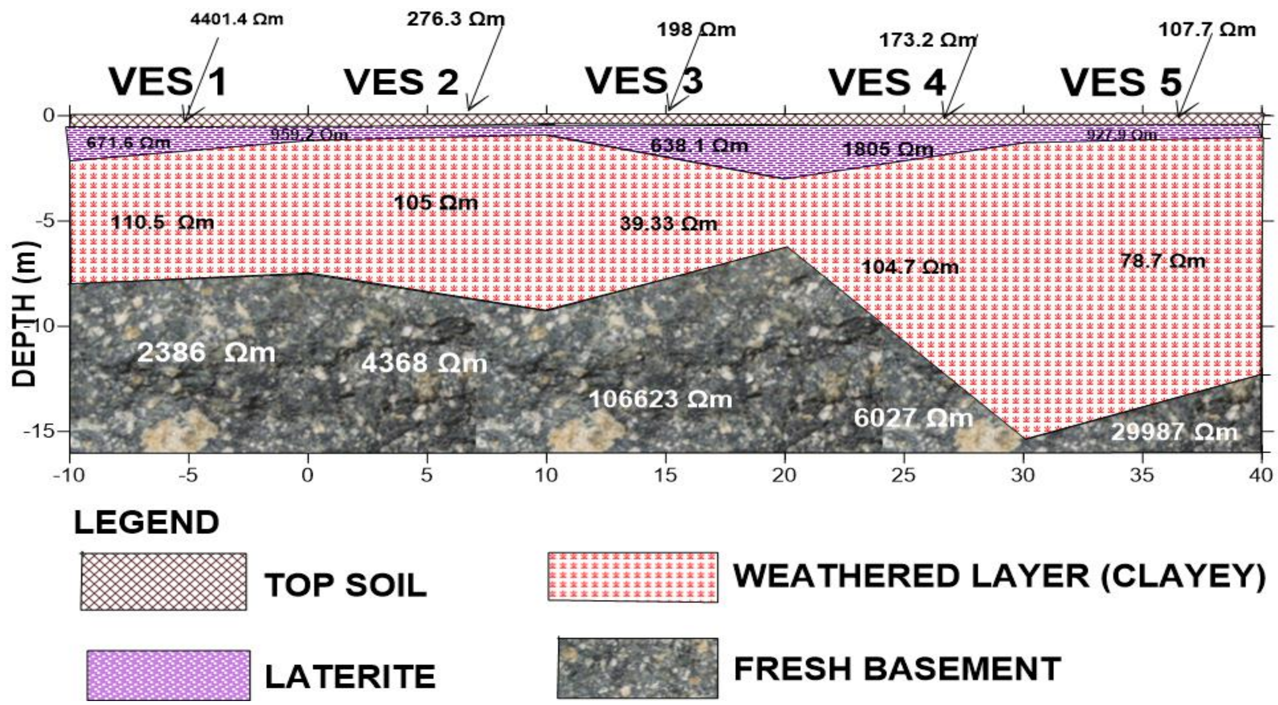

Figure 5: Geoelectric Section Connecting VES 1, 2, 3, 4 and 5 along Traverse Line 1

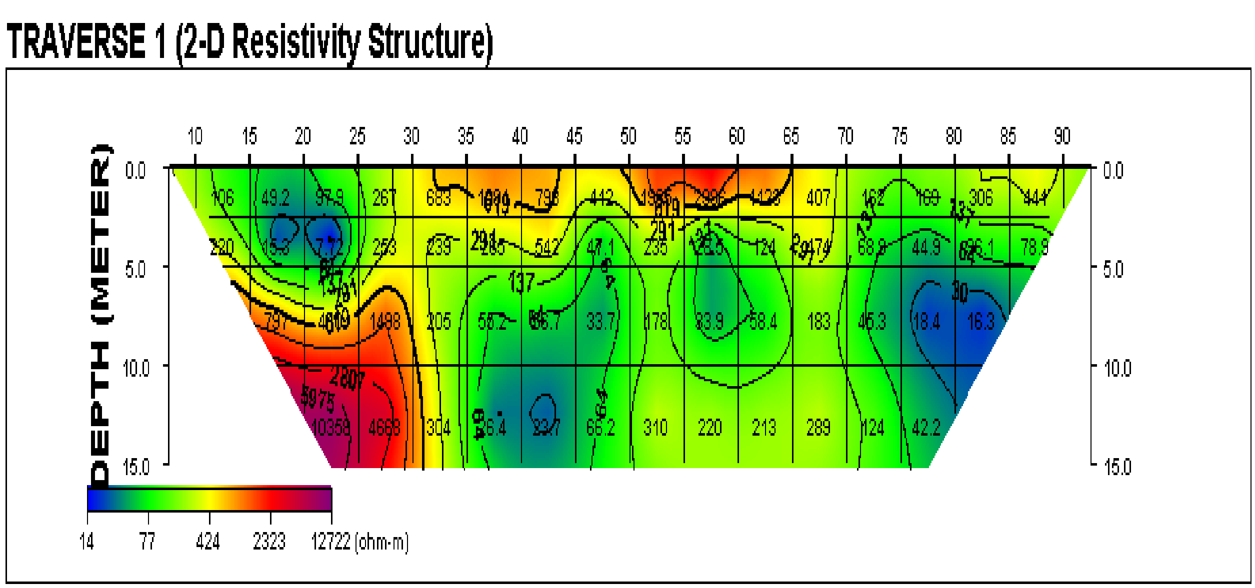

Figure 6: 2-D Resistivity Structure for the Traverse Line 1.

Traverse Line 2

Vertical Electrical Sounding (VES)

The VES interpretation results for traverse line 2 are displayed in Table 2 while the VES curve Type characteristics of this traverse is shown in Figure 7. The VES curve type that was Identified is KH curve type only. This curve type signifies increase in layer resistivity up to the Second layer before a decrease in resistivity and afterwards, continual increase in the resistivity. Hence, four (4) geo-electric layers can be identified, interpreted as the topsoil, laterite, weathered layer (clayey) and fresh basement.

Table 2: Summary of the VES Interpretation Results across the Traverse Line 2

VES No	No. of Layers	Resistivity (Ω m)	Thickness (m)	Depth (m)	Lithological Equivalence	Type Curve
6	1	435.2	1.08	1.08	Top Soil	KH
	2	435.2	1.62	2.70	Laterite	
	3	36.26	3.54	6.24	Weathered Layer (Clayey)	
	4	53314	____	____	Fresh Basement	
7	1	346.8	0.6	0.6	Top Soil	KH
	2	644.8	2.36	2.96	Laterite	
	3	26.6	3.62	6.58	Weathered Layer (Clayey)	
	4	4598	____	____	Fresh Basement	
8	1	345.7	1.26	1.26	Top Soil	KH
	2	606	1.62	2.88	Laterite	
	3	61.23	11.16	14.05	Weathered Layer (Clayey)	
	4	34118	____	____	Fresh Basement	
9	1	83.18	0.49	0.49	Top Soil	KH
	2	531.8	1.61	2.10	Laterite	
	3	31.16	4.41	6.51	Weathered Layer (Clayey)	
	4	779.7	____	____	Fresh Basement	

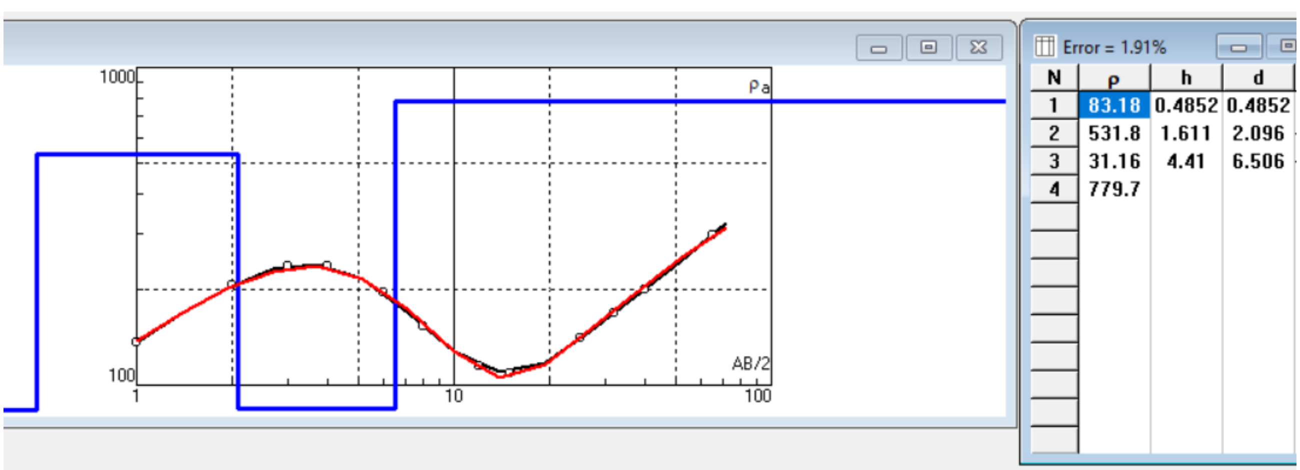

Figure 7: Typical KH-Curve Type of the Study Area along Traverse Line 2

Geoelectrical Section along Traverse Line 2

Figure 8 shows the geoelectric section which relates VES 6, 7, 8 and 9 together and was prepared to image the subsoil sequence in 2-D. This geoelectric section identified four (4) geoelectric layers attributed to the topsoil, lateritic layer, weathered layer and the fresh basement lithologic units. The topsoil has resistivity values varying from 115 to 472 Ω m and thickness values of about 0.7 m to l.0 m. The lateritic layer, found near the surface, had resistivity values ranging from 481 to 771 Ωm and a thickness between 1.0 and 1.8 meters. Below this, the weathered layer showed resistivity values between 49 and 62 Ωm, with a thickness ranging from 4.7 to 10.5 meters. The fresh basement rock, the deepest layer, exhibited resistivity values from 1620 Ωm to infinity, indicating solid, unweathered material. The depth to the rock head (the top of the fresh basement) varied between 7.5 and 12.3 meters across the study area.

The topsoil/laterite constitutes the subgrade material on which the road pavement was placed. The road pavement is underlain by thin laterite (< 2.0 m) as well as the weathered layer that has relatively low resistivity values (<100 Ω m) signifying clay materials that can compress and lead to pavement failures such as potholes and cracking that are observed on the investigated segment of the studied highway.

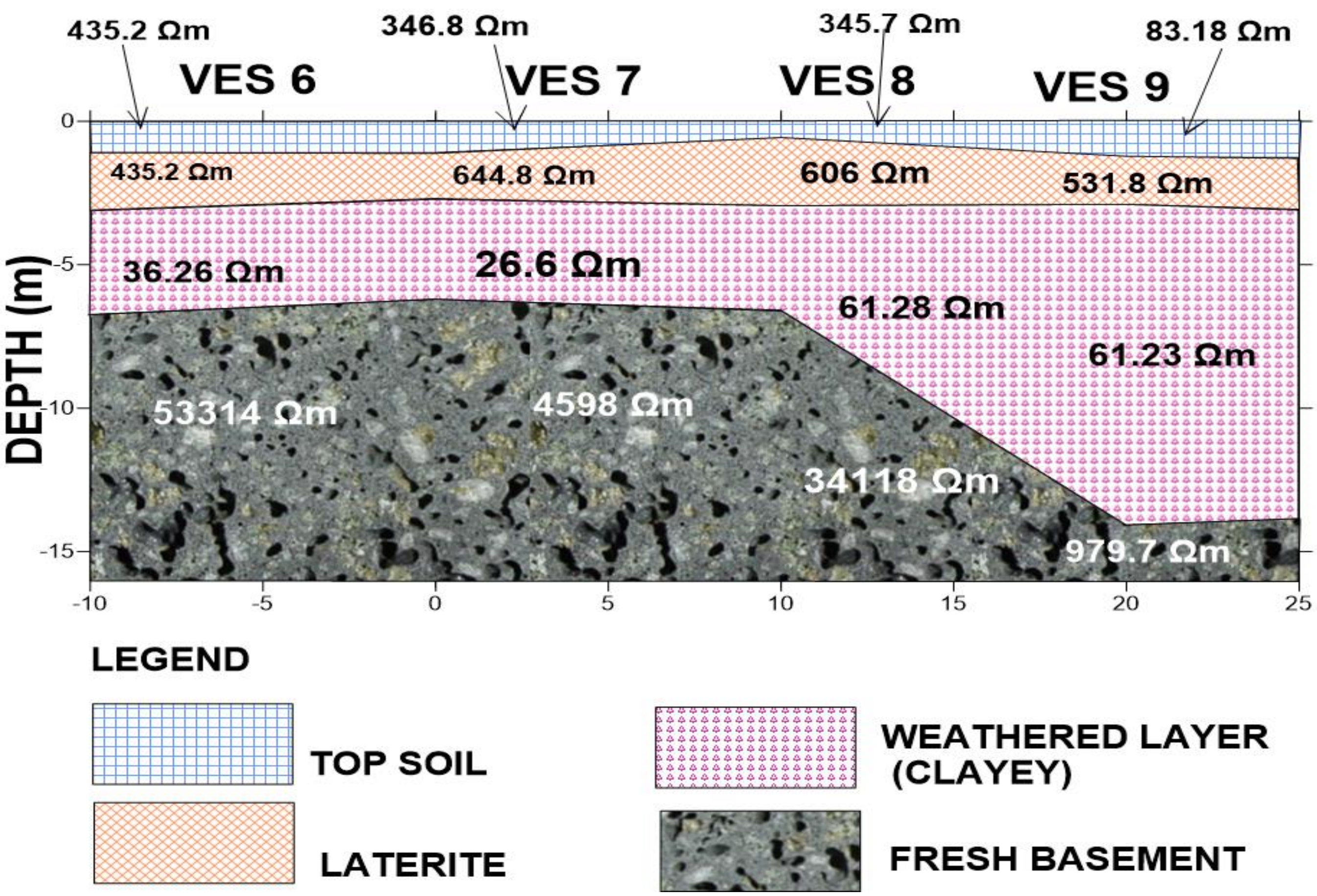

Figure 8: Geo-electric Section Connecting VES 6, 7, 8 and 9 Along Traverse Line 2

2-D Resistivity Structure

Figure 9 shows the 2-D resistivity structure along Traverse Line 1, the resistivity image delineated three distinct geoloelectric layers. The uppermost layer, represented by the red and yellow color bands, corresponds to the topsoil and lateritic subgrade. This layer shows resistivity values ranging from 464 Ω m to approximately 1,693 Ω m and has a thickness slightly exceeding 2.5 m. These relatively high resistivity values are typical of lateritic materials, which are known for their strength and resistance to compression. However, the stability of this layer can vary depending on its thickness and the properties of the underlying layers. Between stations 30 m and 80 m, the lateritic subgrade is thick, providing a more robust foundation for the road pavement. This thickness contributes to the structural integrity of the pavement in this section.

The second layer, indicated by blue and green color bands, represents the weathered zone. The resistivity values in this layer range from 40 Ω m to 156 Ω m, suggesting the presence of clay-rich materials. Clay, being a less resistive and weaker material, compresses easily under heavy loads, making it unsuitable for supporting road pavements. The interaction between the lateritic subgrade and the weathered clay layer is particularly important for road stability, as a thin lateritic subgrade overlying this clayey material can lead to deformation and road failure. In the sections between stations 10 m and 30 m, as well as between 80 m and 95 m, the lateritic subgrade is notably thinner and underlain by the weaker weathered layer. These areas are more vulnerable to surface deformation, such as potholes, due to the reduced support provided by the subsurface layers.

The third layer, represented by yellow, red, and purple bands, corresponds to the fresh basement rock. The resistivity values for this layer range from 453 Ω m to as high as 5,498 Ω m, indicating more consolidated, harder rock material. The fresh basement rock layer is highly resistant to deformation and contributes to the overall stability of the subsurface. However, a significant discontinuity, or basement depression, is observed between stations 40 m and 65 m. This depression may create uneven load distribution, potentially leading to long-term pavement failure, even in areas where the lateritic subgrade is thick. Subsurface weaknesses, such as depressions, can propagate to the surface under the continuous stress of vehicular traffic, eventually manifesting as surface deformities.

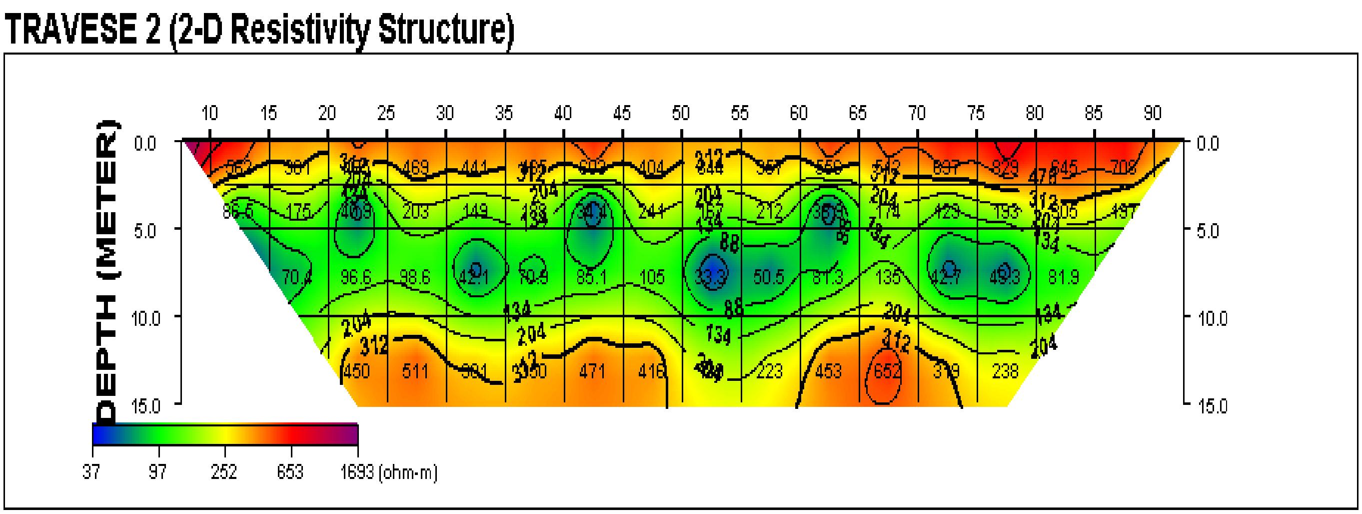

Figure 9: 2-D Resistivity Structure for the Traverse Line 2

CONCLUSIONS

A geophysical survey was conducted at the Oloko section of the Itapa-Ikole highway in Ekiti State, southwestern Nigeria, to investigate the underlying causes of persistent road pavement failures in the region. The electrical resistivity method was employed, utilizing both the Dipole-Dipole and Schlumberger electrode arrays to assess the subsurface conditions. A total of nine Vertical Electrical Sounding (VES) stations were occupied across the study area. The data collected was processed using partial curve matching techniques and interpreted through specialized software, including WinResist and DiprofWIN. The interpretation of the data revealed four distinct geoelectric layers interpreted as: topsoil, laterite, weathered layer, and fresh basement.

The dipole-ipole inverted sections generated along both traverses illustrated significant lateral and vertical varitions in subsurface resistivity values.

These variations provided a detailed image of the subsurface layers. The integration of the VES results and the inverted sections indicated that the highway is devoid of any significant geological structures, such as faults, fractures, joints, or boundaries, that could directly contribute to road pavement instability. This finding suggests that the recurrent road failures in the area are not attributable to geological anomalies but are more likely due to the inadequacy of the subgrade material.

The primary cause of the road pavement failure appears to be the presence of a thin lateritic subgrade However, in some sections of the investigated highway, the lateritic subgrade was measured at barely 1.5 m, rendering it insufficient to provide the necessary support for a flexible pavement. Furthermore, this lateritic layer is directly underlain by a compressible clayey weathered layer. Under the weight of vehicle axle loads, the clay compresses, leading to surface deformities such as rutting and potholes, which were observed along the highway.

Although the highway is currently stable due to recent rehabilitation efforts, the geophysical analysis underscores the need for careful consideration of subgrade thickness and composition in road construction and maintenance. In the absence of an adequately thick lateritic subgrade, roads are prone to recurrent failures, particularly when subjected to heavy traffic loads. Future rehabilitation projects should prioritize enhancing the subgrade's thickness to mitigate similar failures.

RECOMMENDATIONS

It is recommended that during the construction of flexible road pavements, the characteristics of the subsoil should not be the sole factor taken into account. Other critical elements, such as drainage patterns and construction practices, must also be thoroughly considered to ensure the long-term stability and durability of the road. Proper drainage systems are essential to prevent water accumulation, which can weaken the pavement structure and accelerate failure. Additionally, it is crucial that embankments along any highway route be filled with high-quality, competent borrowed materials. This approach will help to avoid failures resulting from subsurface depressions, thereby enhancing the overall integrity of the pavement structure and reducing the likelihood of premature road deterioration.

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