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ORIGINAL PAPER

Application of electrical resistivity in evaluating a section of road conditions—a case study in Ifaki-Oye-Ikole Ekiti Highway, Nigeria

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Abstract

The objective of this study was to use electrical resistivity method in evaluating and characterizing a section of the road subgrade conditions for possible cause(s) of pavement failure. One (1) traverse of 2-D electrical resistivity and geoelectrical resistivity for ten (10) Vertical Electrical Soundings (VES) data were acquired using ABEM Terrameter SAS 300. The 2-D electrical resistivity data collected was processed with the Dippro™ 4.0 software to obtain inverse model 2-D resistivity structure while the apparent resistivity data for VES were processed with the WinResist software to obtain geoelectric layers of the subsurface. The model 2-D resistivity structure and geoelectric layers were correlated to evaluate the subsurface section of the road conditions. Analyzed results revealed four (4) geologic units (layers) namely: the topsoil, laterite, weathered layer, and the fresh basement. The subgrade of the failed section was underlain by low resistivity earth materials suspected to be clay deposit with resistivity value $< 50\ \Omega$m which may be responsible for the instability that cause the road failure. Furthermore, low resistivity-weathered materials of resistivity values $< 100\ \Omega$m within basement depression presumed to be fractured beneath the failed section may also be accountable for the weakening of the subgrade that caused the road to fail. In conclusion, excavation of these low resistivity subgrade materials and filling them with competent material are the best possible solution during the design and preconstruction stage of the road pavement.

Keywords 2-D electrical resistivity structure · Low resistivity subgrade · Geoelectric section · Road failure · Vertical electrical soundings

Introduction

Most Nigeria road fails after few months of its construction and this failure was the result of poor design and drainage factors (Adenika et al. 2018; Divine-favour 2015; Momoh et al. 2008). Proper design is necessary for a good road that will last for a period of time during its usage (Adenika et al. 2018). Modern road design is based on the bitumen-based binding, which consists of four layers namely surface layer, base layer, sub-base layer, and the subgrade (Fig. 1). The surface, base, and sub-base layer constitute the pavement whereas the subgrade is the earth materials (geology) in which the pavement is founded upon. However, if the paved road is constructed on a weak or incompetent geology, failure is imminent because it is the pavement foundation. The subgrade is affected by several geological and hydrogeological factors such as clay, fractures, faults, groundwater, hydraulic conductivity, and erosion that can pose serious damage to the pavement. Therefore, it is imperative to recognize this problem posed by these geological factors. Geophysical method of investigation using electrical resistivity can help to solve this problem because it provides a non-invasive method of imaging the subsurface without much destruction to the subsurface soils. Electrical resistivity method has made a good contribution in investigating and characterizing subsurface geology and hydrogeology conditions (Adenuga & Popoola 2020; Aizebeokhai et al. 2017; Sharafeldin et al. 2017, 2019; Swileam et al. 2019a, 2019b). Bery and Saad (2012) have conducted an electrical resistivity laboratory test to characterize the engineering properties of tropical clayey sand soil by empirically correlating electrical parameter with percentage liquid limit, plastic limit, plasticity index, moisture content, and effective soil cohesion. The result showed that resistivity is directly proportional to

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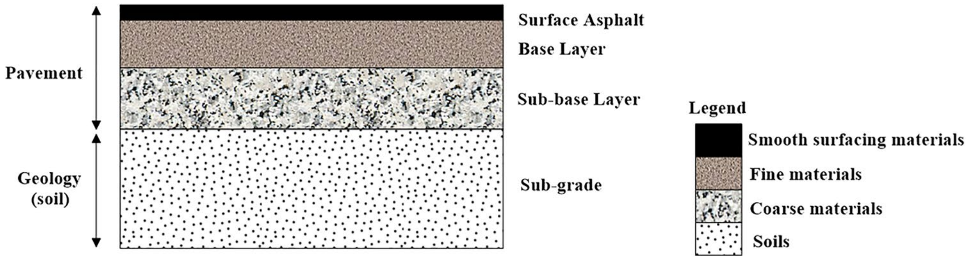


Fig. 1 A Typical road cross section (layers)

effective cohesion. Electrical resistivity is significantly influenced by water content because electrical resistivity decreases with increasing dry densities due to soil particle compactness and better continuity (Bai et al. 2013). Also, Aizebeokhai et al. (2017) have used electrical resistivity method to characterize the subsurface geology to delineate aquifer units beneath the subsurface. Likewise, Sharafeldin et al. (2019) have used electrical resistivity to investigate the hydrogeological conditions of the Great Pyramid of Gaza to characterize the subsurface aquifer groundwater table elevations. Consequently, in Nigeria, several researchers have used electrical resistivity method to investigate the subsurface geology of a failed section of paved road (Adenika et al. 2018; Ifabiyi & Kekere 2013; Layade et al. 2017; Momoh et al. 2008; Osinowo et al. 2011); poor road designed (Divine-favour 2015); engineering properties of soil in failed section of road (Olofinyo et al. 2019); and structural features (Adesola et al. 2017; Akintorinwa et al. 2010) in road failure studies in Nigeria. However, other researcher identified the role of geophysical methods (Jegede et al. 2016) and geotechnical methods (Adiat et al. 2017; Onuoha & Onwuka 2014) in the continuous road failure in Nigeria but their focus was primarily on the effect the failure caused after construction rather than the possible cause of road failure before construction. Therefore, the objective of this study was to use electrical resistivity method to evaluate a section of road conditions for detailing the subsurface (subgrade) for possible cause(s) of road failure in the Ifaki-Omuo Ekiti federal highway. The outcome of the measured field and model electrical resistivity data was statistically analyzed to test for uncertainty in the data for good calibration. The study used 2-D Wenner survey and VES to answer these questions: (i) Is geophysics relevant in the design of road pavement? (ii) Is the geophysical method capable of identify possible cause(s) of road failure in the preconstruction and post construction stage of road pavement?

Location and geology of the study area

The study area lies within latitudes (N07.797249, N07.789936) and longitudes E005.302148, E005.279918. The study site is located along Ifaki-Ayegbaju Ekiti route of the Ifaki-Omuo Ekiti Federal Highway that connects Ekiti State and Kogi State. The failed section of the road is shown in the Fig. 2. Ifaki-Ayegbaju axis of the Ifaki-Omuo Ekiti Federal Highway is undulating with high and low relief along the study location. The study area is drained by the Oye River. The climate condition of the study area enjoys tropical climate with two distinct seasons of wet and dry. These are the rainy season (April–October) and the dry season (November–March). Temperature ranges between 21 and 28 °C with relative high humidity of about 80% (Data obtained from Oye Local Government Area). The geology of study area is underlined with Precambrian igneous and metamorphic rocks of the basement complex of southwestern Nigeria (Odeyemi 1981). The major lithologic units are the migmatite-gneiss complex; the older granites; the charnockitic rocks; the slightly migmatised to unmigmatised paraschists and metaigneous rocks and unmetamorphosed granitic rocks (Rahaman 1976). The major lithologic units in the study location and its environment are older granite, granite-gneiss, and migmatite-gneiss (Babalola et al. 2017). The migmatite-gneiss complex is composed mainly of early gneiss, mafic and ultramafic bands, and the granitic of felsic components. The older granites comprise the porphyritic-biotite granite and the medium-coarse grained granite gneiss (Bayowa et al. 2014).

Methodology and data processing and interpretation

Global Positioning System (GPS) instrument was used to acquire the geographical coordinates (Northing and Easting) and topographic elevation to geo-reference the established traverses and the stations on the base map. ABEM Terrameter SAS 300 including its accessories was used for electrical resistivity data collection. 2-D electrical resistivity and 1-D Vertical Electrical Soundings (VES) data were acquired using Wenner and Schlumberger arrays respectively. Wenner array was used for the 2-D data acquisition, because it has a good vertical resolution and highly sensitive to lateral inhomogeneities which were important for the study and advantageous for data inversion. The depth of investigation for Wenner array is related to the common spacing, a, between the current and potential electrode pairs (Olabode and Ocho 2018). Wenner array was carried

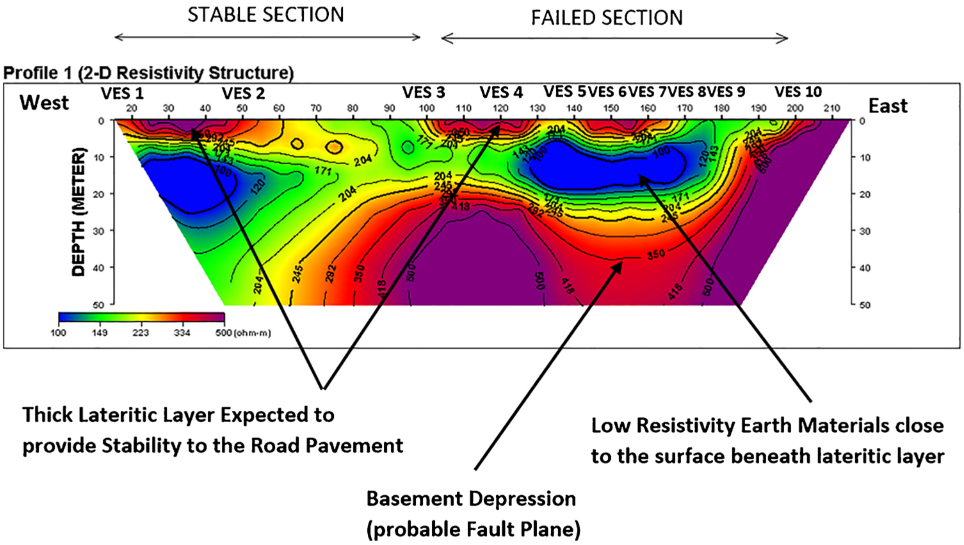
Fig. 2 Failed sections of the Ifaki-Omuo Ekiti Highway

out along the established transverse with electrode spacing intervals of 5, 10, 20, 30, 40, and 50 m. The 2-D data acquired from field investigation was inverted using the Dippro™ 4.0 software (Dippro 2000). The 2-D resistivity structure of the subsurface was obtained from Least square inversion method. VES data were collected using Schlumberger array with maximum half current electrode spacing (AB/2) varied from 1 to 100 m along the established transverse in 10 locations. Schlumberger array was suitable and good for depth soundings. The VES curves were interpreted quantitatively using partial curve matching and computer-assisted forward modeling using the WinResist software (Vander Velpen & Sporry 1993). The WinResist plotted apparent resistivity values against half space distance of current electrodes in a log–log graph. It uses the least square method to fit a line of best fit in the measured data to minimize RMS error. Statistical data analysis was performed on the measured data and model results using mean, variance, and standard deviation. These statistical tools were used to obtain lateral variation of the subsurface geology at different depths of 5 m, 10 m, 15 m, and 25 m for Wenner measured data at 10-m, 20-m, 30-m, and 50-m intervals, and VES data at 15 mm 25 m, 40 m, and 65 m half space distance of current electrodes (AB/2) respectively. The model results were taken at 15 m depth for 2-D Wenner model 30-m interval and VES model result 40 m AB/2.

Results and discussion

Figure 3 shows 2-D resistivity structure of the subsurface beneath the failed and stable sections of the road pavement. The stable section is underlain by a thick lateritic layer with high resistivity values > 200 Ωm. The lateritic layer has thickness greater than 5 m beneath the stable section and sits conformably on a weathered layer zone with resistivities less than 100 Ωm in the eastern part. The high resistivity values of the lateritic layer are an indication of low water content of the lateritic layer because electrical resistivity increases with decrease water content (Bai et al. 2013). It has also been shown that electrical resistivity is directly proportional to effective cohesion (Bery & Saad 2012). Consequently, the lateritic layer may contain low water content and more compacted (cohesion) with considerable thickness that was enough to provide the stability needed for the pavement and preventing it from undergoing failure. The failed section is located on basement depression capped by a thin lateritic layer which is underlain by a concave shaped low resistivity-weathered material of < 100 Ωm on the average (Fig. 3). This low resistivity-weathered layer with resistivities < 100 Ωm situated on a basement depression is presumed to be a fault/fracture zone (Adenika et al. 2018; Adesola et al. 2017) (Fig. 3). The low resistivity is caused by high amount of water content

Fig. 3 2-D resistivity structure (pseudosection) of the subsurface beneath the pavement

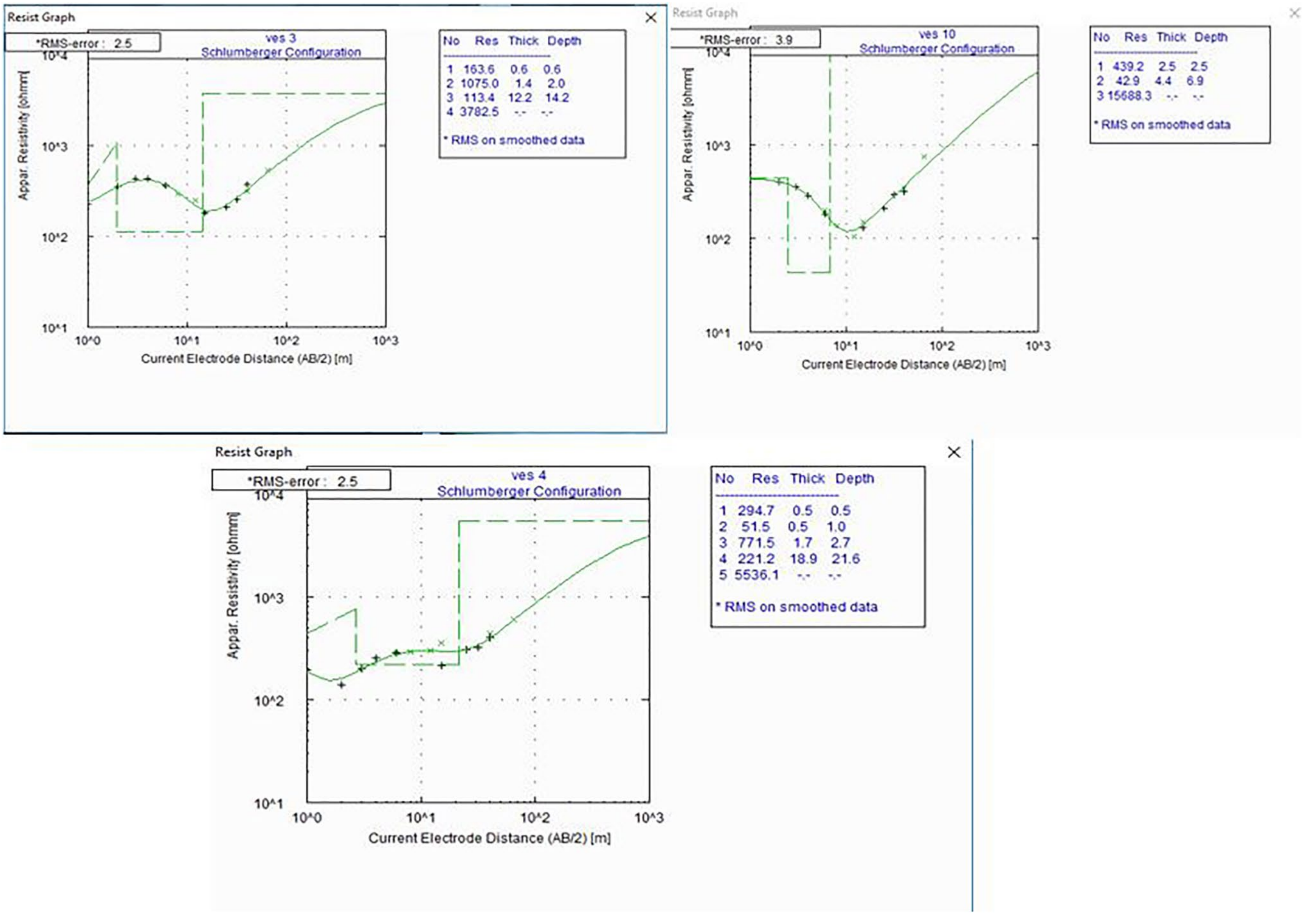


Thick Lateritic Layer Expected to provide Stability to the Road Pavement

Low Resistivity Earth Materials close to the surface beneath lateritic layer

Basement Depression (probable Fault Plane)

in the weathered layer because electrical resistivity decrease with increase water content (Bai et al. 2013). This low resistivity-weathered layer will be highly compressible during loading due to low cohesion because the lower the electrical resistivity the lower the effective cohesion (Bery & Saad 2012). The cause of the road failure was due to this low resistivity-weathered layer because surface runoff may ingress into the subsurface to saturate the weathered layer which weakens the subgrade and cause the road pavement to fail.



*RMS-error : 2.5

No	Res	Thick	Depth
1	163.6	0.6	0.6
2	1075.0	1.4	2.0
3	113.4	12.2	14.2
4	3782.5	-.-	-.-

* RMS on smoothed data

*RMS-error : 3.9

No	Res	Thick	Depth
1	439.2	2.5	2.5
2	42.9	4.4	6.9
3	15688.3	-.-	-.-

* RMS on smoothed data

*RMS-error : 2.5

No	Res	Thick	Depth
1	294.7	0.5	0.5
2	51.5	0.5	1.0
3	771.5	1.7	2.7
4	221.2	18.9	21.6
5	5536.1	-.-	-.-

* RMS on smoothed data

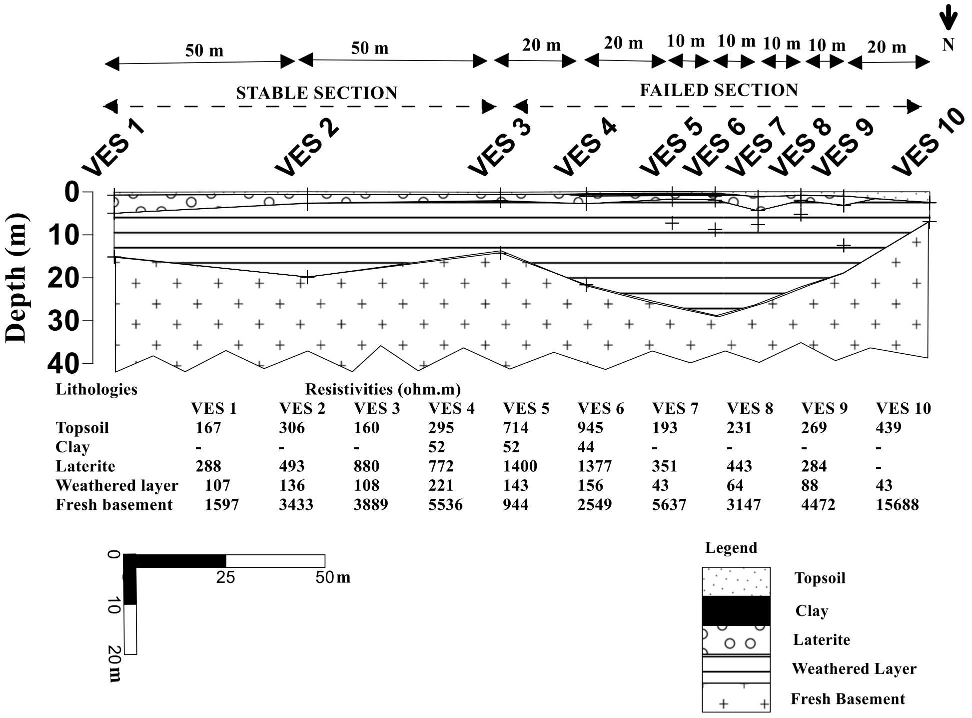
Fig. 4 Typical curve types in the study location are shown in VES 3 is KH, VES 4 is HKH, and VES 10 is H

Figure 4 shows the characteristics VES curve types with the plot of apparent resistivity, (ρ), against separation distance AB/2. Also, Table 1 shows the summarised interpreted results of VES data locations, curve type, layer resistivities, layer thickness, and lithologies which revealed four (4) geologic units delineated from the study location namely: topsoil, lateritic layer, weathered, and fresh basement. Figure 5 shows the geoelectric section generated from the interpreted VES data. The stable section covers 0 to 100 m distance from the east towards west. It is underlain by a thin topsoil of resistivities generally above 160 Ωm, a relatively thick lateritic layer and thick weathered layer with resistivities generally greater than 100 Ωm in most part, which validates the result obtained in Fig. 3. The failed section, which lies between 110 and 190 m, is underlain by thin clay deposit of about 0.5 m thick and resistivity value < 52 Ωm across VES

Table 1 VES data interpretation result in study area

VES	Curve type	Resistivity (Ωm)	Thickness (M)	Depth (M)	Lithologies
1	KH	167	0.7	0.7	Topsoil
		288	4.2	4.9	Lateritic
		107	10.3	15.1	Weathered layer
		1597	——-	——	Fresh basemeent
2	KH	306	0.6	0.6	Topsoil
		493	2.1	2.4	Lateritic
		136	17.1	19.8	Weathered layer
		3433	——	———-	Fresh basement
3	KH	160	0.6	0.6	Topsoil
		880	1.4	2.0	Lateritic
		108	12.2	14.2	Weathered layer
		3889	——-	——	Fresh basement
4	HKH	295	0.5	0.5	Topsoil
		52	0.5	1.0	Clay
		772	1.7	2.7	Lateritic
		221	18.9	21.6	Weathered layer
		5536	———	———	Fresh basement
5	HKH	714	0.3	0.3	Topsoil
		52	0.5	0.8	Clay
		1400	0.9	1.7	Lateritic
		143	25.5	27.2	Weathered layer
		944	———	—-	Fresh basement
6	HKH	945	0.3	0.3	Topsoil
		44	0.6	0.9	Clay
		1377	1.0	1.9	Lateritic
		156	26.8	28.7	Weathered layer
		2549	———	—-	Fresh basement
7	KH	193	1.1	1.1	Topsoil
		351	3.2	4.3	Lateritic
		43	23.3	27.6	Weathered layer
		5637	——-	—-	Fresh basement
8	KH	231	0.7	0.7	Topsoil
		443	1.2	1.9	Lateritic
		64	23.4	25.2	Weathered layer
		3147	——-	—-	Fresh basement
9	KH	269	1.0	1.0	Topsoil
		284	2.1	3.1	Lateritic
		88	19.3	22.4	Weathered layer
		4472	———	———	Fresh basement
10	H	439	2.5	2.5	Topsoil
		43	4.4	6.9	Weathered layer
		15,688	———	_——	Fresh basement

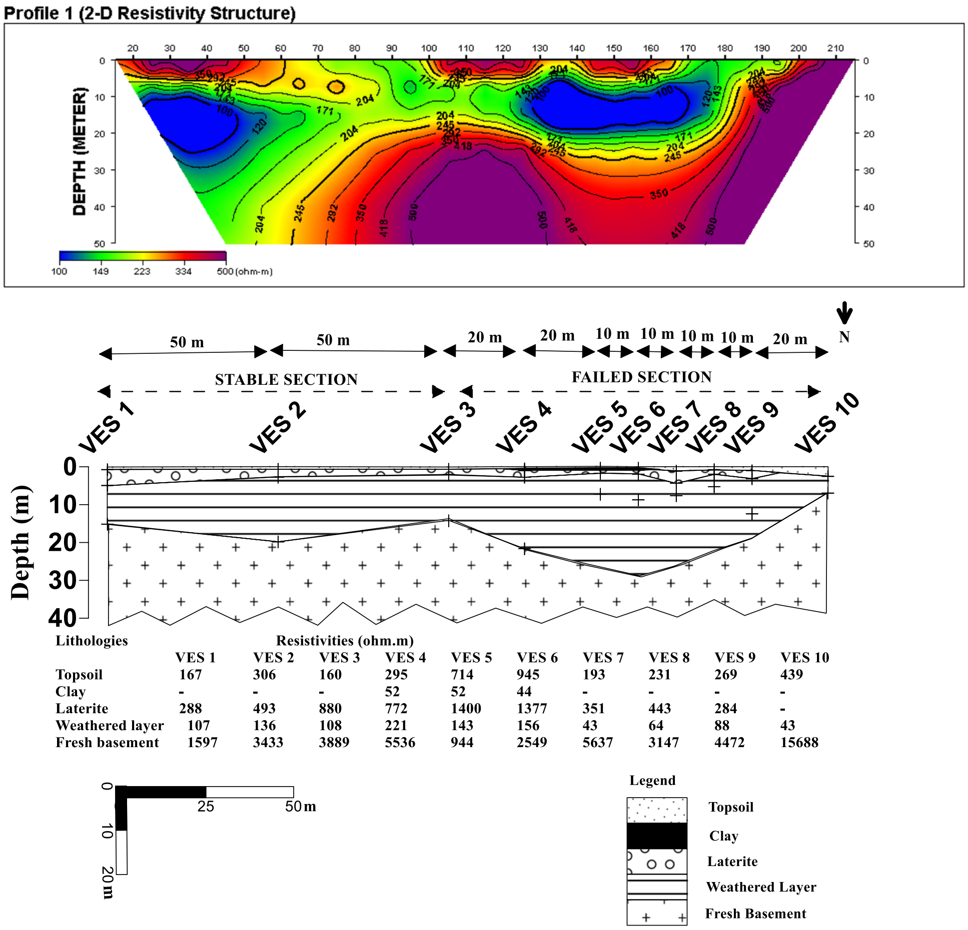
Fig. 5 Geoelectric section across the study area



Resistivities (ohm.m)

Lithologies	VES 1	VES 2	VES 3	VES 4	VES 5	VES 6	VES 7	VES 8	VES 9	VES 10
Topsoil	167	306	160	295	714	945	193	231	269	439
Clay	-	-	-	52	52	44	-	-	-	-
Laterite	288	493	880	772	1400	1377	351	443	284	-
Weathered layer	107	136	108	221	143	156	43	64	88	43
Fresh basement	1597	3433	3889	5536	944	2549	5637	3147	4472	15688

Fig. 6 Juxtaposing results of different techniques to show correlation



Resistivities (ohm.m)

Lithologies	VES 1	VES 2	VES 3	VES 4	VES 5	VES 6	VES 7	VES 8	VES 9	VES 10
Topsoil	167	306	160	295	714	945	193	231	269	439
Clay	-	-	-	52	52	44	-	-	-	-
Laterite	288	493	880	772	1400	1377	351	443	284	-
Weathered layer	107	136	108	221	143	156	43	64	88	43
Fresh basement	1597	3433	3889	5536	944	2549	5637	3147	4472	15688

4, 5, and 6 and extends from 110 to 140 m beneath a thin topsoil. The clay may expands and contracts during wet and dry seasons resulting in instability that can cause the road to fail (Adenika et al. 2018; Momoh et al. 2008), as it was observed in Fig. 3. The weathered layer underneath VES 4, 9, and 10 is relatively thick and has low resistivity values of less than 100 Ωm suggesting a weak and incompetent layer (subgrade) as a result of ingress of water during rainfall (Adesola et al. 2017; Layade et al. 2017) (Fig. 5). The clay deposit (kaolin) may have resulted from the hydrothermal alteration of granitic basement in the study area. Groundwater can be collected beneath VES 4 to VES 9 within the basement depression with a linear feature presumed to be fracture or fault zone (Adenika et al. 2018; Adesola et al. 2017; Momoh et al. 2008; Olabode et al. 2017). The continuous loading of the under compacted topsoil may likely threaten the stability of the road causing instability that resulted in road failure (Olabode et al. 2020). It can be deduced that the thick lateritic layer and topsoil between VES 1 to VES 3 within 0–100 m distance may be responsible for the stability of the road pavement in the east whereas the thin clay deposit may be responsible for the road pavement failure in the west, which validates the result of the 2-D resistivity data. Figure 6 shows the juxtaposition of the two different techniques used in the study to obtain the correlation between their results. The bedrock relief is undulating and roll from east to west with depth to the bedrock varied between 6.9 and 28.7 m. Shallow basement is observed in the east of the study from the results of the two techniques (Fig. 6). Basement depression was observed within the distance of 120 to 200 m while basement rise was also observed in the 100 m mark and thick lateritic layers were identified in both the 2-D resistivity structure and geoelectric section in the west within 0–50 m distance. The juxtaposition of the results revealed that there is a significant correlation between the techniques used.

The uncertainty test of data variability for the 2-D Wenner measured data and model result was presented in Table 2 and the VES measured data and model result of data variability are also presented in Table 3. The result of statistical data analysis shows high soil resistivity variability in the Wenner 2-D measured data within 0–10 m depth and VES measured data within 10–25 m depth (Tables 2 & 3). The Wenner 2-D model result standard deviation of 36 at 15 depths revealed a close relation to the measured data with standard deviation of 41 suggesting that the model is accurate while the VES model standard deviation of 50 at the same 15 m depth showed large deviation from the measured data with standard deviation of 153 indicating point sampling but the model may be accurate compared to the Wenner 2-D model. It can be concluded that the low or high resistivity variability observed in VES model was due to point sampling but not necessarily homogeneity or inhomogeneity of materials at these depths, whereas the high resistivity variability that was observed in the Wenner 2-D measured data within 0–10 m depth was the consequence of inhomogeneity and the low resistivity variability below 10 m depth was due to homogeneity of the materials at this depth (Table 2), which supports the results of the 2-D resistivity structure and geosection.

Table 2 The variability of 2-D Wenner measured data and model result

2-D Wenner measured data				2-D Wenner model	
Interval (m)	Depth (m)	Mean (μ)	Standard deviation (σ)	Mean (μ)	Standard deviation (σ)
10	5	256	125		
20	10	221	79		
30	15	196	41	121	36
50	25	289	77		

Table 3 The variability of VES measured data and model result

VES measured data				VES model	
AB/2 (m)	Depth (m)	Mean (μ)	Standard deviation (σ)	Mean (μ)	Standard deviation (σ)
15	5	202	54		
25	10	267	69		
40	15	433	153	118	50
65	25	696	340		

Conclusion

Application of electrical resistivity method has been used to investigate the failed section portion between Ifaki and Ayegbaju axis of the Ifaki-Omuo Ekiti Highway to evaluate and determine the relevance of geophysical method in road construction and statistical analysis of uncertainty in the measured resistivity data and model result. The geophysical method was able to identify the possible cause of the road failure and the uncertainty of the measured resistivity data were well detailed. The results of the investigation were correlated, and the following conclusions were reached:

- The measured resistivity data show high resistivity variability within 0–10 m depth because the materials were inhomogeneous and low resistivity variability below 10 m depth due to homogeneous of the materials at this depth.

- Four (4) geologic units (layers) namely: the topsoil, laterite, weathered layer, and the fresh basement.
- The pavement failed because the geology beneath the failed section is underlined by fractured basement depression that is composed of saturated low resistivity and less cohesive weathered layer which may be highly compressible during loading.
- The pavement failure was also ascribed to the identified thin layer of clay deposit with resistivity value of < 52 Ωm, as a result of hydrothermal alteration of granitic basement, which extends from VES 4 to VES 6 with a length greater than 30 m.

Excavation of this weak and incompetent material (subgrade) and filling with competent material are the best possible solution during the design and preconstruction stage of the road pavement.

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Author contribution O.P.O is responsible for the project conceptualization, design, acquisition, processing, interpretation, and write-up. A.A. assisted in the data acquisition and processing. All authors read and approved the final manuscript.

Data availability The datasets analyzed in the study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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