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Integrated geophysical investigation of subsurface conditions influencing road failure along the Lusada–Ketu–Ado Odo Road, Ogun State, Southwestern Nigeria

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Abstract

The Lusada–Ketu–Ado Owie Road, which links Crawford University, Lusada Market, and Ado Owie town, has experienced significant structural degradation, reflective of the growing trend of road failures across Nigeria. This study employs an integrated geophysical approach using both one-dimensional Vertical Electrical Sounding (VES) and two-dimensional Electrical Resistivity Tomography (ERT) to investigate subsurface conditions contributing to the road's failure. The Wenner array configuration was utilized with an inter-electrode spacing of 5 m across four ERT profiles, and six levels of data acquisition per profile. VES data were also acquired at each profile location, with one site (VES 3/Profile 3) serving as a control due to its satisfactory pavement performance. Resistivity values varied significantly across profiles: 52.3–3183 Ωm in Profile 1, 136–1522 Ωm in Profile 2, 252–6362 Ωm in Profile 3, and 198–25595 Ωm in Profile 4. Low-resistivity zones (less than 126 Ωm) detected across all profiles indicate the presence of water-saturated clayey materials, known for their high porosity, low permeability, and poor load-bearing capacity—factors that lead to swelling, differential settlement, and eventual road failure. In contrast, high-resistivity zones (>1800 Ωm) suggest compacted, competent subsurface materials conducive to long-term pavement stability.

The comparison between 1D and 2D results highlights the limitations of using VES alone, as it fails to capture lateral heterogeneities and discontinuities evident in the 2D profiles. This integrated geophysical approach proves crucial for identifying critical failure zones and informing targeted engineering interventions. Recommendations include the excavation of unstable clay-rich soils, replacement with suitable materials, and implementation of robust drainage systems. The findings underscore the value of combining geophysical techniques for sustainable road design, rehabilitation, and maintenance in geologically complex environments.

Keywords: Vertical Electrical Sounding (VES); Electrical Resistivity Tomography (ERT); Geotechnical investigation; Subsurface characterization;

1. Introduction

Road infrastructure is fundamental to economic growth and social integration, especially in developing countries like Nigeria, where road transport remains the most accessible and widely used mode of transportation [1][2]. However, the persistent deterioration of road pavements—manifesting as cracking, potholes, rutting, and surface deformation—continues to undermine transportation efficiency, safety, and service delivery [3][4]. Nigerian roads, often subjected to excessive axle loads and insufficient maintenance, frequently fail before reaching their design lifespan [5-12]. Despite ongoing rehabilitation efforts, road failure along the Lusada–Ketu–Ado Owie corridor in Ogun State remains a recurring issue. [13] described Nigeria's road condition as "scandalous," and researchers have consistently highlighted the neglect of subsurface conditions during road construction as a key factor [14]. Geological and geotechnical variables such as

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lithological heterogeneity, the presence of laterites, fractures, faults, and ancient stream channels have been identified as significant contributors to pavement failure [15-21]. The inappropriate use of lateritic soils, poor drainage design, and high groundwater tables have further exacerbated subgrade instability [22-24].

Furthermore, inadequate drainage and geomorphological oversight promote water infiltration and subsoil weakening, ultimately accelerating material fatigue [25-29]. As highlighted by [30] and [31], even well-constructed roads deteriorate without routine maintenance.

To mitigate these challenges, integrating geophysical techniques into preconstruction planning has gained attention. Electrical resistivity methods particularly Vertical Electrical Sounding (VES) and 2D resistivity imaging offer cost-effective, non-invasive means to evaluate subsurface conditions, delineate lithological boundaries, and identify geotechnical weaknesses. These techniques detect variations in electrical resistivity associated with moisture content, porosity, and material composition, thereby revealing concealed anomalies critical to pavement stability [15][16].

This study focuses on the geophysical investigation of a frequently failing road segment linking Crawford University, Lusada Market, and Ado Owie town. The route is economically vital, particularly for local farmers, but its degradation has hindered agricultural transport, discouraged commercial usage, and enabled criminal activity. By applying integrated VES and 2D resistivity methods, this research aims to characterize the subsurface conditions responsible for road failure, map anomalies beneath the pavement, and recommend sustainable design strategies suited to geologically sensitive environments.

2. Location and Geology of the Study Area

The study area covers the Lusada–Ketu–Ado Owie road corridor in Ogun State, Southwestern Nigeria, situated between longitudes 3°05′01.4″E and 3°04′19.7″E, and latitudes 6°35′03.6″N and 6°35′55.2″N (Fig. 1). This road network serves as a critical link between Lusada Market, Crawford University, and the town of Ado Owie. Additionally, it connects to the Atan–Agbara expressway via Lusada, thereby providing access to Lagos State on the eastern flank. The region is predominantly rural, with agriculture as the primary economic activity among residents. Climatically, the study area lies within the humid equatorial belt and is characterized by two distinct seasonal patterns: the rainy season and the dry season. The rainy season typically spans from April to July (marked by intense precipitation) and October to November (with moderate rainfall). The dry season is interrupted by a brief interlude in August and September and extends more prominently from December through March. Annual precipitation in the area exceeds 1,800 mm, and the mean annual temperature hovers around 27°C. Humidity levels remain high throughout the year, generally above 70%, except during the harmattan period in December, when it stops briefly. Vegetation in the region is largely influenced by the climatic and topographic setting, comprising swamp forests, wetlands, and mangrove ecosystems. The low-lying terrain and proximity to the coast contribute to the prevalence of tropical swamp forest zones with both freshwater and brackish water influences. The physiographic characteristics of the study area reflect the general relief and drainage features associated with Nigeria’s coastal plain [32].

Geologically, the Lusada–Ketu–Ado Owie road lies within the eastern margin of the Dahomey Basin (also referred to as the Benin Embayment), a coastal sedimentary basin situated along the West African continental margin (Fig 2). This basin stretches from southeastern Ghana through southern Togo and the Republic of Benin into the southwestern part of Nigeria, where it terminates at the Benin Hinge Line a major structural boundary that delineates the western limit of the Niger Delta Basin [33]. The subsurface lithology of the Dahomey Basin comprises a sequence of Cretaceous to Recent sedimentary units. These include marine and non-marine deposits ranging from shales, sandstones, claystones, and limestones to unconsolidated alluvial materials. In the Nigerian sector of the basin, the sedimentary sequence is underlain by Precambrian Basement Complex rocks composed of migmatites, banded and granite gneisses, which are intruded by granitic and charnockitic bodies of Pan-African age [34]. Tectonically, the Dahomey Basin originated during the Late Jurassic to Early Cretaceous rifting events associated with the opening of the South Atlantic Ocean. Its evolution was controlled by extensional faulting and subsidence, resulting in variable sediment thickness across the basin. The thickest sediment accumulations are observed near the Nigeria–Benin border, slightly west of the study area [35]. The geological and geomorphological setting of this region exerts a significant influence on the geotechnical behavior of near-surface materials, which in turn affects the performance and stability of engineering structures such as roads. Therefore, a detailed understanding of the local geology is imperative for interpreting the causes of road failure and designing appropriate mitigation strategies

3. Materials and Methods

3.1. Survey Design and Data Acquisition

The geophysical survey was conducted using a Campus Resistivity Meter, employing both the Schlumberger Vertical Electrical Sounding (VES) and Wenner array 2D resistivity imaging techniques. A total of four VES points and four 2D resistivity profiles were established within the study area. The survey lines ranged in length from 55 m to 100 m, with an inter-electrode spacing of 5 m for the Wenner array. The orientation of the traverses was designed to optimize subsurface imaging across different directions: Profiles 1 and 2 were oriented in the North–South (N–S) direction, while Profiles 3 and 4 were aligned East–West (E–W).

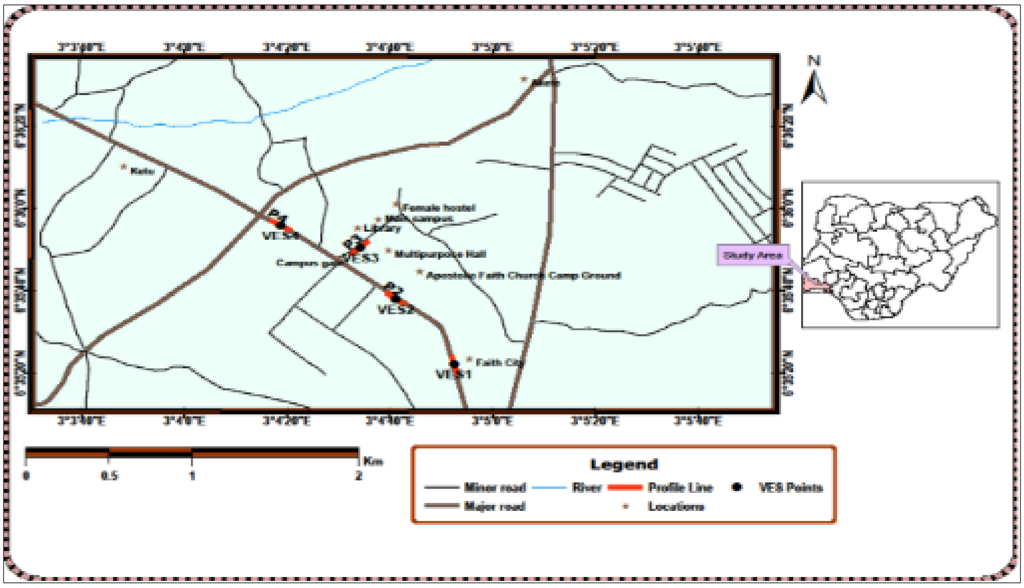


Figure 1 Location map showing the Lusada-ado - owie road

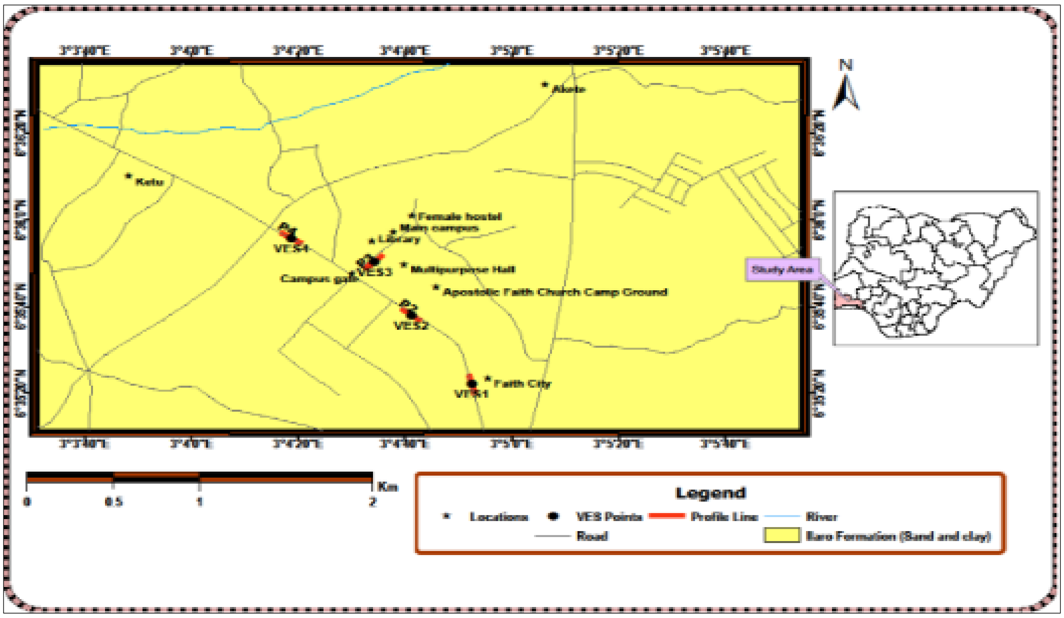


Figure 2 Geologic map of the study area.

Vertical Electrical Sounding (VES) Initial interpretation of the VES data was performed manually. Apparent resistivity values were plotted against half the current electrode separation (AB/2) on log-log paper, and interpreted using partial curve matching techniques based on standard master curves for horizontally stratified earth models. Each observed field curve was matched with theoretical curves to determine resistivity, thickness, and depth parameters of the subsurface layers. Subsequently, the data were inverted using WINRESIST 1.0 software to obtain more accurate resistivity models that fit the observed data. This allowed for the generation of geoelectric sections showing the vertical variation in subsurface resistivity, which served to delineate lithological boundaries and infer geotechnical properties.

The Wenner array configuration was utilized for all 2D profiles due to its high signal-to-noise ratio and superior resolution of horizontal features. Each profile had a maximum electrode spread of 100 m, with 5 m spacing between electrodes. Measurements were taken at six different levels to enhance vertical resolution. The acquired field data were processed and inverted using RES2DINV software (Loke & Barker, 1996). The software employed a robust least-squares inversion algorithm to convert apparent resistivity data into true resistivity sections, producing 2D resistivity models that represent the spatial distribution of subsurface resistivity. These models aided in identifying lithological variations, weak zones, and potential geologic features contributing to pavement failure.

3.2. Data Processing

The VES data were initially subjected to manual interpretation. Apparent resistivity values were plotted against half the current electrode spacing (AB/2) on log-log paper. These plots were then interpreted using the partial curve matching technique, comparing the field curves with standard master curves developed for a horizontally layered earth model. Points of coincidence between the field and theoretical curves were identified to determine the resistivity, thickness, and depth of individual subsurface layers. For enhanced precision, the manually interpreted results were further analyzed using WINRESIST 1.0 software. This computer-aided inversion refined the resistivity models by generating best-fit curves aligned with theoretical responses, thus providing reliable 1D geoelectric parameters. The 2D resistivity data were processed using the RES2DINV inversion software [36]. Field data were first displayed as pseudosections, showing apparent resistivity distribution. These were subsequently inverted using a robust least-squares algorithm to obtain true resistivity models that provide a realistic picture of the subsurface. The processed data yielded 2D resistivity models delineating subsurface features such as lithological boundaries, anomalous zones, and weak strata that may contribute to pavement instability.

4. Results and Discussion

The characterization of subsurface units for engineering purposes incorporated comprehensive methodologies designed to evaluate subsoil suitability for road construction. Detailed geological field mapping documented critical environmental factors including geomorphological features, topographical variations, and drainage patterns that could influence road stability and performance over time. The investigation employed non-invasive and non-destructive geophysical techniques to gather subsurface information crucial for addressing engineering and geotechnical challenges. These methods provided valuable insights without disturbing the existing ground conditions, making them particularly appropriate for infrastructure assessment. As noted by [37], such approaches are widely applied across various infrastructure investigations, from building foundations to critical structures like dams, roadways, and dikes.

These geophysical techniques served multiple essential functions in the road engineering context: they helped determine the vertical stratification of soil layers, verified the thickness of constructed pavement sections, and most importantly identified potential problem areas before they could develop into structural failures. This proactive identification of subsurface anomalies allows engineers to implement appropriate design modifications or remediation measures before construction or during maintenance phases, enhancing overall infrastructure resilience and longevity. The results were presented in the form of field curves, geoelectric sections and 2D profiles.

4.1. Ves 1

The top layer shows relatively low resistivity (29.5 ohm-m), which typically indicates moisture-rich, clay materials. This suggests a weak subsurface condition that could be susceptible to deformation under load. The shallow depth (just 1.2m) means this problematic layer is directly beneath the road base. The middle layer shows moderate resistivity (105.1 ohm-m), suggesting better drainage and possibly higher strength material, but it's sandwiched between the problematic top layer and very high resistivity bottom layer. The sharp contrast between these layers (especially between the middle and bottom layers) creates a condition where water can accumulate at layer boundaries. During wet seasons, this could lead to saturation of the upper layers, reducing their strength and causing road deformation. The geoelectric sequence identified at VES 1 reveals that road failure in the Lusada region may be attributed to the presence of a low-resistivity, moisture-laden topsoil, which is unable to adequately support pavement loads. Differential settlement and pavement deformation are likely where this weak layer has not been properly excavated or stabilized. The underlying second and third layers, by contrast, demonstrate significantly better geotechnical characteristics, underscoring the need for subgrade improvement practices or deep foundation techniques in road construction projects in this terrain.

Table 1 Geoelectric layer parameter of Ves 1

Geoelectric layer	Apparent Resistivity (Ωm)	Thickness (m)	Depth (m)	Lithology	Curve Type
1	29.5	1.2	1.2	Top soil (Clay)	A
2	105.1	2.1	3.3	Sandy clay	
3	1100.0	_	_	Fresh basement	

4.2. Ves 2

In comparison to VES 1, this profile shows significantly different subsurface conditions, the top layer has a much higher resistivity (98.8 ohm-m vs. 29.5 ohm-m in VES 1), suggesting better-drained materials with likely lower clay content. This indicates a more competent material in the immediate subsurface that would provide better support for road infrastructure. The middle layer shows high resistivity (310.3 ohm-m), which typically indicates sandstone. This layer is relatively thick (3.7m) and would provide good structural support. The bottom layer with very high resistivity (739.0 ohm-m) likely represents dry bedrock or highly consolidated materials. The interpreted A-type resistivity curve at VES 2 provides insight into the progressive competence of the subsurface. The near-surface unit may pose challenges for road foundations due to its potential susceptibility to moisture variation and load deformation, especially during periods of high rainfall. This layer may need mechanical stabilization or replacement in engineering designs to prevent premature pavement deterioration. However, the underlying strata exhibit significantly improved geotechnical characteristics. The second layer offers a suitable subgrade for road construction, provided that the topsoil is appropriately treated. If foundation systems are extended to interact with the third layer, the result would be a highly durable and stable substructure, minimizing the likelihood of settlement-induced road failures.

Table 2 Geoelectric layer parameter of VES 2

Geoelectric layers	Apparent Resistivity (Ωm)	Thickness (m)	Depth (m)	Lithology	Curve Type
1	98.8	1.1	1.1	Top soil (clay)	A
2	310.3	3.7	4.8	Sandstone	
3	739.0	----------	----------	Fresh Basement	

4.3. Ves 3

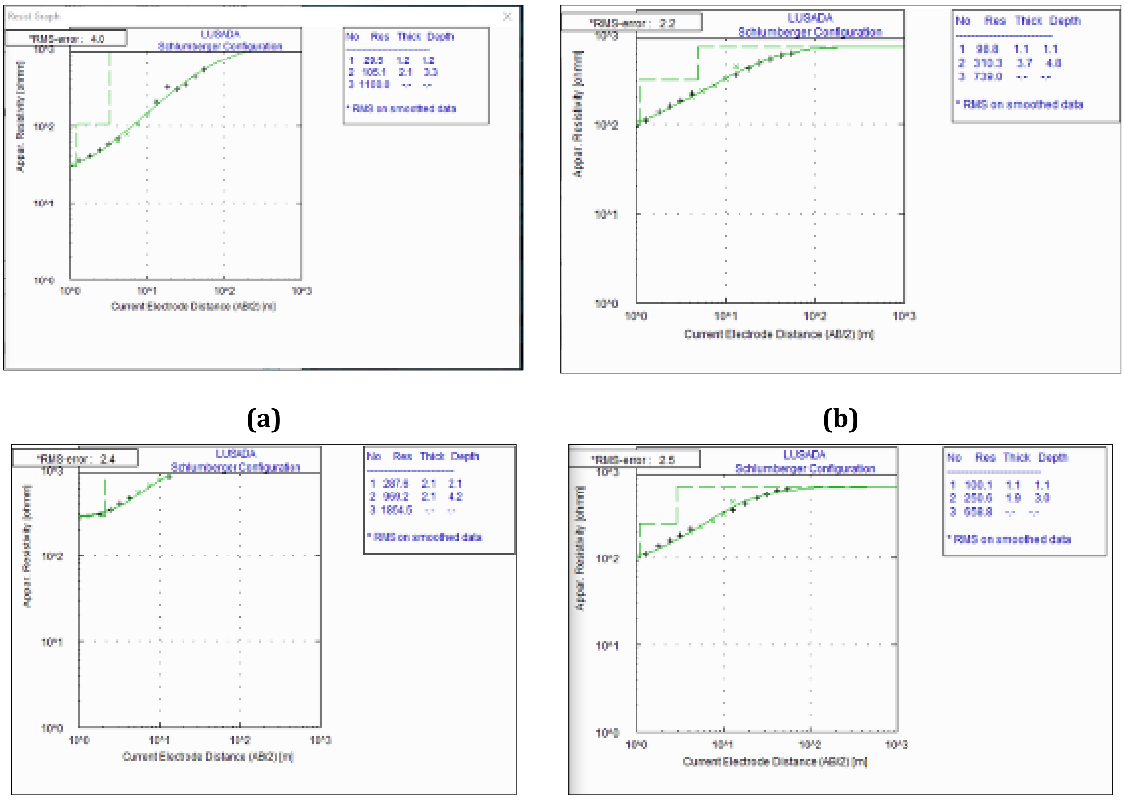
This profile reveals notably different subsurface conditions compared to the previous VES points because it was conducted on the stable road in the premises of Crawford university to serve as control to the remaining ves points. The top layer shows high resistivity (287.6 ohm-m), which is significantly higher than VES 1 (29.5 ohm-m), VES 2 (98.8 ohm-m), and VES 4 (100.1 ohm-m). This suggests very well-drained, possibly coarse-grained materials with minimal clay content and low moisture retention. This high resistivity in the immediate subsurface indicates excellent support capacity for road infrastructure. The middle layer exhibits very high resistivity (969.2 ohm-m), suggesting extremely well-drained, likely gravelly or rocky material with minimal fine-grained components. This provides exceptional structural support for overlying road structures while the bottom layer shows extremely high resistivity (1854.5 ohm-m), the highest among all VES points examined. This indicates very competent, dry bedrock or highly consolidated materials. The geophysical signature of VES 3 indicates high subsoil competence due to the persistent increase in resistivity with depth, pointing to a dry and well-consolidated profile, the absence of clay-rich or water-bearing zones reduces the risk of subgrade saturation, swelling, or differential settlement common contributors to pavement failure. The shallow depth (~4.2 m) to basement implies that foundation elements such as piles or stone columns can be designed to interact directly with the second or third layers, ensuring long-term structural stability of road pavement. VES 3 location would likely perform exceptionally well under road loading conditions, even during extreme weather events, and would be the least likely location to experience road failure among all sites surveyed.

Table 3 Geoelectric layer parameter of VES 3

Geoelectric layers	Apparent Resistivity (Ωm)	Thickness (m)	Depth (m)	Lithology	Curve Type
1	287.6	2.1	2.1	Sand	
2	969.2	2.1	4.2	Sandstone	A
3	1854.5	----------	----------	Fresh Basement	

4.4. Ves 4

This profile shows favorable subsurface conditions for road stability, the top layer has moderately high resistivity (100.1 ohm-m), which is very similar to VES 2 and much higher than VES 1. This suggests relatively well-drained materials with lower clay content in the immediate subsurface, providing better support for road infrastructure than what was seen in VES 1. The middle layer has high resistivity (250.6 ohm-m), indicating well-drained materials likely consisting of coarse-grained sediments like sand or gravel with minimal clay content. While slightly lower than the middle layer in VES 2 (310.3 ohm-m), it still represents good structural support material. The bottom layer shows very high resistivity (658.8 ohm-m), typical of dry, consolidated materials or bedrock, providing a solid foundation. The first layer's low resistivity suggests it may retain moisture or contain clay fractions. If not properly removed or stabilized, it could pose a moderate risk for subgrade instability, such as differential settlement, shrink-swell behavior, or rutting under repeated traffic loading. The second layer's improved resistivity and compactness indicate a more stable material suitable for supporting pavement layers. Road failures are less likely if foundation elements are seated here or if proper compaction is ensured during construction. The shallow depth to basement (~3.0 m) is beneficial for engineering foundations. It ensures a short transmission path to competent rock, minimizing potential deformation under dynamic or static loading.



(a) (b)

(c) (d)

Figure 3 (a) Resistivity curve of VES 1, (b) Resistivity curve of VES 2, (c) Resistivity curve of VES 1, (d) Resistivity curve of VES 1

Table 4 Geoelectric layer parameter of VES 4

Geoelectric layers	Apparent Resistivity (Ωm)	Thickness (m)	Depth (m)	Lithology	Curve Type
1	100.1	1.1	1.1	Sandy clay	A
2	250.6	1.9	3.0	Sandstone	
3	658.8	-------	--------	Fresh basement	

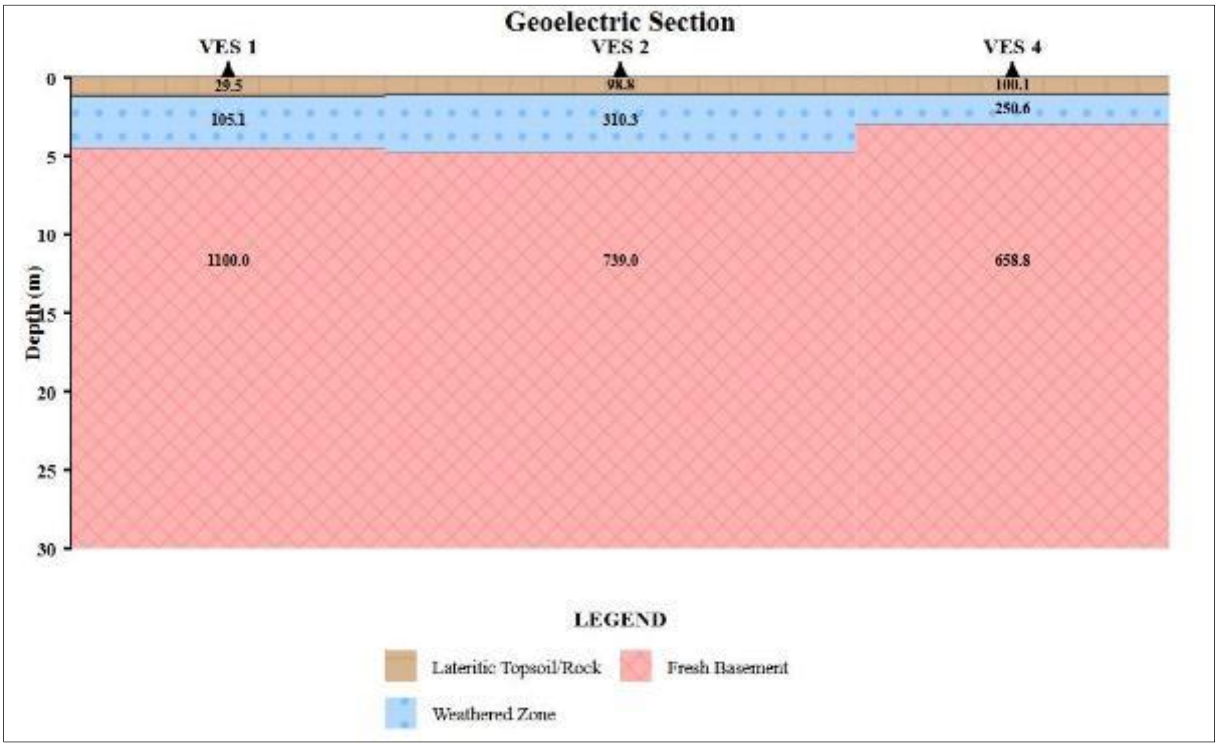


Figure 4 Geoelectric section of Ves 1, 2 and 4

4.5. Profile 1

Profile 1 reveals a subsurface predominantly composed of low-resistivity clay-rich materials, particularly within the surface layer (0–1.2 m), where resistivity values range from 10 to 40 Ωm. These materials are highly susceptible to deformation under load, especially when saturated, and thus pose a significant risk to road stability. A critical failure zone is observed between 25–45 m horizontal distance, marked by a localized depression with deeper penetration of low-resistivity material (extending to 5–6 m), likely representing a pocket of saturated clay. This zone is prone to differential settlement and is considered a high-risk area for road failure. In contrast, high-resistivity zones (>1000 Ωm) between 60–75 m, interpreted as bedrock or compacted dry material, suggest more stable conditions but may also induce stress contrasts with adjacent weaker zones. Additionally, horizontal lithological transitions from clay to clayey sand at approximately 30 m and 85 m indicate subsurface variability, further compromising the uniformity of load-bearing capacity. The failed segment of the road coincides with the blue-colored zone of low resistivity in the pseudosection, underscoring the role of weak, clay-dominated subgrade in the failure mechanism. Overall, the profile highlights the need for ground improvement or alternative foundation solutions in areas dominated by saturated clays to mitigate future pavement failures.

VES 1 revealed a low-resistivity top layer (29.5 Ωm) at a shallow depth of 1.2 m, which correlates well with the widespread low-resistivity surface zone (10–40 Ωm) observed in Profile 1's 2D resistivity section. This consistency confirms the dominance of clay-rich materials in the immediate subsurface, a key factor contributing to road failure. While VES 1 offers detailed vertical stratification at a single location highlighting a sharp transition from the low-resistivity surface layer to a high-resistivity layer (1100 Ωm) at depth Profile 1 expands this understanding by mapping the lateral distribution and variability of these layers. The alignment between the two datasets enhances the confidence in the interpretation, reinforcing the conclusion that poor subgrade conditions are widespread along the road corridor. The low-resistivity clay materials identified pose significant geotechnical risks, particularly under wet conditions, leading to differential settlement and structural instability. Therefore, remediation strategies must consider both the vertical layering captured by VES 1 and the lateral variations highlighted in Profile 1. The integration of these complementary geophysical methods provides a comprehensive and reliable assessment of subsurface conditions, forming a solid basis for the design of effective and targeted road rehabilitation measures.

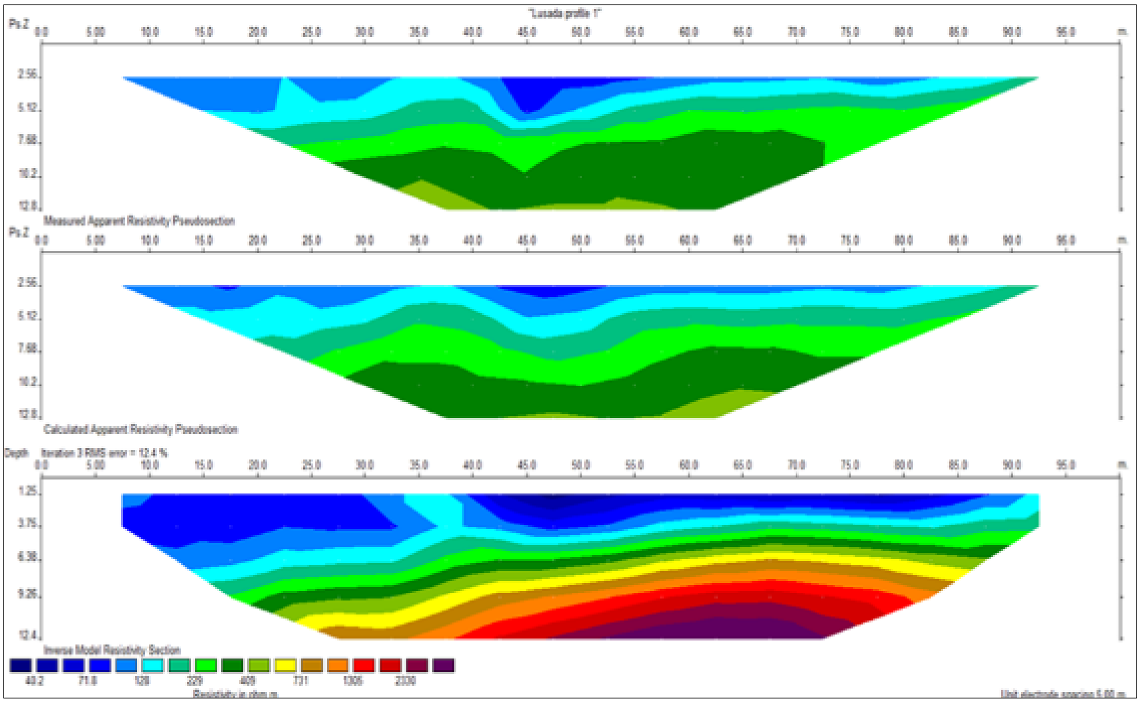


Figure 5 Result of 2D Inversion of profile 1

4.6. Profile 2

Profile 2 reveals considerable subsurface heterogeneity, as illustrated in the 2D electrical resistivity model (fig 6). The near-surface layer (0–3.75 m) displays low to moderate resistivity values (blue), indicative of clayey sand, which is known for its poor geotechnical strength and vulnerability to deformation under load. A high-resistivity zone (800–1400 Ωm) appears at depth in the central part of the profile, likely representing compacted dry material or bedrock. A distinct anomaly between 70–75 m, where resistivity patterns are disrupted, suggests the presence of a structural feature such as a fault, fracture, or lithological change. This zone could negatively affect load-bearing capacity and subsurface drainage, warranting focused geotechnical evaluation. The failed road segment aligns with the low-resistivity zone in the pseudosection, highlighting the influence of weak subgrade materials on pavement failure. Deeper layers (up to 8 m) with resistivity values ranging from 136 to 210 Ωm indicate a lithological transition from clayey sand to more competent sandstone, especially between 70–80 m, corresponding with a more stable road section.

VES 2 complements these findings by showing a three-layer subsurface structure, with increasing resistivity with depth. The stratification observed in VES 2 aligns with the layering in Profile 2, while the lateral variations and the anomaly at 70–75 m are only evident in the 2D imaging. This reinforces the importance of combining 1D and 2D geophysical methods for comprehensive site characterization. Overall, the subsurface conditions in this area are moderately favorable for road construction, though the anomaly zone presents a potential risk, particularly during wet seasons. A combined interpretation supports the development of targeted engineering solutions to improve road durability and performance

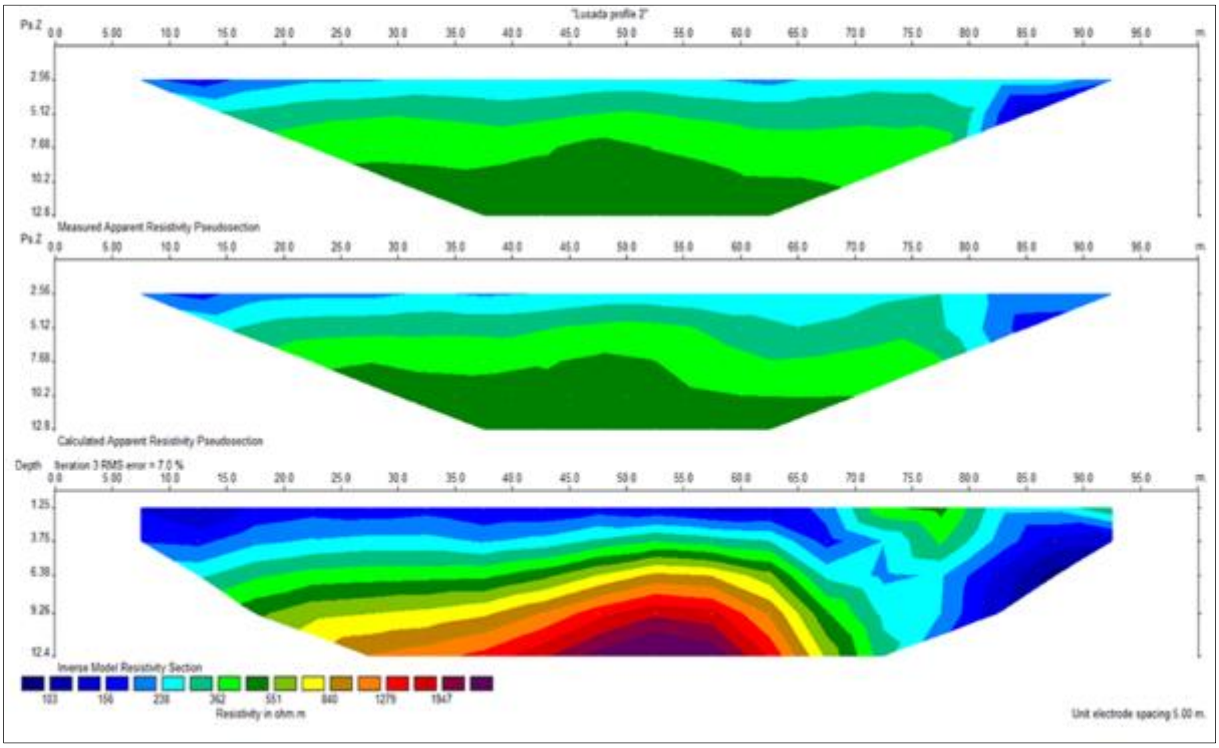


Figure 6 Result of 2D Inversion of profile 2

4.7. Profile 3

Profile 3, conducted within Crawford University as a control, offers essential baseline data due to the stable condition of the roads in this area. The 2D resistivity model (fig 7) reveals a well-layered and geotechnically favorable subsurface. The topsoil layer, with resistivity values ranging from 184 to 321 Ωm, corresponds to clayey sand extending to depths of about 5 m, particularly between 5–20 m and 80–89 m lateral distances. A more competent sandstone layer (300–589 Ωm) is observed between 30–75 m spread, reaching depths of approximately 7 m. Deeper high-resistivity anomalies, up to 4111 Ωm around 65–75 m and 80–90 m at depths of 9–12 m, likely represent compacted dry material or unweathered bedrock.

The near-surface zone (<3.75 m) shows relatively uniform low-resistivity values (blue), indicating consistent surface material, in contrast to the variability seen in failed road sections elsewhere. These observations suggest minimal geological disturbances, reduced weathering, and excellent drainage properties—key factors contributing to the road's durability.

The results align closely with VES 3 data, which also indicates a three-layer structure with high resistivity values (287.6 Ωm → 969.2 Ωm → 1854.5 Ωm), confirming the presence of competent, well-drained subsurface materials. Neither method indicates low-resistivity zones associated with clay-rich or saturated layers. The strong correlation between the vertical (VES) and lateral (2D profile) data enhances confidence in the interpretation.

Overall, Profile 3 and VES 3 collectively identify this location as having the most structurally competent subsurface in the study area, making it the least susceptible to failure. These findings provide a reliable control benchmark for evaluating fewer stable profiles and guiding road design and rehabilitation efforts.

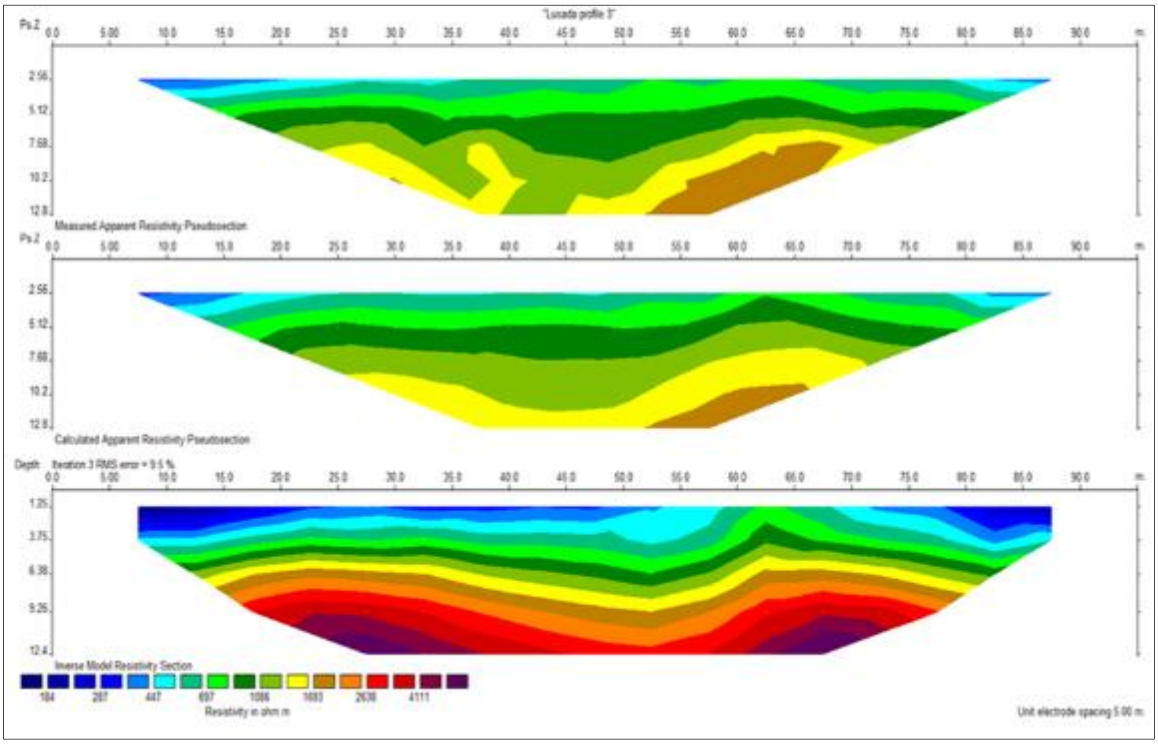


Figure 7 Result of 2D Inversion of profile 3

4.8. Profile 4

Profile 4 reveals complex and heterogeneous subsurface conditions with direct implications for road performance. The upper 3.75 m is characterized by very low resistivity values (<126 Ωm, dark blue), indicative of clay-rich or water-saturated materials, which are typically associated with poor geotechnical properties. A distinct lateral resistivity contrast occurs around the 30 m mark, where values increase significantly toward the right side of the profile. The left section (0–30 m) maintains extremely low resistivity throughout most of the depth range, highlighting weak subgrade conditions. Conversely, the right portion displays a high-resistivity anomaly (>5000 Ωm), with peak values approaching 20,000 Ωm at greater depths, suggesting the presence of dry, compacted material or unweathered bedrock.

The combination of low-resistivity surface materials and abrupt subsurface transitions makes this section particularly vulnerable to pavement failure. In contrast to the more favorable conditions in the control profile (Profile 3), Profile 4 underscores the importance of identifying subsurface heterogeneity in road design and the need for targeted engineering interventions to mitigate potential failures.

The comparison between Profile 4 and VES 4 underscores a significant limitation of relying solely on 1D resistivity soundings for site characterization. While VES 4 indicates favorable subsurface conditions, with resistivity values increasing progressively with depth, Profile 4 reveals substantial lateral heterogeneity that the VES measurement fails to capture. This discrepancy highlights the critical need for 2D resistivity imaging in the proper assessment of sites, especially for linear infrastructure like roads. Profile 4 shows dramatic lateral variations in resistivity, particularly around the 30 m mark, where a sharp transition from low-resistivity clay-rich material to high-resistivity zones occurs. This heterogeneity indicates the presence of differential support conditions, which could lead to uneven settlement and drainage issues if not carefully addressed during road construction. If the road design were based solely on VES 4 data, it might overlook these critical subsurface variations, potentially leading to premature road failure, especially along the left portion of the profile where the low-resistivity zones dominate.

The findings emphasize that while VES provides valuable vertical stratigraphy, it cannot fully capture lateral subsurface variations. The comprehensive 2D resistivity data from Profile 4 offers a more accurate depiction of the site's subsurface conditions, revealing potential risks and the need for tailored engineering solutions to mitigate differential settlement and drainage concerns.

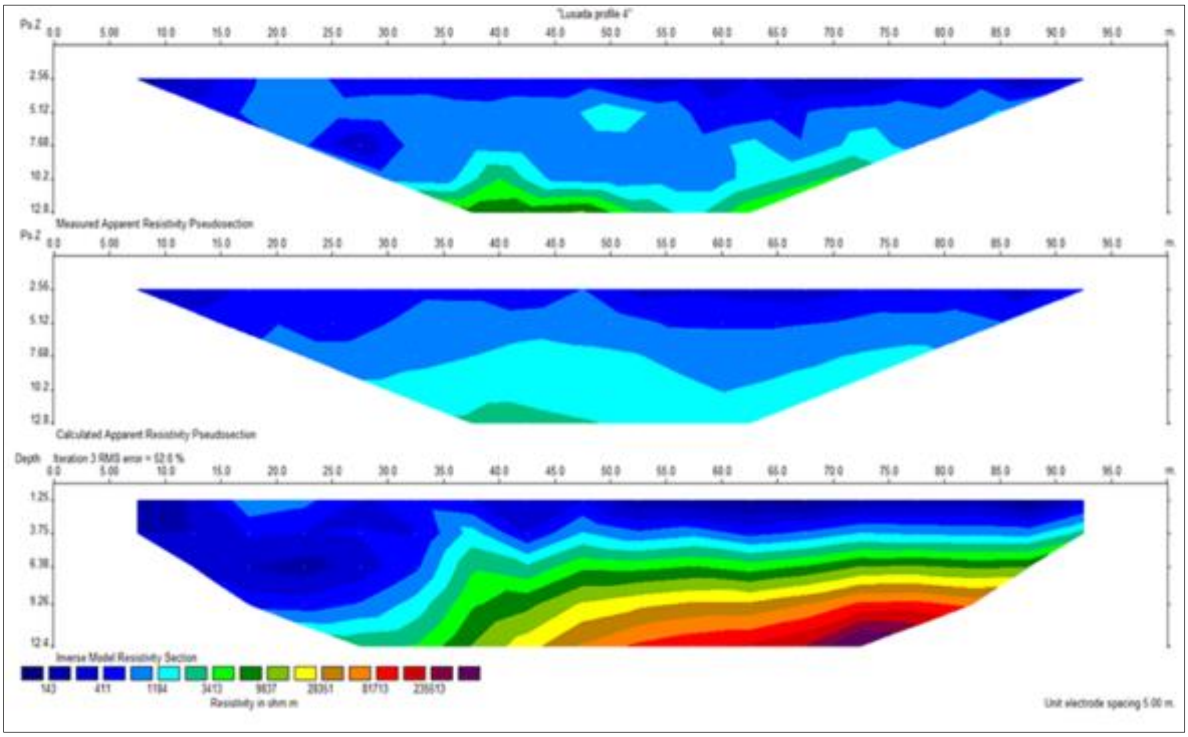


Figure 8 Result of 2D Inversion of profile 4

5. Conclusion

The geoelectrical investigation of road failure along the Lusada-Ketu-Ado Owie Road revealed significant subsurface heterogeneity, which directly influences the road's performance. The study identified poor subgrade materials, water-retentive sands, and inadequate asphalt thickness as key factors contributing to road failure. The shallow surface layers, dominated by low-resistance clay-rich materials, absorb water and swell under pressure, exacerbating pavement distress. Inadequate drainage systems, coupled with the road's thin surface, have led to significant fissures that could not withstand heavy traffic loads. The results emphasize the critical role of soil conditions and drainage patterns in the structural integrity of the road.

Through the integration of 1D and 2D geophysical methods, the study identified critical failure zones, with low near-surface resistivity values and sharp lateral transitions indicating differential settlement risks. The control site (VES 3/Profile 3) demonstrated optimal conditions, with high resistivity values indicative of excellent drainage and structural stability, offering a benchmark for comparison. The study also highlighted the limitations of relying solely on point-based VES measurements, underscoring the value of 2D resistivity profiling for capturing lateral heterogeneity and discontinuities.

Recommendations

For areas exhibiting characteristics similar to VES 1 (e.g., poor subgrade materials and low resistivity), it is recommended to replace the subgrade with well-draining materials to a depth of at least 1.5 m, implement robust subsurface drainage systems, and consider geotextile reinforcement to enhance stability. In zones resembling the left section of Profile 4, soil stabilization techniques such as lime or cement treatment should be applied, along with interceptor drains to mitigate water accumulation. For areas with anomalous features (e.g., the 70-75m zone in Profile 2), localized excavation and replacement should be conducted, coupled with targeted drainage improvements and geogrid reinforcement.

Additionally, to refine the geophysical interpretations, selected soil borings should be performed, and seasonal variations in moisture content should be assessed through repeated measurements. By incorporating these measures, the likelihood of premature road failure can be significantly reduced, improving the road's durability, sustainability, and long-term resilience. These recommendations provide a comprehensive approach to road rehabilitation, contributing to more reliable infrastructure planning and maintenance.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors (Rereloluwa Bello, Valentine Ezennubia, Anjolaoluwa Joseph Adebisi) declare no conflict of interest.

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