Applied Sciences, Computing and Energy, 2025, 3(1), 66-87

Geophysical and Geotechnical Approaches in investigating causes of road failure along Zone 8 - Crusher Road, Lokoja, Kogi State

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Received: 27 May 2025/Accepted:28 June 2025/Published: 01 July 2025

Abstract: *Roads are an important engineering structure that are crucial in international trade and transportation because they connect cities, states, and nations, respectively. A good number of variables, such as poor construction methods, lack of maintenance, and poor subsurface soil conditions, are major contributors to road instability globally. This study aims to investigate the causes of road failures in Lokoja and its environs, Nigeria. The study employs an integrated approach using 2D Electrical Resistivity Tomography (ERT), Very Low Frequency Electromagnetic (VLF-EM) surveys, sieve analysis, and Atterberg limit tests to investigate the causes of failure along the Zone 8-Crusher road. Eight (8) locations were examined, and soil samples were collected for analysis. The ERT and VLF-EM results revealed three distinct resistivity zones: low, intermediate, and high. The low and intermediate resistivity zones, particularly in the road's failed sections, are likely associated with water-saturated weathered materials. Sieve analysis showed that the percentage of soil passing through sieve number 200 (0.075mm) ranged from 0.1% to 0.3%, indicating a lack of clay content, which suggests that clay was not a contributing factor to road failure in this investigated site. The Atterberg limits revealed liquid limits between 29.1% and 33.5%, plastic limits between 14.15% and 18.35%, plasticity indices between 14.95 and 15.15, and moisture content values between 8.2% and 16.8%. These results indicate low plasticity, falling within the acceptable range for soils used in* road construction, thereby ruling out poor soil plasticity *as a cause of the road's instability in this investigation. Therefore, the study concluded that the failures are due water water-saturated units of the topsoil and shallow weathered zone of the affected area. It may also be due to poor construction materials and a lack of road maintenance.*

Keywords: *Subsurface investigation, failure mechanisms, Atterberg limit, Electrical Resistivity Tomography, geotechnical appraisal and survey.*

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1.0 Introduction

Transportation is vital for every individual as well as the entire nation. It determines the economic growth of any country. It's crucial to keep in mind those communities without good transport experience economic hardship. However, the development of a country's road network has a major impact on the growth of its gross domestic product (GDP). There is a favourable correlation between the quality of a country's road network and its economic progress. A network of rural roads should be carefully planned and constructed to maximise the intended social, cultural, and economic benefits (Ighodalo 2009).

A road failure is any kind of impairment or deterioration on a typical road or pavement surface that makes it impossible for automobiles, bikes, pedestrians, or other users to use it as a smooth surface. Since roads are constructed on geologic materials, the properties of these materials affect how well they function as a transport medium (Gupta and Gupta 2003). From base to top, the primary components of several common flexible highway pavements are subgrade, sub-base, base course, and riding surfaces (Gupta and Gupta 2003; Adeyemi 2013). However, there have been fatalities and property losses associated with inadequate design and poor construction techniques brought on by a disregard for established norms.

Potholes, deformation, peeling, cracking, shoving, upheavals, and ravelling are a few examples of issues that might cause a road to fail. Knowledge of subsurface conditions such as lithology, fluid content and structures is critical in any design, including roads, buildings and even oil company infrastructures. This also involves determining and characterizing the nature of the subsurface soil fluid content (Ibrahim *et al*. 2015, Ibrahim and Raji, 2025a)

The growing frequency of reported road collapses has been linked to a range of factors, including geological and geotechnical conditions, poor design and construction, upkeep, and road usage (Oke *et al*. 2009; Nwankwoala *et al*. 2014). Geotechnical examination of subsurface materials, according to Daramola *et al*. (2015) and Amadi *et al*. (2015), offers answers for problems pertaining to both expansive and unexpansive soils as well as helps understand the behaviour of soils that can seriously impede the construction of roadways. Only failures brought on by excessive moisture content, clay mineral content and inadequate foundations can be successfully identified using geophysical and geotechnical techniques. They are able to identify the geological structures that cause breakdowns, such as joints, sinkholes, and faults.

Integrated geophysical and geological study of a site has been established to be the best approach in site investigation (Ibrahim, 2016). Abdulbariu et al., 2024b carried out site investigation in Adankolo Campus of Federal University Lokoja and stated that cracks in the building were due to the presence of clay materials within the subsurface, which is incompetent to withstand load.

Geophysical studies also provide the subsurface data needed for building infrastructure that strengthens and stabilises roads (Abdulbariu *et al*, 2024a). These geophysical studies are used to determine bedrock depth, map critical structures, and evaluate subsurface competency (Burland & Burbidge 1981). Electrical resistivity imaging is being used to solve a growing range of hydrological, environmental, and geotechnical issues. Two-dimensional (2D) electrical resistivity imaging is used in geotechnical testing to find underground cracks and cavities under structures such as roads, bridges, buildings, and dam construction. The technique has proven to be a successful way to determine anomalies and gauge how complex the underlying geology is (Griffiths & Barker, 1993; Andrews *et al*., 2013).

Geophysical investigations using 2-D resistivity images and VLF-Electromagnetic methods were conducted in conjunction with geotechnical techniques in Lokoja, Nigeria, to determine the reasons underlying road failure along the Zone 8-crusher axis. Groundwater location, crack and void detection, and changes in subsurface geology can all be identified with the 2-D resistivity technique, which is a geophysical approach that maps underlying features using electrical resistivity measurements (Akintorinwa and Adeusi 2009; Akintorinwa and Oluwole 2018; Aminu *et al*., 2022, Nanfa *et al*., 2022). Conversely, the VLF (Very Low Frequency) Electromagnetic method is a geophysical technique that uses electromagnetic signals to map subsurface features; it can be used to locate geological structures like faults and fractures as well as identify conductive materials like water (Abdulbariu *et al*, 2023a, Abdulbariu *et al*, 2024a).

The work of these authors employed several geophysical approaches independently and or jointly in investigating road failure without a rigorous integration of various geophysical approaches in conjunction with geotechnical data, with an in-depth collaborative interpretation. They had also not investigated one after each element or parameter that can be responsible for the downgrading and collapse of our road. Therefore, these previous works have not satisfactorily provided a holistic explanation about the causes of road failure, which this work is set to shed light on.

The aim of the study is to enhance the understanding of the underlying causes of road failure in the Zone 8-Crusher Road, in Lokoja, and to provide practical solutions to mitigate the problem. The objectives involve analyzing the collected geotechnical and geophysical data to pinpoint the causes of road failure; proposing solutions to reduce road failure based on the data analysis; offering suggestions for designing and constructing roads resilient to the area's geotechnical and geophysical challenges; and contributing to the body of knowledge on geotechnical and geophysical investigations of road failure to support future research.

1.1 Geologic Setting

The study area is situated within and around Lokoja, Kogi State, in north-central Nigeria, and lies between latitudes 7°49'0"N and 7°51'0"N and longitudes 6°39'30"E and 6°42'0"E. Geologically, this area is part of the southwestern segment of the Nigerian Basement Complex, which consists of a variety of metamorphic and igneous rocks that were affected by multiple orogenic events, notably the Pan-African Orogeny about 600 million years ago (Woakes *et al*., 1987). The Nigerian Basement Complex is characterized by the presence of migmatite-gneiss complexes, granite-gneiss, and older granitoids that intruded during the Pan-African tectonic event. These rocks, formed during significant tectonic processes, represent a key portion of the structural geology in the region (Rahaman and Ocan, 1978; Dada, 2006). The Lokoja area also lies on the southern flank of the Mid-Niger (Bida) Basin, an intracratonic basin that trends northwest-southeast. This basin consists of various sedimentary formations, including the Lokoja, Patti, and Agbaja Formations, which were deposited during the Cretaceous period. The Lokoja Formation is characterized by conglomerates, sandstones, siltstones, and claystones, primarily deposited in fluvial environments (Sanni et al., 2016, Mua'wiya *et al*., 2023). This formation exhibits subangular to subrounded cobbles and pebbles within a clay matrix, suggesting a high-energy braided stream environment with some marine influence, as evidenced by the presence of arenaceous foraminifera in certain layers (Petters, 1986). Overlying this is the Patti Formation, which consists predominantly of siltstones, claystones, shales, and ironstones, reflecting deposition in a low-energy environment such as a flood plain or a restricted shallow marine setting (Braide, 1992b). The Agbaja Formation, capping the sequence, is known for its ironstone beds and sandstones, indicating periodic marine inundation and lateritic weathering (Ladipo *et al*., 1994).

Structurally, the basement rocks in this area are marked by numerous faults, fractures, and folds, which have influenced the drainage patterns and geomorphology of the region. The trellis and dendritic drainage systems observed in Lokoja are controlled by these structural features, allowing rivers and streams to flow along planes of weakness within the underlying rocks (Ige *et al*., 2018). This combination of tectonic and sedimentary processes has shaped the region's geological complexity and is critical to understanding the causes of road failures within the area.

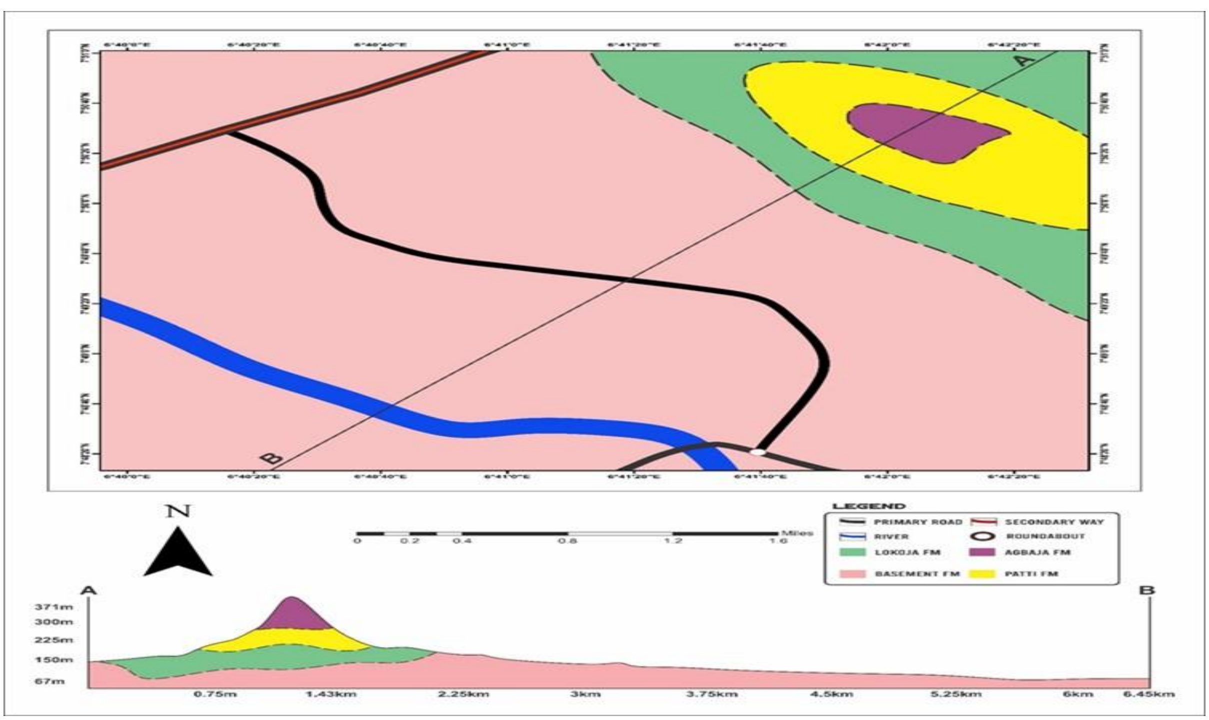

Fig 1: Geologic map of the study area

2.0 Materials and Method

This study involved a combination of geological field mapping, geophysical surveys, and geotechnical analysis. Geologic field mapping was carried out within the study area. The fieldwork began with a reconnaissance survey of the study area, which involved a desk study and literature review and this aims to gather information about the study area, mainly focusing on the road of interest. This was followed by geological mapping, which involved studying, identifying and mapping various lithologies and geological structures such as faults and fractures, taking coordinates and elevations using a GPS device, and collecting rock outcrop samples. Measurements of dip and strike for outcrops were taken using a compass clinometer. Eight samples were also collected from different locations within the study area. These preliminary investigations and observations involving reconnaissance and geological survey provided a foundation which further guided the appropriate locations for geophysical investigations and geotechnical sampling points.

2.0 Geophysical Surveys

Geophysical surveys included the Electrical Resistivity Method and Very Low Frequency Electromagnetic (VLF-EM) Method. A DDR-3 Geosensor resistivity meter was used for the resistivity data acquisition, while ADMT-300SX was used for VLF-EM data acquisition. The resistivity method used both Wenner and dipole-dipole configurations to determine subsurface resistivity. The choice of using Wenner and dipole-dipole configurations depends on the field conditions. The dipole-dipole array is faster than that of Wenner and seems to sample deeper, while the Wenner array reveals fine details of the subsurface, though the procedure is time-consuming. The resistivity measurements were taken at eight profiling locations parallel to both failed and stable road segments, with a 2-meter spacing between electrodes. The maximum profile length ranges from 0-50 m, with some even less than this length, depending on the length of the failed portions of portions being investigated. The aim was to investigate the lateral and vertical variations in ground resistivity, which could indicate areas of subsurface weakness. Apparent resistivity values were calculated by measuring the current and voltage through electrodes implanted in the ground, and then adjusting with a geometric factor based on the electrode configuration. The VLF-EM method uses electromagnetic waves to map conductive subsurface materials, which are often associated with water-saturated zones or geological structures like faults and vertically or steeply dipping fractures. It was applied at the same locations as the resistivity profiles to complement the electrical resistivity results in order to test for corroboration.

2.1 Geotechnical Analysis

Geotechnical analysis involved the collection of soil samples from eight locations. The eight soil samples were collected from both stable and failed sections of the road and they were along the geophysical profile lines. The eight samples were collected by manually drilling or excavating to a depth of 1-1.5 meters below the ground surface, and they were stored in labelled polythene bags. This was followed by laboratory tests, including sieve analysis, Atterberg limit test, and moisture content test, all performed according to ASTM standard methods. The sieve analysis followed ASTM D422 to determine grain size distribution, classifying soils based on their suitability for road construction. The Atterberg limit test was conducted according to ASTM D4318, providing insights into the soil's liquid and plastic limits and the plasticity index, which revealed the soil's potential to contribute to road failure. The moisture content test was performed in line with ASTM D2216, assessing water levels in the soil, which could reduce its strength and lead to road instability.

3.0 Results and Discussion

3.1 Geophysical Results

Profile 1 (Fig. 2) has a lateral distance of 0-50 meters with a resistivity ranging from 2-18385 Ωm and a depth of 10 m. The 2-D subsurface resistivity structure shows that at surface distance 0-30m, at a depth of 0-4 m, a zone of low to medium resistivity ranging from 24-221 ohm-meter, indicating probably a weathered basement material consisting of clay or water water-saturated unit. Beneath this zone of low resistivity at surface distance of 0-26m exists an underlying moderate resistivity zone at a depth of 5m to 10m with a resistivity value of 221-250 ohm-meter. At a surface distance of 37-42 meters a high resistivity unit greater than 2040 ohm-meter exists down to a depth of 3m, indicating probable fresh basement. At surface distance 34-36m at depth 2-10 m exists a very low resistivity zone less than 24 ohms, which may be a result of water saturation and this may cause road failure.

VLF-EM profile (Fig. 3) showed that at profile line 2-9 exist a high resistivity zone exists from a depth of 5-40 m; this may be a zone of high resistivity material such as lateritic soil. At profile line 12-25, from a depth of 5-100 m is a low resistivity zone probably as a result of weathered basement or water saturated zone, which may result to road failure.

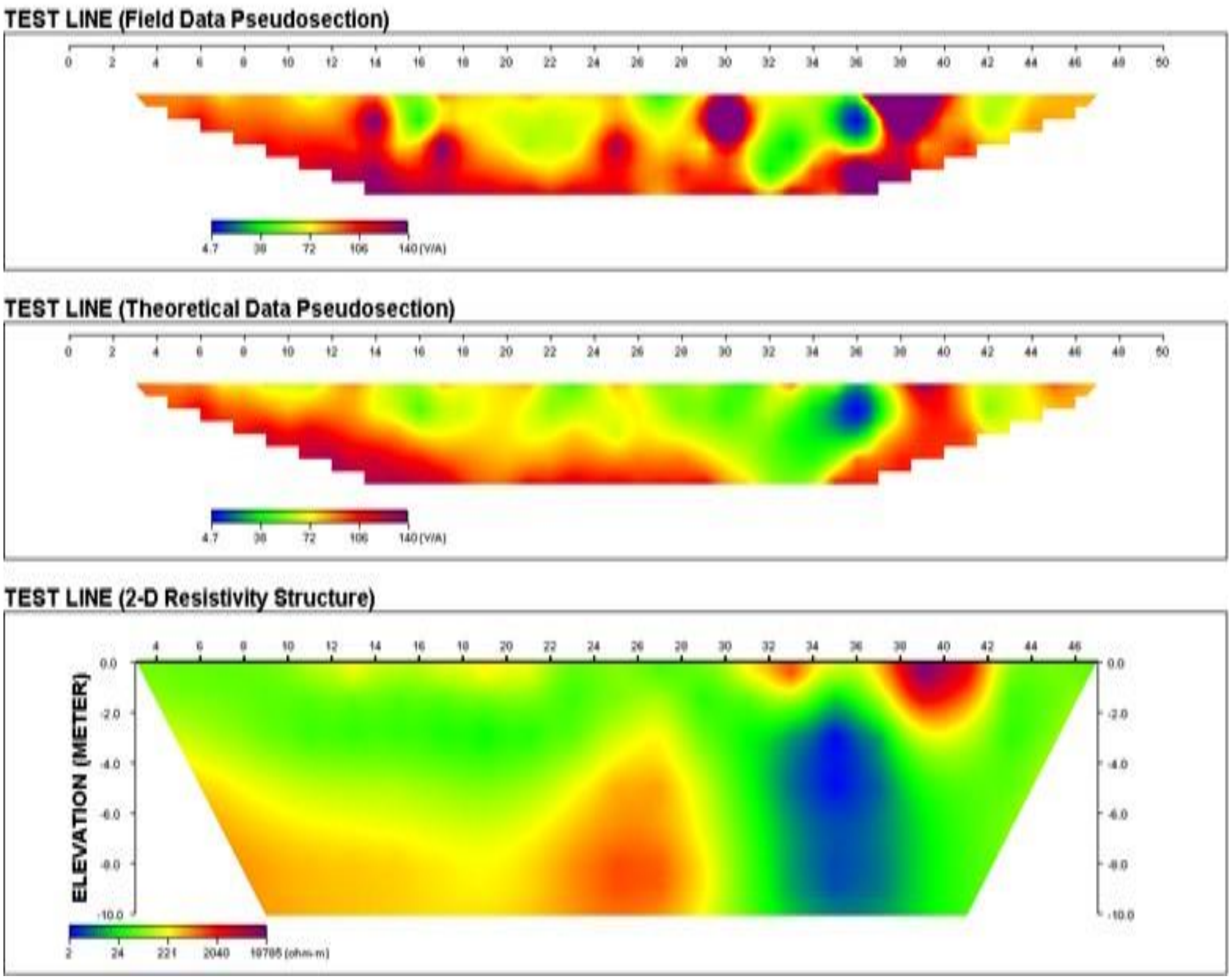

Fig. 2: 2D Resistivity for Profile 1 (Failed Segment) showing resistivity variation across the entire profile line

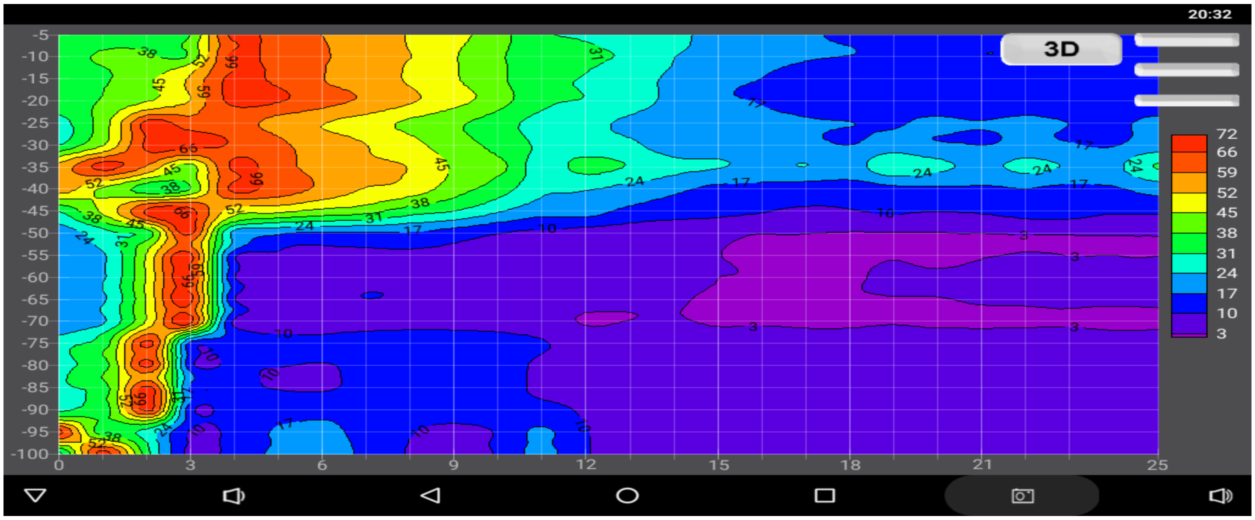

Fig. 3: VLF-EM Profile 1 (Failed Segment) showing variation in resistivity

The profile length and resistivity of the 2D resistivity for profile 2 (Fig. 4) range from 0-45 m and 0-121857 Ωm, respectively. High resistivity value of about 90-121857 Ωm is seen at shallow and deeper depths across the profile. However, low resistivity values of about 0-89 Ωm occur at profile lengths of 14-16m, 16-28 m and 41-45 m at the depth of 0-1m, 2-10m and 0-1.3 m, respectively. This low resistivity zone is mostly concentrated in the middle of the profile, which may imply the presence of a fault or fracture or water-saturated zone, and this might lead to failure of the road.

The VLF-EM result for profile 2 (Fig. 5) revealed a high resistivity zone across the profile from line 0-17 (0-34 m), while a low resistivity zone occurs mostly from line 22-25 (44-50m) with a depth of 5-20 m. The VLF-EM result further confirms that the area has a zone saturated with groundwater, causing the road instability.

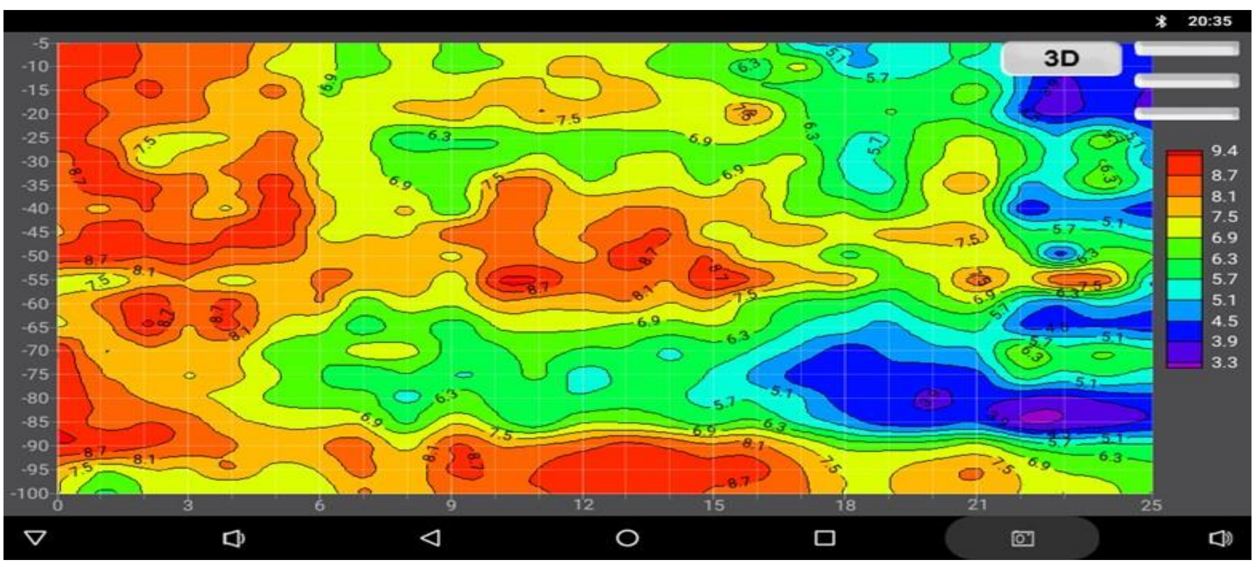

Fig. 4: 2D Resistivity for Profile 2 (Failed Segment) showing variation in resistivity variation across the entire profile length

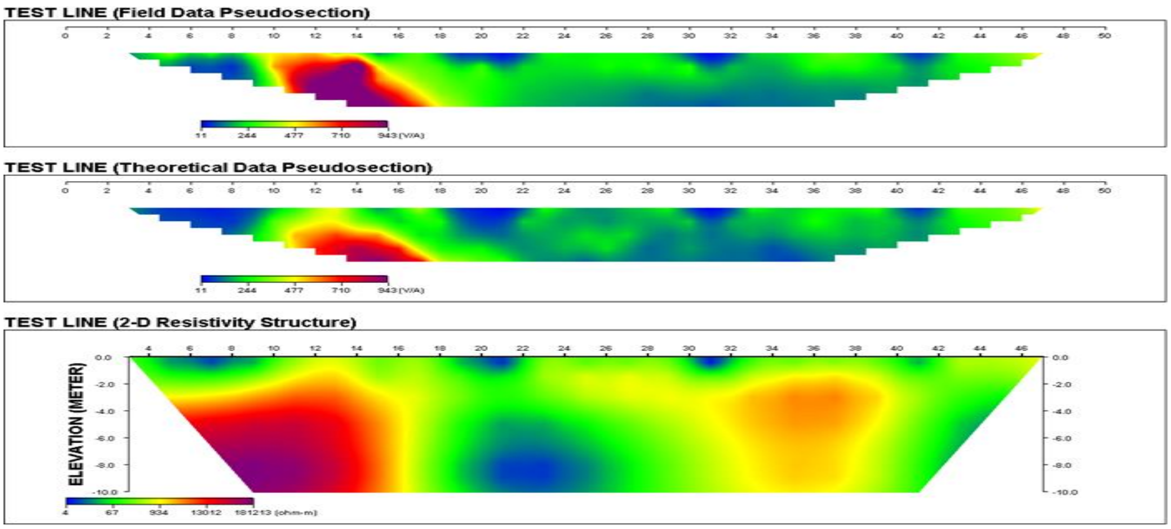

Fig. 5: VLF-EM Profile 2 (Failed Segment) showing variation in resistivity across the entire profile line

The resistivity for profile 3 (Fig. 6) ranges from 4 to 181213 Ωm with a profile length of 0 to 50m. High resistivity value of about 934-181213 Ωm is seen at profile distances of 4-16m and 30-38m at a depth of 3-10m. However, low resistivity layers with a value of about 4-50 Ωm occur in patches at profile lengths of 5-9m, 19-22m, 30-32 and 18-24m at the depth of 0-0.5m, and 5-10m. Moderate resistivity zones with a value of about 50-850Ωm occur mostly in the profile. And since the low resistivity layer is not prominent in the area, confirm the reason why the road did not experience failure.

The VLF-EM result for profile 3 (Fig 7) revealed low resistivity zone (blue colour) at shallow depth, though not too close to the ground surface (10m and 20m) and deeper depth (45m) across the profile line, this layer may be interpreted as fracture or water saturated zone which may affect the road. High resistivity zone (red colour) occurs mostly at deeper depth of 50-100m. The moderate resistivity (green colour) is found at the surface (0-7m depth) and between the low and high resistivity zones.

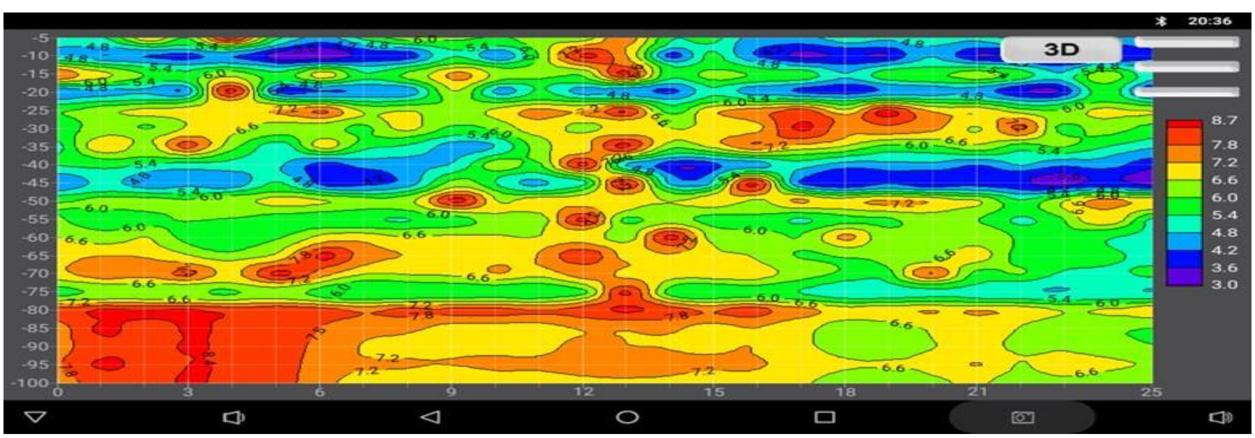

Fig. 6: 2D Resistivity for Profile 3 (Non-failed Segment) showing resistivity variation in across the entire profile length

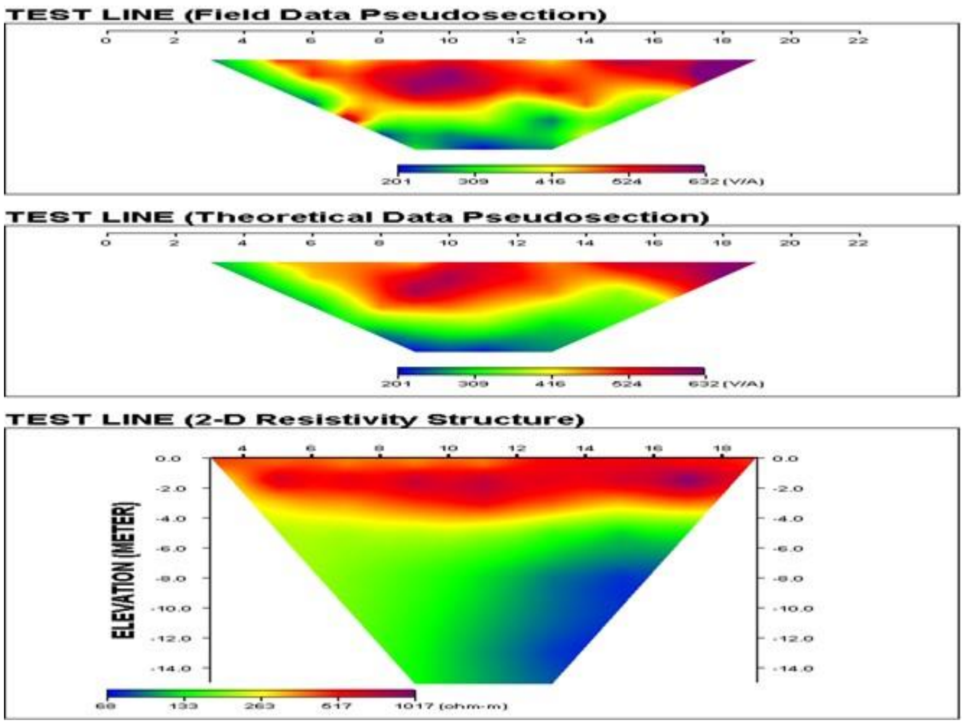

Fig. 7: VLF-EM Graph Profile 3 (Non-failed Segment) showing variation in resistivity across the entire profile length.

The profile length of the 2D resistivity for profile 4 is 0- 22m (Fig. 8) and the resistivity ranges from 68-1017 Ωm. High resistivity value of about 200-1017Ωm is seen at the top layer along the entire profile length and extends from the surface to a depth of 3.6 m; this layer may represent the lateritic clay. This layer was followed by moderate resistivity value of 100-200Ωm, this layer extends from 3.6m depth down to 14m along the profile, except at profile distances of 12-16m and stops at the depth of 6m and a low resistivity layer occurs down to 14m depth. This implies that the area has materials that are competent and might not affect the road.

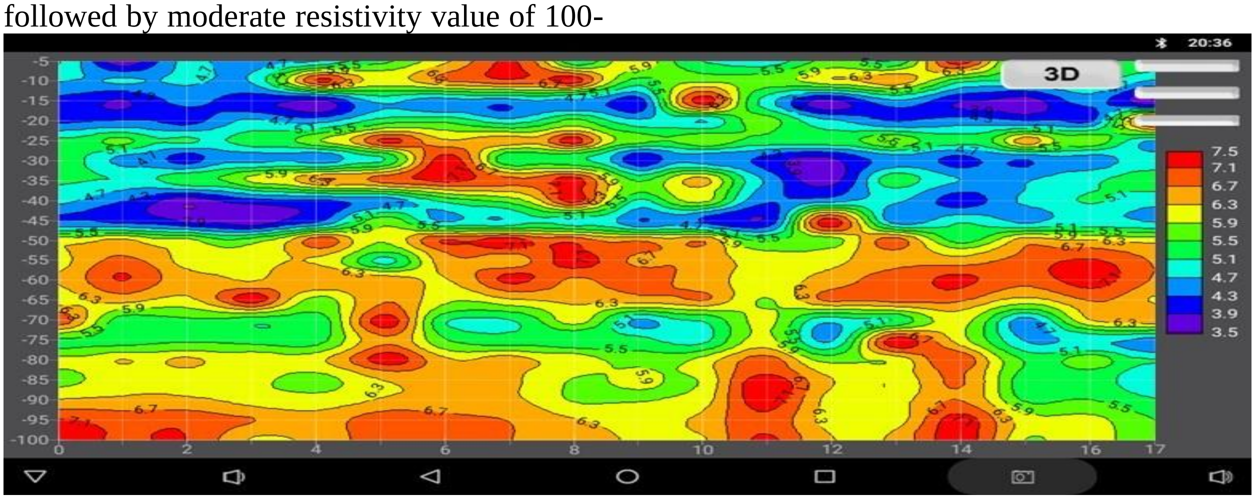

Fig. 8: 2D Resistivity for Profile 4 (Failed Segment) showing resistivity variation across the entire profile length

The VLF-EM result for profile 4 (Fig. 9) revealed a low resistivity zone (blue colour) at the depths of 0-20 m, 30m and 40-45m for line 0-3. Other areas with low resistivity are at line 4-17 at the depths of 15m, 30m and 45m along the profile. This layer may be interpreted as clay or fracture, or a water-saturated zone, which may affect the road. Moderate to high resistivity zone (green to red colour) occurs mostly at deeper depth of 50-100 nm, except at line 4-15 (8-30m) where they are at the depth of 0-12m and 25-35 m. The VLF-EM result corroborates the result of the 2D resistivity profile mostly at line 3-15, which has shallow depth for high resistivity value.

Fig. 9: Profile 4 (Failed Segment) showing variation in resistivity across the entire profile line. The resistivity and profile length of the 2D resistivity profile 5 (Fig. 10) range from 6-6540Ωm and with a profile length of 0-18m. High resistivity value of about 6540 Ωm is seen at the top layer along the entire profile length, having a shallow depth of about 0-1.8m, this layer may represent the lateritic clay. Below is a moderate resistivity layer with a value of 30-183 Ωm, this layer has a lateral distance of 0-18 m and also a depth of 1.8-9m. A low resistivity layer with a resistivity value of less than 20Ωm lying within this moderate resistivity layer mentioned earlier at a lateral distance of 0-18 meters with a thickness of about 1.5m, this layer is probably clay as a result of basement weathering or water water-saturated unit, which might lead to road failure. At a depth of 9-15 m extending to a lateral distance of 0-14m, there is a zone of high resistivity of 183-6540 Ωm, which also seems to be a competent zone at depth.

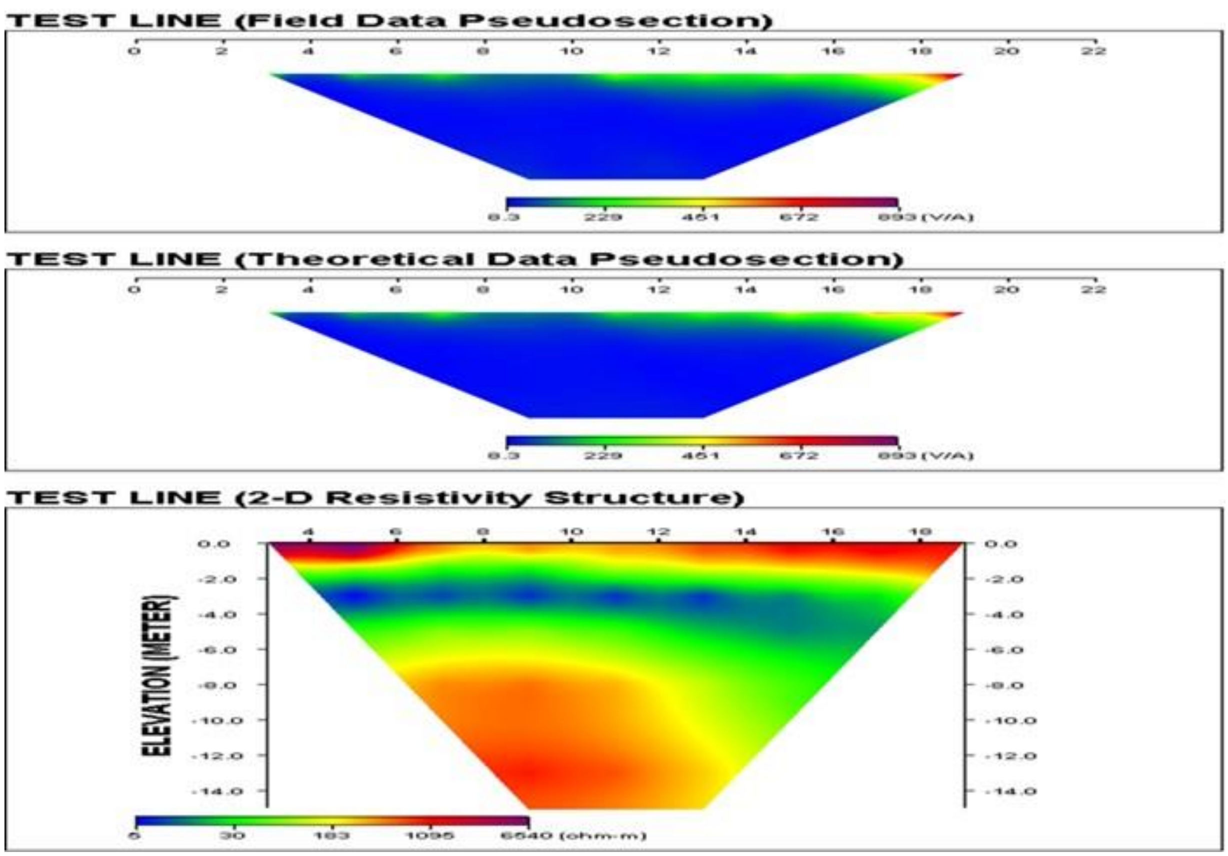

Fig. 10: 2D Resistivity for Profile 5 (Failed Segment) showing resistivity variation across the entire profile length

The VLF-EM Graph of profile 5 (Fig 11) has resistivity variation across he profile. Corresponding to the 2D resistivity image of the profile (Fig. 10) at 5 m depth, exist zone of low resistivity (blue colour) indicating a zone of fracture or water-saturated zone, which may cause instability of the road segment. A moderate resistivity layer (green colour) exists below the low resistivity layer at a depth of 15-20 m. At deeper depth of 25-100m exist high resistivity zones (red colour) indicating stable basement rock.

The resistivity of the 2D resistivity profile 6 (Fig. 12) ranges from 50-946 Ωm with a profile length of 0-16m. At surface distances of 0-16m and shallow depth of about 0-2m (even beyond this depth at some segments, especially between surface distances of 10-16m) exist a high resistivity zone of about 400-946 Ωm exists, probably representing a lateritic pan. Underlying the zone of high resistivity is a moderately resistivity zone from a lateral distance of 0-16m at a depth of 2-20m with resistivity values ranging from about 105-218 Ωm. Below the moderate resistivity zone, at a lateral distance of 4-6m at a depth of 4-12 m, exists a low resistivity zone of below 70 Ωm, which may be a clayey zone or water saturated zone and may cause road instability, especially when the road is plied by heavy trucks.

The VLF-EM result for profile 6 (Fig. 13) showed resistivity variation. The result revealed a moderate to high resistivity zone (green to red colour) at a depth of 5-100m. At line 0-2 at a depth of 5-25 m, there is a low resistivity zone (blue colour), possibly a fracture or water saturated zone corresponding to the low resistivity zone of the 2D resistivity image of the same profile (Fig.12) at the same depth.

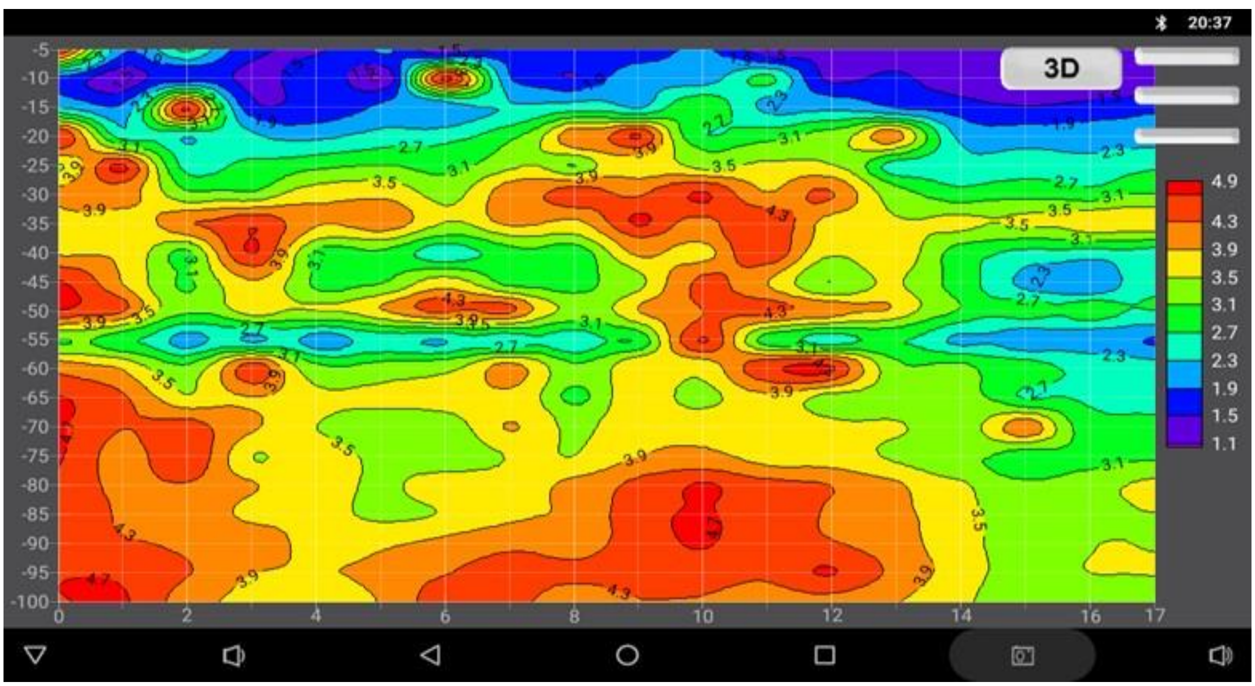

Fig. 11: VLF-EM Graph profile 5(Failed Segment) showing variation in resistivity across the entire profile line

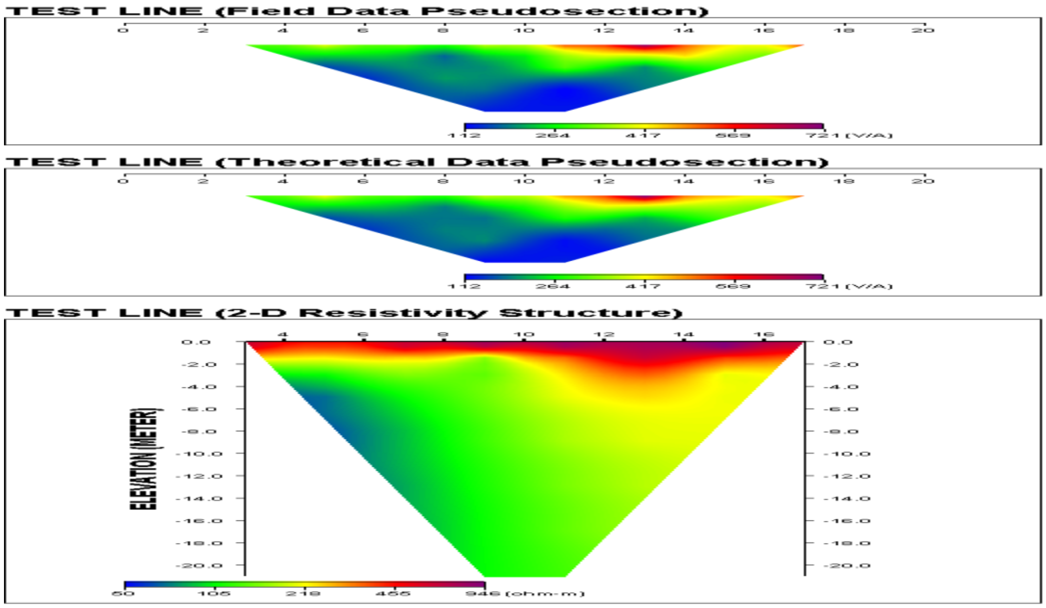

Fig. 12: 2D Resistivity for Profile 6 (Failed Segment) showing resistivity variation across the entire profile length

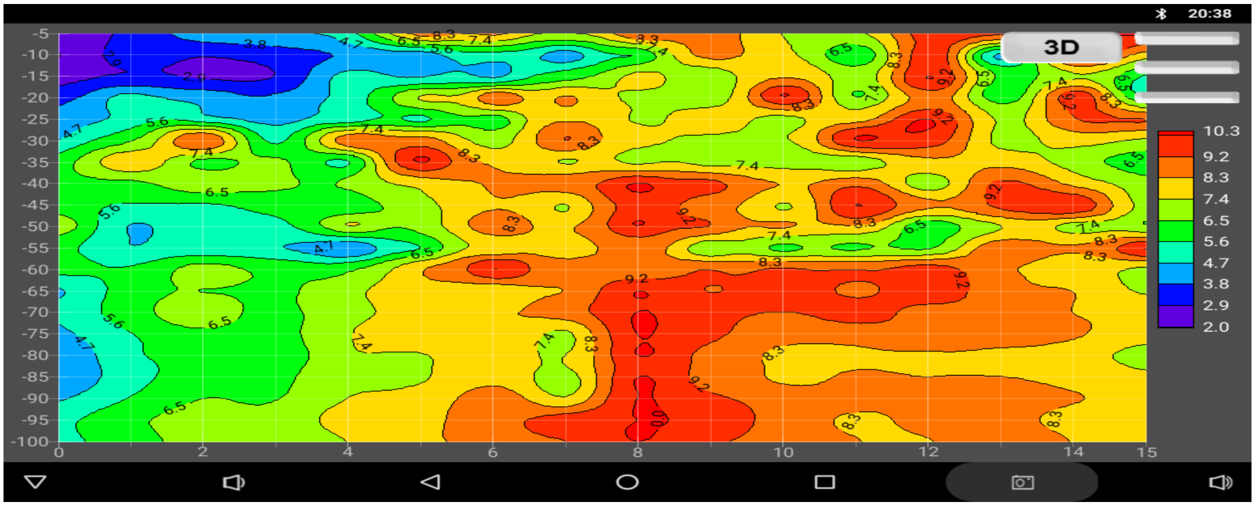

Fig. 13: VLF-EM Graph profile 6 (Failed Segment) showing variation in resistivity across the entire profile line

The profile length and resistivity of the 2D resistivity profile 7 are 0-14m (Fig. 14) and 13-97Ωm, respectively. At surface distance 0-14m there is high resistivity zone of about 35-97Ωm extending down to a depth of 8m, this zone is probably a zone of lateritic clay.

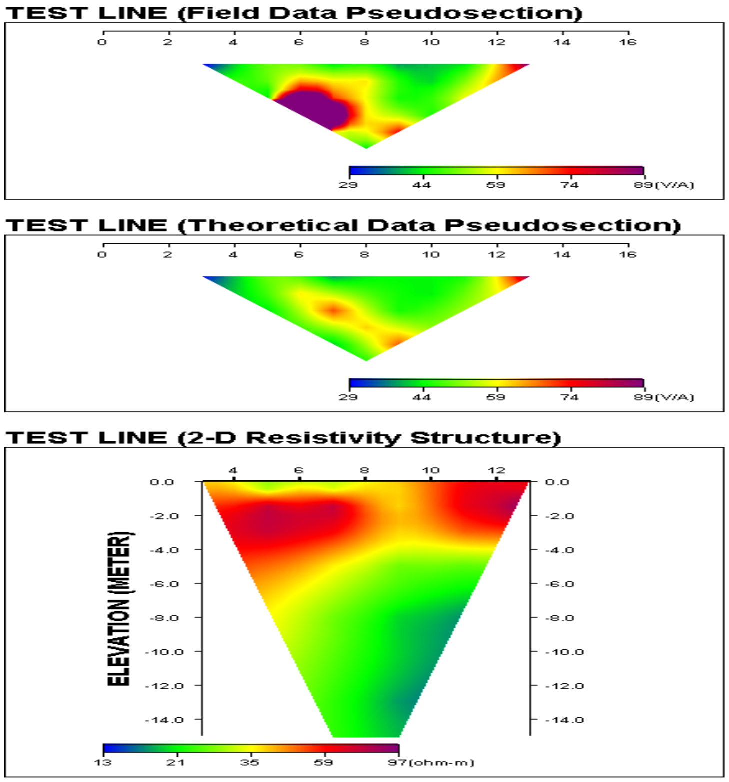

Fig. 14: 2D Resistivity for Profile 7(Stable Segment) showing resistivity variation across the entire profile length

At a depth of 8-14m, there is a medium resistivity zone of about 21-35 Ωm. This zone extends laterally a surface distance of 0-10 m. Towards the edge of this profile at the right-hand side, there is a low resistivity zone of less than 15 Ωm at a lateral distance of 11-14 m, which could be a zone of weathered basement rock or water water-saturated zone.

The VLF-EM result for profile 7 (Fig.15) showed that the resistivity value. The result revealed a moderate resistivity zone (green colour) at a depth of 5-15 m. At a depth of 16-20 m, there is a low resistivity zone (blue colour) and this zone is seen at line 1-13. This is probably a fracture or water-saturated zone and can possibly contribute to pavement failure. Below this zone lies zones of medium to high resistivity (green to red colour) to a depth of 100 m. This can represent an electric basement with stability.

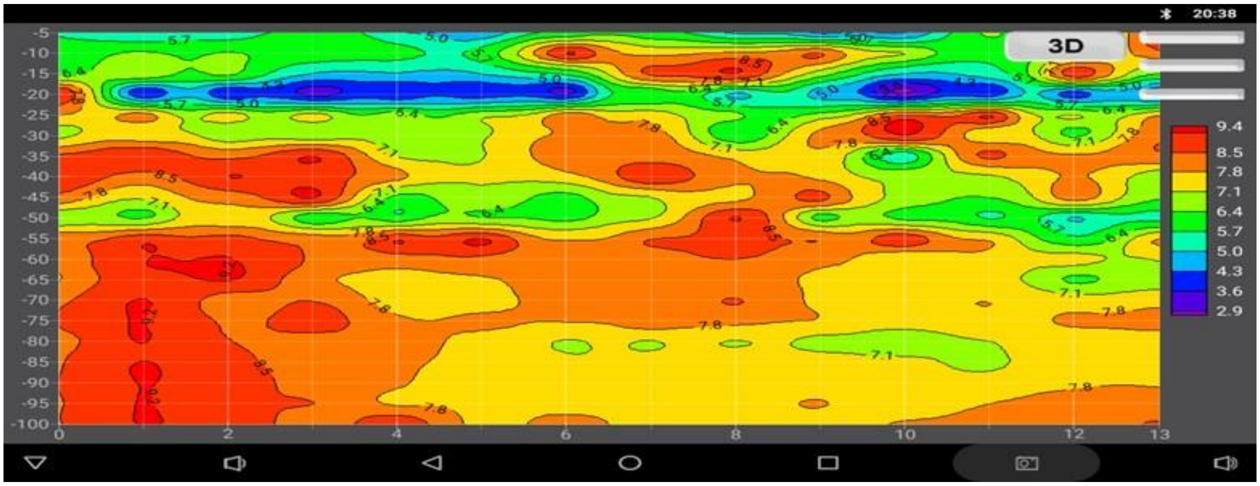

Fig. 15: VLF-EM Graph profile 7(Stable Segment) showing variation in resistivity across the entire profile line

The resistivity and profile length of the 2D resistivity profile 8 is 13-436Ω m and 0-16m, respectively (Fig. 16). At a surface distance of 0-16m at a depth of 0-2 m there is a high resistivity zone of about 76-436 Ωm and this is a zone of lateritic clay. Underlying this zone of high resistivity lies a zone of medium resistivity and extends down from a depth of 2 to 10m. There is a low resistivity zone that also occurs at the extreme left of the profile, showing a resistivity value of less than 22 Ωm, this could probably be a zone of weathered basement or water water-saturated zone.

The VLF-EM result for profile 8 (Fig.17) showed the resistivity value. The result revealed a low resistivity zone (blue colour) at depth 5-10m from line 0-5 corresponding to the low resistivity zone on the 2D profile.

This zone could be as a result of fracture or water saturated zone. Below this zone lies zone of moderate to high resistivity (green to red colour The VLF-EM result corresponds to the result of the 2D resistivity result.

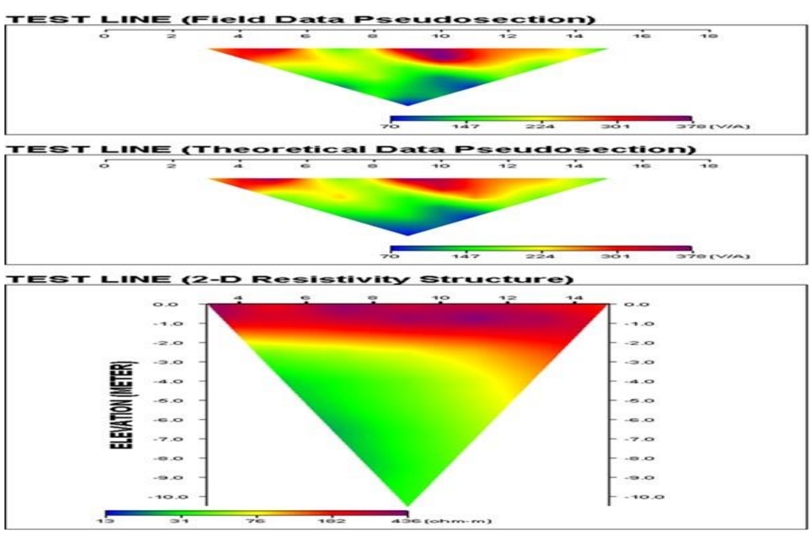

Fig. 16: 2D Resistivity for Profile 8 (Failed Segment) showing resistivity variation across the entire profile length

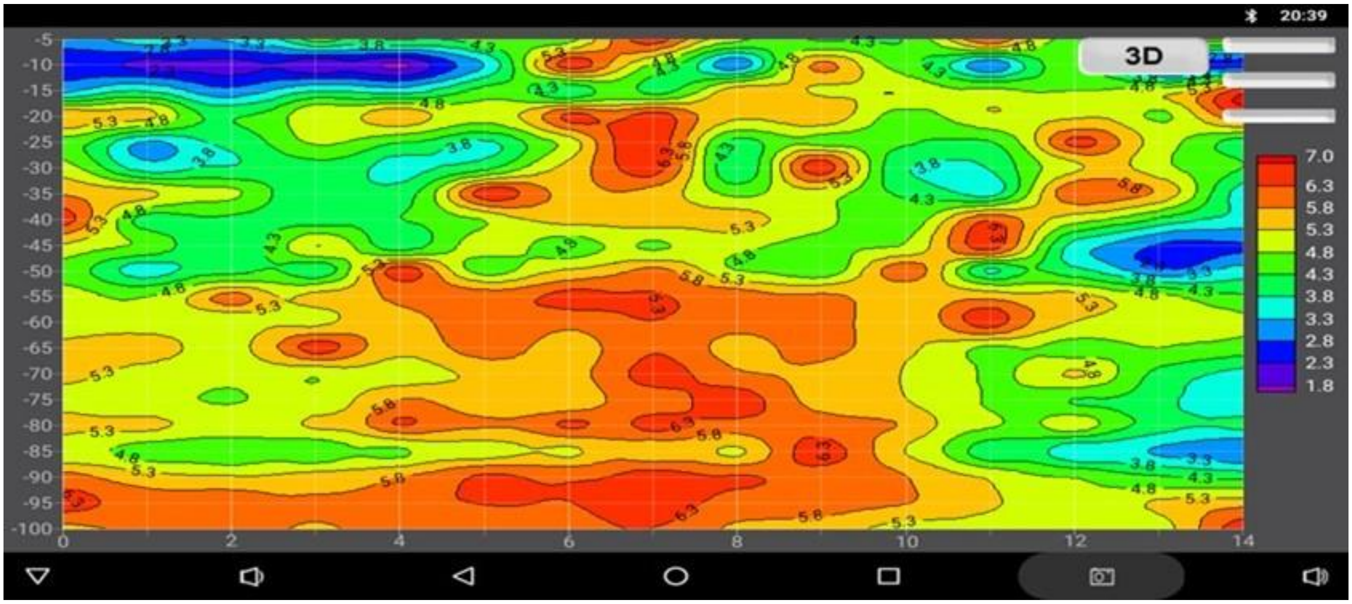

Fig. 17: VLF-EM Graph profile 8 (Failed Segment) showing variation in resistivity across the entire profile line

Geotechnical Results

The sieve analysis results for the eight samples reveal varied particle size distributions across different sieve sizes (Table 1). Most samples retained little to no weight in larger sieve sizes (20.00 to 5.00 mm), indicating a general absence of coarse particles. As the sieve size decreased, significant variations in the percentage weight retained emerged. Sample 8 exhibited the highest retention (23.6%) at the 2.00 mm sieve size, while other samples showed more moderate values, such as Sample 1 with 2.4% and Sample 2 with 1.4%. Notably, finer sieve sizes (0.425 mm) showed considerable retention, with Sample 6 retaining 57.9% and Samples 5 and 7 retaining 40.7% and 26%, respectively. The percentage retained at the 0.075 mm sieve size was minimal across all samples, ranging from 0.5% in Sample 1 to 2.5% in Sample 8. A graphical representation of it is shown in Fig 18. These results suggest a dominance of medium to fine particles in the soil samples, indicating that they mostly consist of sand and silt, with minimal clay content.

The moisture content results for the eight samples vary, ranging from 8.2% to 16.8%. Sample 7 recorded the lowest moisture content at 8.2%, while Sample 3 showed the highest at 16.8%. Most of the samples exhibited moderate moisture content values, such as Sample 1 at 12.62%, Sample 2 at 12%, and Sample 6 at 11.1%. Samples 4 and 5 recorded slightly lower values at 11.4% and 11.35%, respectively, while Sample 8 had a moisture content of 11% (Table 2).

Table 2: Moisture Content of Samples

Sample No	Moisture Content (%)
Sample 1	12.62
Sample 2	12.00
Sample 3	16.80
Sample 4	11.40
Sample 5	11.35
Sample 6	11.10
Sample 7	8.20
Sample 8	11.00

Table 1: Weight Retained of All the Samples

Sieve No.	Sieve Size (mm)	S1 (%WR)	S2 (%WR)	S3 (%WR)	S4 (%WR)	S5 (%WR)	S6 (%WR)	S7 (%WR)	S8 (%WR)
¾ Inch	20.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.530 Inch	14.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3/8 Inch	10.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	5.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	3.35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	2.00	2.4	1.4	2.6	4.1	1.2	0.5	2.0	23.6
16	1.18	8.3	14.2	3.8	8.9	0.7	2.9	7.1	34.7
30	0.60	33.0	35.3	14.1	24.5	15.4	9.4	13.6	14.1
40	0.425	37.1	19.1	47.0	29.7	40.7	57.9	26.0	10.5
50	0.30	5.9	13.6	26.4	26.5	12.9	17.9	42.7	7.4
70	0.212	11.4	14.7	2.8	3.0	4.4	5.3	4.6	4.4
100	0.150	1.3	0.3	2.3	2.2	22.9	4.1	2.6	2.6
200	0.075	0.5	1.1	0.9	1.0	1.5	1.9	1.2	2.5
Pan	–	0.1	0.3	0.1	0.1	0.1	0.1	0.3	0.2

****, S1–S8: Sample 1 to Sample 8, %WR: Percentage Weight Retained and Pan: The bottom container used to collect particles passing through the smallest sieve.**

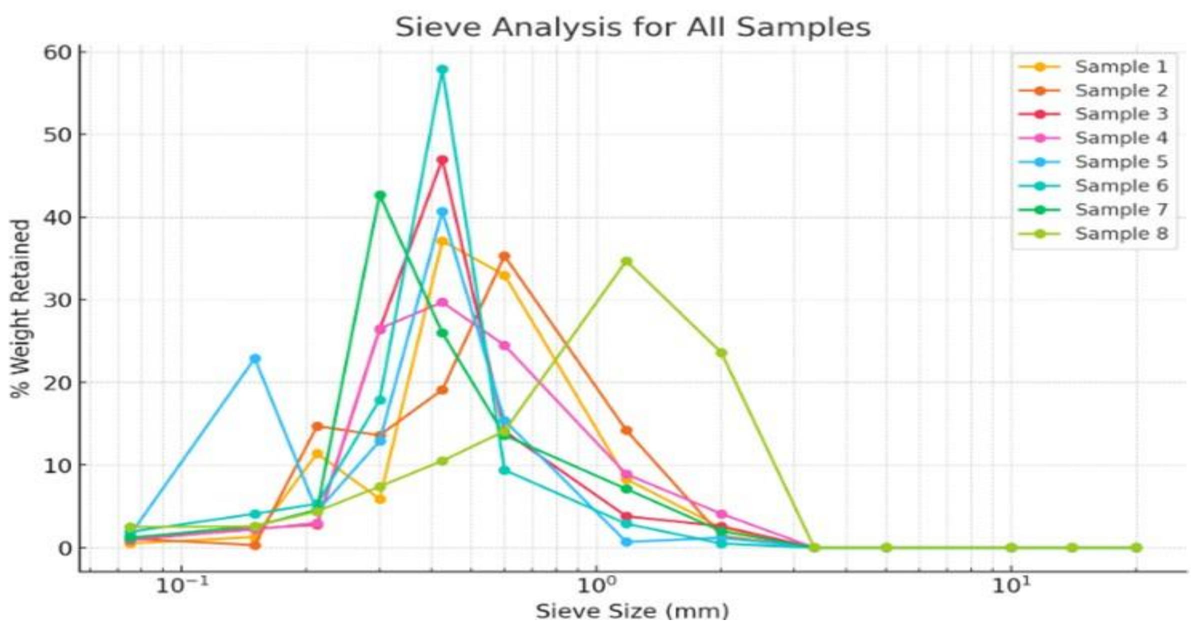

Fig 18: Graphical representation of particle distribution curve for Samples 1 to 8

The Atterberg limits test was conducted for Samples 1 and 2 because they served as representative of others and their results indicate low plasticity, which is favourable for road construction (Table 3). Sample 1 has a liquid limit (LL) of 29.1%, a plastic limit (PL) of 14.15%, and a plasticity index (PI) of 14.95%. Similarly, Sample 2 has a liquid limit of 33.5%, a plastic limit of 18.35%, and a plasticity index of 15.15%

The integrated geotechnical and geophysical investigations conducted in the study area aimed to assess the subsurface conditions and their implications for road failure. The combined results from geophysical surveys, sieve analysis, moisture content tests, and Atterberg limits provide a comprehensive view of the soil behaviour and its suitability for road construction. The geophysical analysis, which included 2D electrical resistivity tomography and Very Low Frequency Electromagnetic (VLF-EM), offered critical insights into the subsurface structure and potential causes of road instability. This was supplemented by the geotechnical tests, which evaluated the physical properties of the soil.

Table 3: Atterberg Limits Test Results of Samples

Sample No	Liquid Limit (LL%)	Plastic Limit (PL%)	Plasticity Index (PI%)
Sample 1	29.1	14.15	14.95
Sample 2	33.5	18.35	15.15

The 2D electrical resistivity tomography and VLF-EM techniques revealed significant subsurface variations that could influence road stability. The resistivity profiles showed that the study area is underlain by zones of varying resistivity, which indicate differences in material composition and moisture content. High resistivity zones, especially at shallow depth, were interpreted as lateritic soils, which are typically dense and stable, making them suitable for road construction. Conversely, low resistivity zones, particularly in the failed segments of the road, indicated potential water-saturated zones or weathered clay materials (as also stated by Griffiths & Barker, 1993). These low-resistivity areas are problematic because saturated soils tend to have reduced strength, which can lead to differential settlement and eventual road failure.

The VLF-EM results corroborated the findings from the resistivity profiles, highlighting conductive zones associated with water accumulation or clay layers. The VLF-EM technique is particularly sensitive to detecting subsurface features like faults and fractures, which could allow water infiltration into the soil, further weakening the foundation (McNeill, 1990). In several profiles, high conductivity values were detected at shallow depths, suggesting that water-saturated zones may be present close to the road surface. These findings align with previous studies that have linked road failure to underlying saturated or weak geological units (Momoh *et al*., 2008; Ogungbe *et al*., 2021).

The resistivity values ranged significantly across the profiles. For instance, the low resistivity zones, with values as low as 24 ohm-meters, were interpreted as saturated clays or waterlogged areas, both of which can compromise the load-bearing capacity of the subgrade (Burland & Burbidge, 1981). On the other hand, resistivity values above 200 ohm-meters indicated lateritic material, which is much more stable and capable of supporting road construction (Aizebeokhai *et al*., 2010). The depth and extent of these resistive layers are critical for understanding the potential failure mechanisms. The deeper low-resistivity zones suggest that while surface soils may be suitable for construction, underlying weaknesses could result in long-term instability if not properly addressed during the construction phase. Moreover, the 2D electrical resistivity results showed that the failed segments of the road are predominantly characterized by a combination of low to medium resistivity zones at shallow depths, which are indicative of water-saturated soils. These findings are consistent with similar studies in Nigeria that have attributed road failure to subsurface water accumulation, especially in regions with inadequate drainage systems (Akintorinwa *et al*., 2010). Thus, the geophysical data suggest that poor drainage and water infiltration into the road subgrade are significant contributors to road failure in the study area.

The sieve analysis provided further insight into the particle size distribution of the soil samples, which is a key determinant of the soil's suitability for road construction. All samples showed a minimal percentage of fines (particles passing through sieve number 200), with values ranging from 0.5% to 2.5%. According to the Federal Ministry of Works and Housing, Nigeria (FMWHN, 2000), soils with less than 35% fines are considered suitable for road construction because they have limited clay content. This is important because high clay content can lead to swelling and shrinkage under varying moisture conditions, resulting in road cracking (Rahman *et al*., 2014).

Especially if the clay is rich in montmorillonite mineral. Most of the samples exhibited significant amounts of medium to fine sand, indicating that the soils are primarily sandy in nature. The absence of excessive fines suggests that the soil will likely have good drainage characteristics, which is essential for preventing water accumulation in the subgrade. This aligns with previous research showing that well-draining soils are less prone to retaining moisture, thereby reducing the risk of weakening the road base (Amadi *et al*., 2015). Therefore, the sieve analysis suggests that the soils are suitable for road construction, with minimal risk of clay-related expansion and shrinkage problems.

The moisture content results ranged from 8.2% to 16.8%, indicating moderate to low water retention in the soil. These values are within acceptable limits for road construction, as excessively high moisture content could lead to a reduction in soil strength (Ademila, 2019). High moisture content in soils can lead to water migration into the pavement, lubricating the soil particles and reducing their interlocking strength, which increases the likelihood of deformation under load (Ola, 1981). The relatively low moisture content values across most samples suggest that the soil has good drainage characteristics and is not overly saturated, which is crucial for maintaining road stability. The variability in moisture content across the samples could be attributed to localized differences in soil composition and drainage patterns. The moderate moisture content levels observed in most samples suggest that while water saturation is a concern in some areas, and hence the road tends to fail in those regions with high moisture content. Therefore, it is not uniformly problematic across the entire study area. This reinforces the need for localized drainage improvements in areas where water accumulation is detected.

The Atterberg limits test results further support the conclusion that the soils are suitable for road construction. Samples 1 and 2 were tested for their liquid and plastic limits, and showed low plasticity with liquid limits of 29.1% and 33.5%, respectively, and plasticity indices of 14.95% and 15.15%. These values fall within the acceptable range for road construction, as the FMWHN (2010) recommends a liquid limit below 35% and a plasticity index below 17%. Soils with low plasticity are less likely to undergo significant volume changes due to moisture fluctuations, making them more stable for construction (Ola, 1981). The low plasticity of the soils in the study area indicates that they will not shrink or swell excessively, reducing the risk of road cracking or deformation. These findings are consistent with previous research on Nigerian residual soils, which have shown that low plasticity soils are generally more stable and suitable for use in road subgrades and bases (Amadi *et al*., 2015). The plasticity index values for the samples indicate that the soils have enough cohesion to provide stability without being excessively plastic, which could lead to deformation under load.

The soils in the study area are typically deemed appropriate for road construction, based on the geotechnical evaluations. But the geophysical data revealed isolated pockets of water saturation, which may be a factor in road collapse, especially in places with inadequate drainage. The soils' low clay content and plasticity, which lowers the chance of swelling and shrinking, were validated by the sieve analysis and the Atterberg limits test. The soil has high drainage qualities and moderate water retention, according to the results of the moisture content analysis. Although the geophysical investigation showed zones that are saturated with water, localized drainage improvements are required to address the issue.

4.0 Conclusion

A geophysical and geotechnical investigation was conducted on the Zone 8-Crusher road using 2D Electrical Resistivity Tomography (ERT), Very Low Frequency Electromagnetic (VLF-EM) surveys, sieve analysis, and Atterberg limit tests. The 2D resistivity tomography results identified three distinct resistivity zones: low, intermediate, and high. The low and intermediate resistivity zones, particularly in the failed portions of the road, are likely due to water saturation in the weathered materials beneath the surface. This finding aligns with the VLF-EM results from all surveyed locations.

Sieve analysis revealed that the percentage of soil passing through sieve number 200 (0.075mm) was below 35%, indicating minimal clay content, which suggests that clay is not a contributing factor to the road failure. This was further supported by the Atterberg limits, which showed that the liquid limit, plastic limit, plasticity index, and moisture content values all fall within the acceptable range for soils used in road construction. The road's failure can likely be attributed to a combination of factors, including ageing, the use of substandard construction materials, poor compaction techniques, and the absence of an efficient drainage system to control water infiltration. Additionally, heavy stationary loads from parked trailers and loaded tipper trucks placed sustained pressure on the road surface, which may have contributed to structural degradation over time.

The study concludes that geophysical methods, such as 2D electrical resistivity and VLF-EM, combined with geotechnical tests, are reliable tools not only for identifying the underlying causes of road failure but also for optimizing road design and rehabilitation strategies.

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Declaration

Consent for publication

Not applicable

Availability of data

Data shall be made available on demand.

Competing nterests

The authors declared no conflict of interest

Ethical Consideration

Not applicable

Funding

There is no ource of external funding.

Authors' Contribution

All components of this manuscript were developed by the author