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Geophysical Investigation of Road Pavement Failure Along the Mubi Bypass Road, Jambutu, Jimeta, Yola, Adamawa State

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ABSTRACT

A good road network is essential for accelerating the economic development of any region. However, in the present study area, the deteriorating condition of road pavements has contributed to frequent accidents, leading to loss of lives and property. To investigate the causes of these pavement failures, a geophysical survey employing the electrical resistivity method was conducted. The Wenner configuration was specifically chosen due to its suitability for noisy environments and its high resolution for detecting near-surface anomalies. The geophysical results show that resistivity range of the failed sections FS1, FS2, FS3 and FS4 are respectively 23.5 – 82.7 Ωm, 9.81 – 29.7 Ωm, 7.84 – 21.9 Ωm and 11.8 – 22.8 Ωm while those of the stable sections SS1, SS2, SS3 and SS4 are respectively 38.9 –138 Ωm, 28.2 – 121 Ωm, 13.7 – 20.3 Ωm and 14.5 – 21.9 Ωm. Lithologies of the stable sections (SS) 1 and 2 were inferred as very hard clay, sandy clay, and sandstone, which are moderately competent, whereas those of stable sections (SS) 3 and 4 were inferred as dry clay, silty and sandy clay though overlying weak/saturated zone. Failed section sample 1 (FSS) 1 was inferred as saturated clay and sandy clay, all of which are incompetent, whereas failed section samples (FSS) 2, 3, and 4 were inferred as weak zones of saturated moist clay, silty sand, and sandy clay with exposed clay deposit. The study concludes that the primary causes of road pavement failure in the area include the incompetent nature of silty clay and silty sand subbase/subgrade materials, inadequate drainage systems, and the area's proximity to the Benue River, making it flood-prone. These challenges pose a significant threat to pavement integrity. To mitigate these failures, the implementation of functional drainage systems and effective soil stabilization techniques is recommended.

Keywords:
Electrical Resistivity,
Tomography,
Subsurface Layer,
Wenner Configuration,
Road Pavement Failure.

INTRODUCTION

Roads are the backbone of modern transportation, playing an important role in connecting communities, enabling social growth, facilitating economic activities and connectivity. A road's hard crust overlying a subgrade is called the pavement. Whereas, a road network's discontinuity or deformation which causes cracks, potholes, bulges, buckles, depressions, and other forms of defects, ruts, fractures, and road-cutting leading the pavement to heave differently, is referred to as pavement failure. Irrespective of geographic locations, some of the consequences of road pavement failures include accidents, injuries, fatalities, repair and maintenance costs, and traffic gridlocks, which ensures substantial economic difficulty. Superb access road is made up of continuous stretch of asphalt, concrete, brick, or gravel layer for a smooth ride, while a bad section on such a stretch of road pavement constitutes failure which is either caused by un-recommended traffic load, poor construction materials, or inadequate maintenance strategy (Adegoke - Anthony & Agada, 1980). The Electrical prospecting primarily involves the detection of surface effects produced by electrical current flow in the subsurface (Al-Rahim, 2020). It could be electrical resistivity method, Induced polarization (IP) method, Self-potential (SP) method, Electromagnetic (EM) method. Environmental and engineering applications of geophysical methods particularly electrical resistivity prospecting techniques are rapid, affordable, and non-destructive in providing data regarding subsurface characteristics, such as depth to bedrock, structural mapping, assessment of integrity of the subsoil,

distribution of conductive fluids, location and orientation of faults and fractures underneath the surface (Reynolds, 1998). The method evaluates the underlying layer of the road pavement so as to examine the competence and the possible weak sections that culminate into road damage.
Bisong *et al.* (2023) applied the electrical resistivity tomography along Jonathan bypass – Lafarge – Akansoko road in Calabar metropolis, Cross River State. Their results revealed resistivity values between 26.0 – 68.0 Ωm and 173.0 – 19259.0 Ωm at the failed and stable sections respectively, and they concluded that clay/shale/weathered geologic and low resistivity materials caused the road failure. Using vertical electrical sounding (VES) and 2D imaging dipole-dipole imaging techniques, Oguntade (2022) evaluated the compositions of the bedrocks of near surface geologic materials along Oloko road, Apatapiti, Akure, Nigeria. The study shows thin topsoil and a weathered layer. The resistivity of the basement ranged from 168 –261 Ωm at a depth of 45 – 205 m. They observed a thick near surface structure of low resistivity at less than 5 m depth that accumulated groundwater as reason for the observed failure. Medjor *et al.* (2022) used the 2D electrical resistivity tomography (ERT) to investigate the sources of perennial pavement failures along Jalingo – Zing road in Taraba State, Nigeria. Results showed that the resistivity of all profiles in the top layers range from 0 to 61.6 Ωm. They indicated that the road was constructed on thick incompetent top soils of clay or shale constituents and hence adjudged to be the cause of pavement failure. Aderemi and Adeola (2021) used a geophysical approach to examine the root causes of road failure on a community road in Abadina, Ibadan, Oyo State, Nigeria. The outcomes revealed that the geo-electric layer is made up of a topsoil, clay, and basement rock with resistivities of 120.3 Ωm, 36.1 Ωm and 377.4 Ωm respectively. They concluded that the road pavement failed as a result of the presence of incompetent sub-grade and clayey formation having high porosity and very low permeability. Udoinyang *et al.* (2021) adopted the Vertical Electrical Sounding (VES) method to assess cause(s) of road pavement failure along Ikot-Ekpene - Umuahia road, the research revealed that the failed portions are situated next to a densely low resistive layer of less than 100 Ωm on a worn-out and porous basement. They hence arrived at a conclusion that the road failed as a result the presence of saturated, loamy overburden, and fractured clay/laterite basement, which were worsened by low grade construction materials. Rafiu *et al.* (2020) investigate the cause of road pavement failure along Minna-Bida road, Niger State using the geophysical protocol. They concluded that the road failed as a results of the intercalation of clayey top/sub-grade soils, waterlogged sands having low resistivity ranging between 0.10 – 30.4 Ωm this is because the road pavement could not withstand the pressure exerted on it by vehicular movements. Adenika *et al.* (2018) conducted a combined geophysical study along Ibadan-Ife Highway in Southwestern, Nigeria. They intended to unravel the physical and geologic features that caused the failure on the road pavement. Their results show resistivity values in the range; 139–324 Ωm (topsoil) and depth of 0.6 – 1.1 m, 20 – 66 Ωm (weathered layer) and thickness of 5.4 –17.0 m, 30 – 473 Ωm (moderately weathered/fractured basemen) and thickness of 11.5 – 25.8 m and 762 – 850 Ωm (unweathered basement) and depth to basement varying from 11.7–31.9 m respectively. They concluded that the factors inducing the frequent pavement failures are abundant and low resistivity clayey substratum (<100 Ωm), subsurface linear structures like fractures, or weak zones that enhance the accumulation of water. Adesola *et al.* (2017) used integrated geophysical methods on parts of the Ogbomoso-Ilorin highway, the study revealed fracture/fault zones of low resistivity values less than 150 Ωm, clayey subgrade soil, lateral inhomogeneities that accounted for the likelihood of the pavement to damage. Falowo and Akintorinwa (2015) also conducted geophysical investigations along the failed portions of the Akure-Ijare road. They indicated that the road pavement failure was due to an incompetent topsoil and clayey nature of the subgrade materials (< 100 Ωm). Momoh *et al.* (2008) used geophysical approach to assess the Ilesha-Owena highway. They observed low resistivity subsurface between 22 – 100 Ωm, and indicated the presence of thin dyke, and very clayey materials. In their opinion, the subsurface structural features such as clayey topsoil/sub-grade soils, near-surface linear features, and weak zones were responsible for the observed pavement failure.
Most road failures occur shortly after construction as a results of (excessive) usage, poor supervision, inadequate construction materials, and lack of adherence to standard specifications or design, and insufficient knowledge about the properties the soils over which the pavements are constructed. The planning, design, and building of roads must be reliant on vast knowledge of the geo-electrical properties of the underlying soil and their condition. The current study is focused on the investigation of causes of road pavement failure using geophysical method and exploring the relationship between geophysical properties of soil, pavement structure, and failure mechanisms, thereby contributing to the establishment of more efficient pavement in terms of design, construction, and maintenance strategies.

Location and Geology of the Study Area

Mubi Bypass Road, Jambutu, Jimeta is located in Benue Trough, between latitudes 9°17'20"N and 9°18'26"N, and longitudes 12°25'E and 12°29'E (Figure 1), along the southern bank of the Benue River. The area is largely typified by smooth to gently undulating terrains, and wholly drained by Benue River, which has massive flood plains where we have lake Geriyo and lake Njuwa. Both lakes borders the Jimeta area, while being dissected by several small streams and tributaries (Ntekim & Bello, 2001). On the contrary, Yola is bordered by lake Njuwa on the eastern side (Ishaku, 2011). The geology of the study area is overlying the oldest formation in the upper Benue Trough termed the Albian-Aptian Bima Sandstone on the Northeastern, Southeastern and Southwestern sides, at the base of the sedimentary succession and unconformably superimposed on the Basement Complex, with the sedimentary deposit within the rift traversing centrally through the Yola arm. The recent (Quaternary age) river coarse alluvium consisting of poorly graded clays, siltstone, sand and pebbly sand (Ishaku, 2011) is distributed all across the primary course of River Benue and trails towards Northeastern and Southern parts of Jimeta.

The Bima sandstone is composed of beds of pebble, sandstone of feldspar origin, and the intermittent insertions of clay. In addition, the bima sandstone formation has been classified into various Bima groups (Allix, 1983; Carter *et al.*, 1968; Guiraud, 1991), viz the lower Bima (B1), the middle Bima (B2) and the upper Bima (B3). The Lower Bima (B1) offshoots at the core of the Lamurde anticline. It is made-up of coarse- grained feldspathic sandstone intersecting with red, purple shale and occasional bands of calcareous sandstone and siltstone. The unit is very variable with an average thickness ranging from 0 m to over 500 m (Meludu et al., 2010). An upper Aptian/Albian age has been assigned to this subdivision of the Bima sandstone (Kogbe, 1989). The middle Bima (B2) is a largely uniform unit consisting of highly coarse-grained, feldspathic sandstone with thin Bands of clay, silts, shale and intermittent calcareous sandstone. The thickness varies from 300 - 1200 m (Meludu *et al.,*, 2010). The deposits are not distal from the Benue river (Guiraud, 1991; Zaborski *et al.*, 1997) and are typified by trough and platy cross-bedding (Ishaku, 2011). Based on pollens and radiometric data obtained from intercalated lavas, a provisional middle Albian age was assigned to it by Whiteman (1982). Finally, the upper Bima (B3) is largely homogenous, fairly mature, varies from fine-grained to coarse-grained sandstone deposit composed of planar cross-bedding, fold-like overlapping bedding and capsized cross-bedding (Zaborski *et al.,*, 1997), thick-bedded sandstone with copious amount of sedimentary structures. It is widely distributed and the thickness can range from 500 to 1700 m. The geological sequence was deposited under fluvatile to deltaic environment (Carter *et al.,*, 1968) and the rock sequence in the area shows the presence of laterites, mudstones, ironstones, clays and siltstones. The late Albian to early Cenomanian *age was assigned to this upper* fold *subdivision of the Bima sandstone by Whiteman (1982)*.

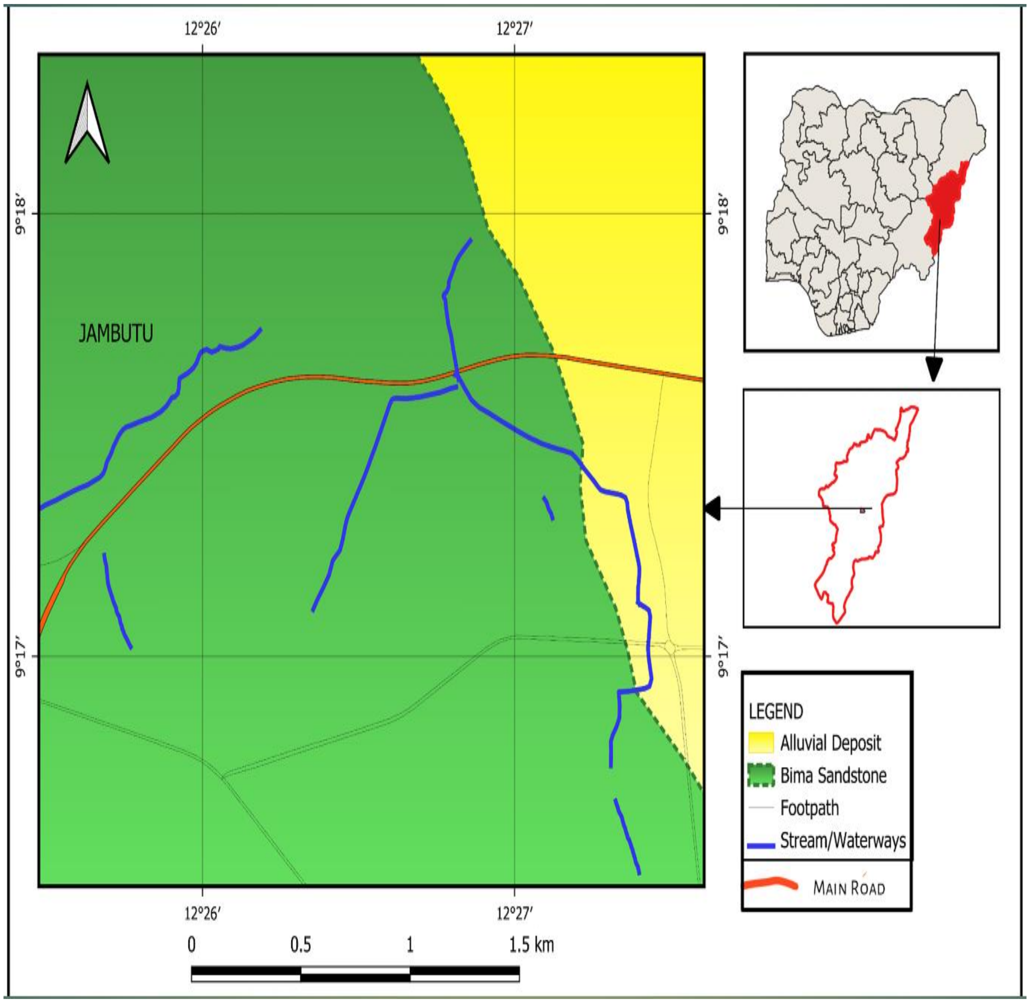

Figure 1: Geologic map of the study area

MATERIALS AND METHODS

A geophysical survey was conducted along a 800 m stretch of the road (Figure 2) using the electrical resistivity method, with both the stable and failed sections measured parallel to the road pavements. The geophysical investigation method used was the two-dimensional electrical resistivity imaging applying the Wenner configuration. In this array, four (4) electrodes were inserted along the line of traverse, with current electrodes on the outer ends and potential electrodes in the middle. These electrodes were spaced at 5 m apart for each of the profiles to provide high-resolution of the subsurface. The total length surveyed for each profile (100 m) were chosen considering the available space and the unavoidable vehicular (traffic) obstructions. The Wenner Configuration was chosen because it has high signal-to-noise ratio (SNR), hence suitable for noisy environment and exhibits better resolution for near-surface features (Al-Rahim, 2020), all of which makes the electrode configuration more ideal for investigating road pavement failures where shallow subsurface variations in electrical resistivity of soil or sediment are very crucial.

The obtained resistivity data were inverted and processed using RES2DINV software (Loke, 2010), so to generate pseudo-sections of the subsurface under investigation. These pseudo-sections offer an approximate imagery of the subsurface characteristics, which makes for easy interpretation. Furthermore, a qualitative interpretation was also conducted by correlating the data processed with equivalent knowledge of the apparent resistivity of soils, rocks, minerals and geology of the study area. The materials used in acquiring the field data were the earth resistivity meter (Terrameter), which was used to measure lateral and vertical variations in soil resistivity, electrodes, reels of cable, hammers, measuring tapes, global positioning system (GPS) and recording material.

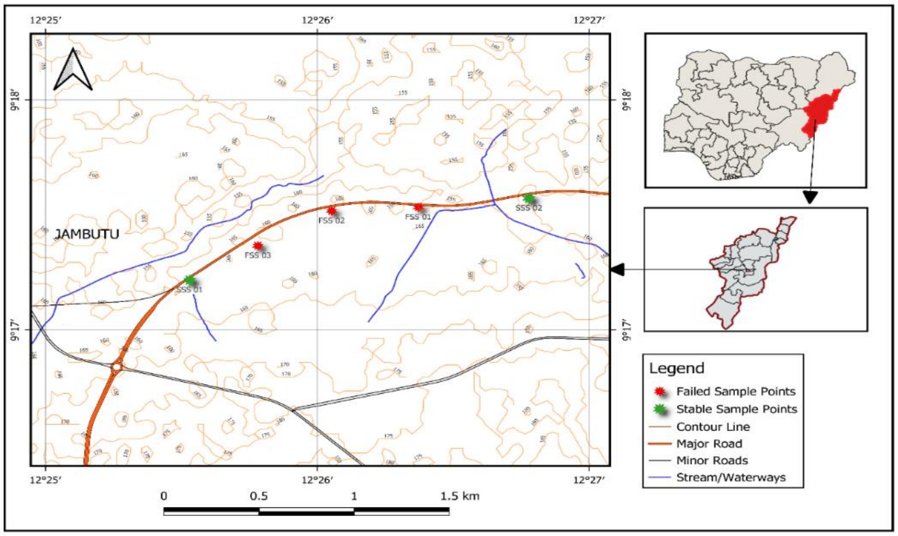

Figure 2: Map of the study area showing the road pavement under investigation, geophysical survey points and geotechnical sampling points

RESULTS AND DISCUSSION

Pseudo-sections of the Failed Sections (FS) and Stable Sections (SS)

Figures 3 – 10 show results of the processed Wenner two dimensional (2-D) inverse model electrical resistivity measurements generated for all measurement points, which expresses approximate imagery of the subsurface properties in the form of pseudo-sections. These images and apparent resistivity values give insight into the root causes of the road pavement failure in the study area.

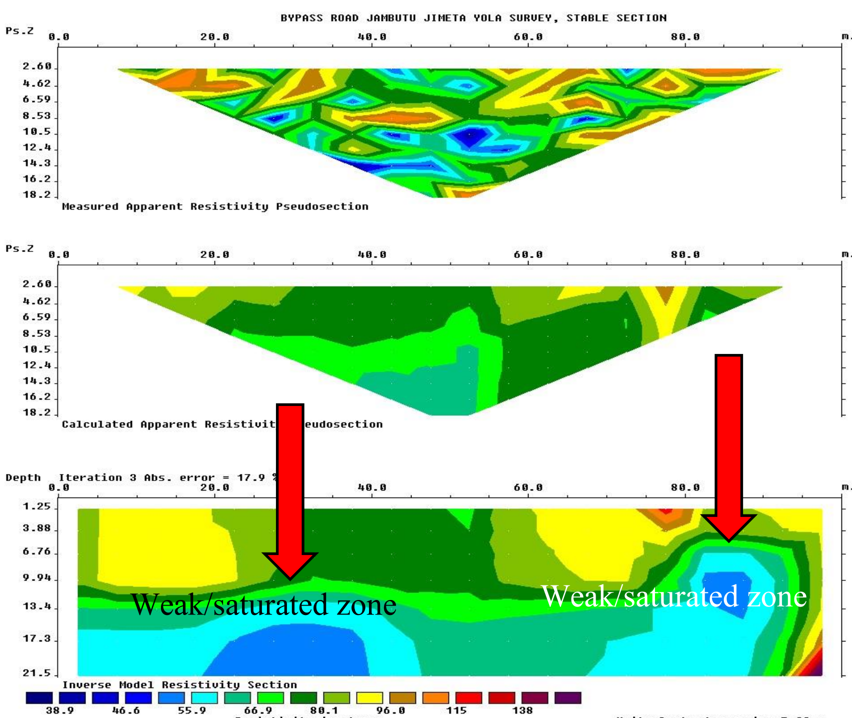

Figure 3: Pseudo-section plots showing the measured apparent resistivity, calculated apparent resistivity and inverse model resistivity section for Stable Section 1 (SS1)

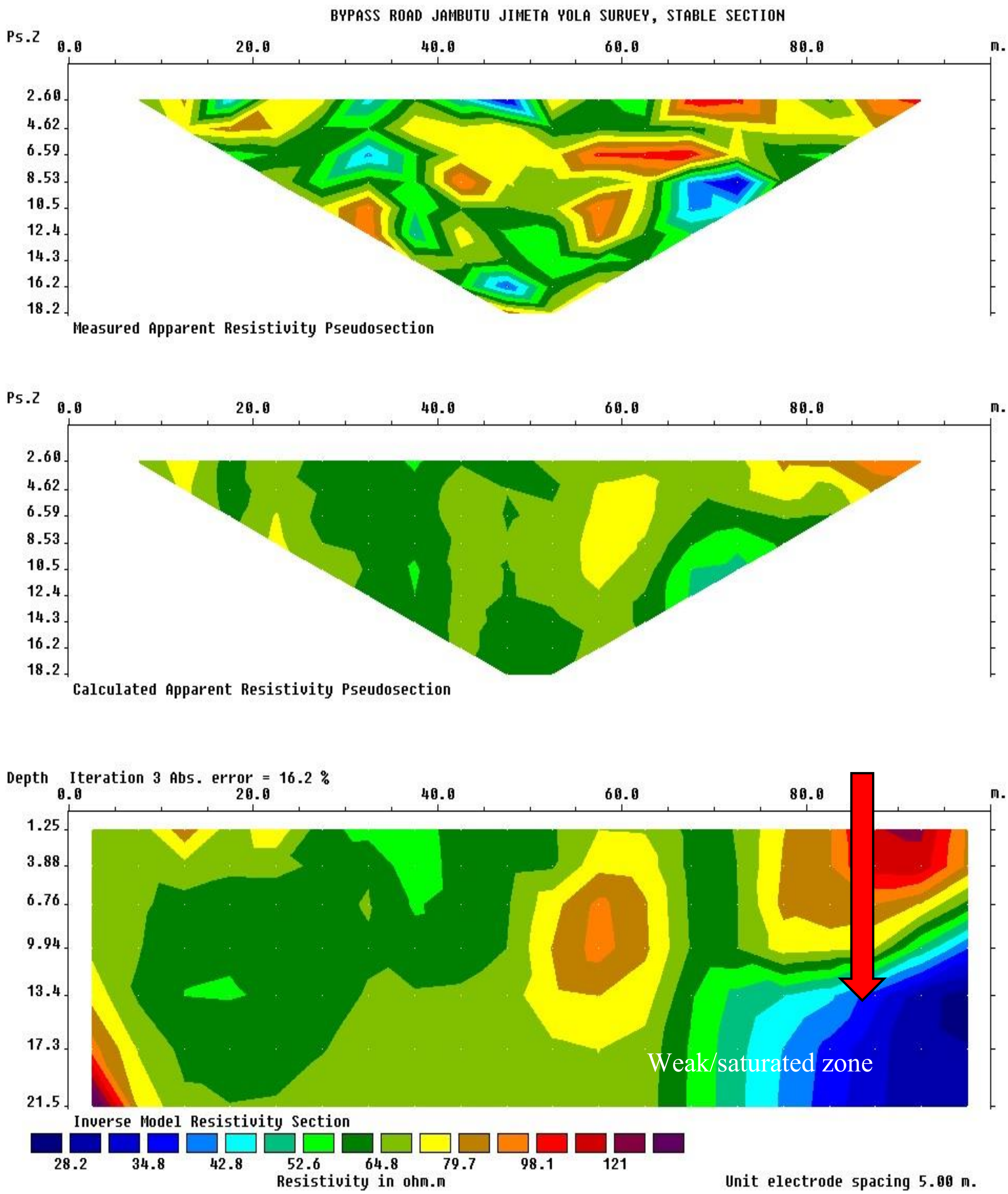

Figure 4: Pseudo-section plots showing the measured apparent resistivity, calculated apparent resistivity and inverse model resistivity section for the Stable Section 2 (SS2)

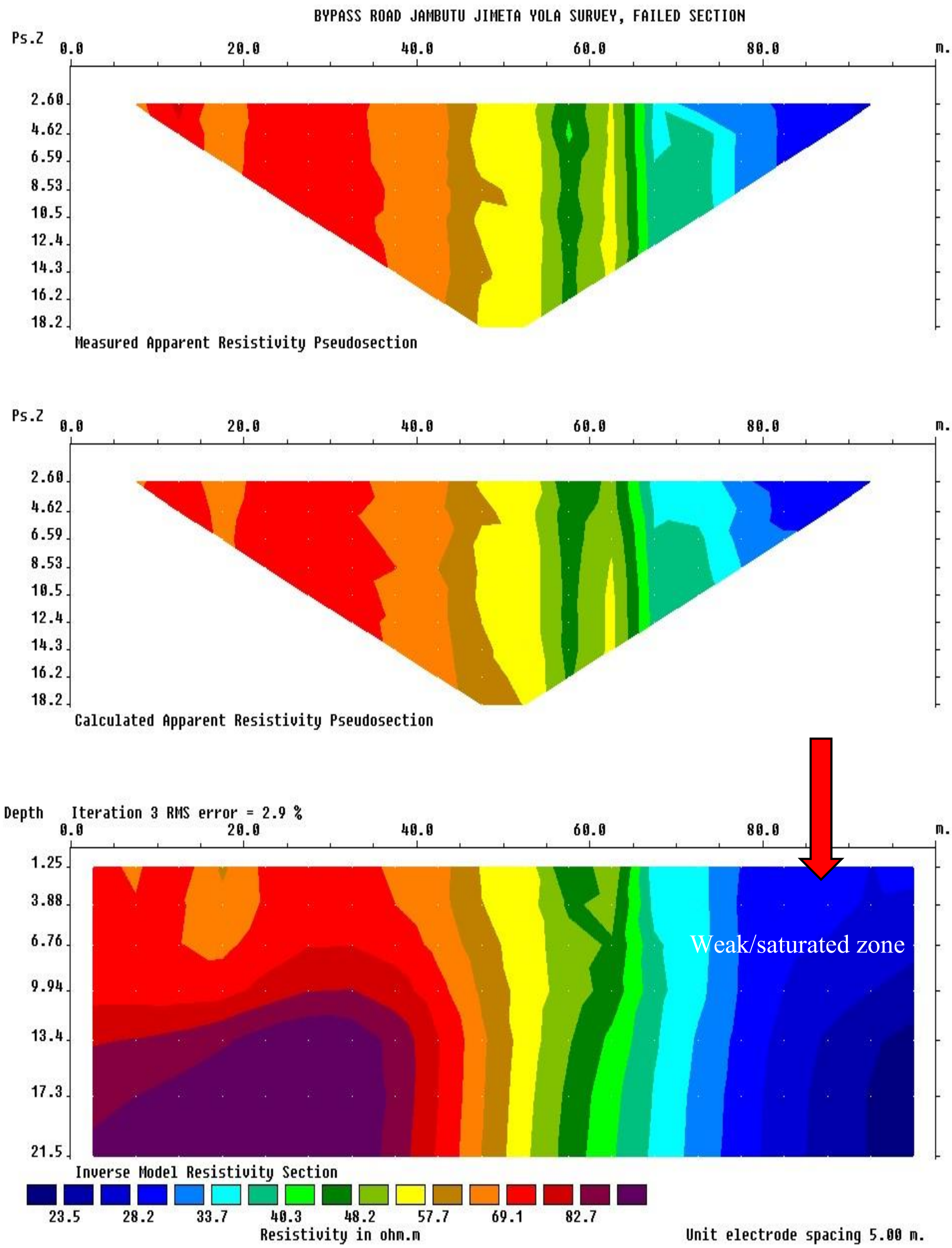

Figure 5: Pseudo-section plots showing the measured apparent resistivity, calculated apparent resistivity and inverse model resistivity section for the Failed Section 1 (FS1)

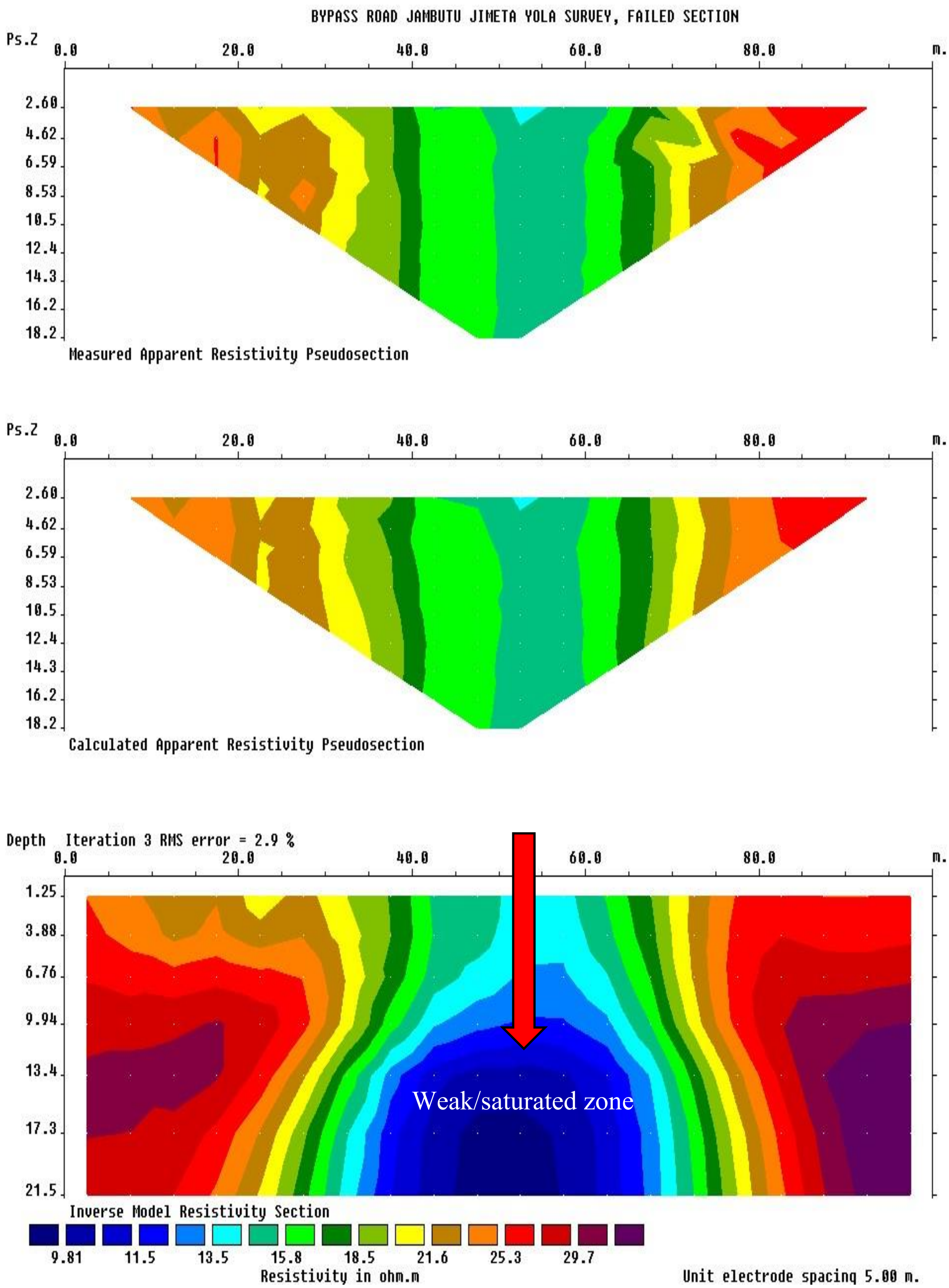

Figure 6: Pseudo-section plots showing the measured apparent resistivity, calculated apparent resistivity and inverse model resistivity section for the Failed Section 2 (FS2)

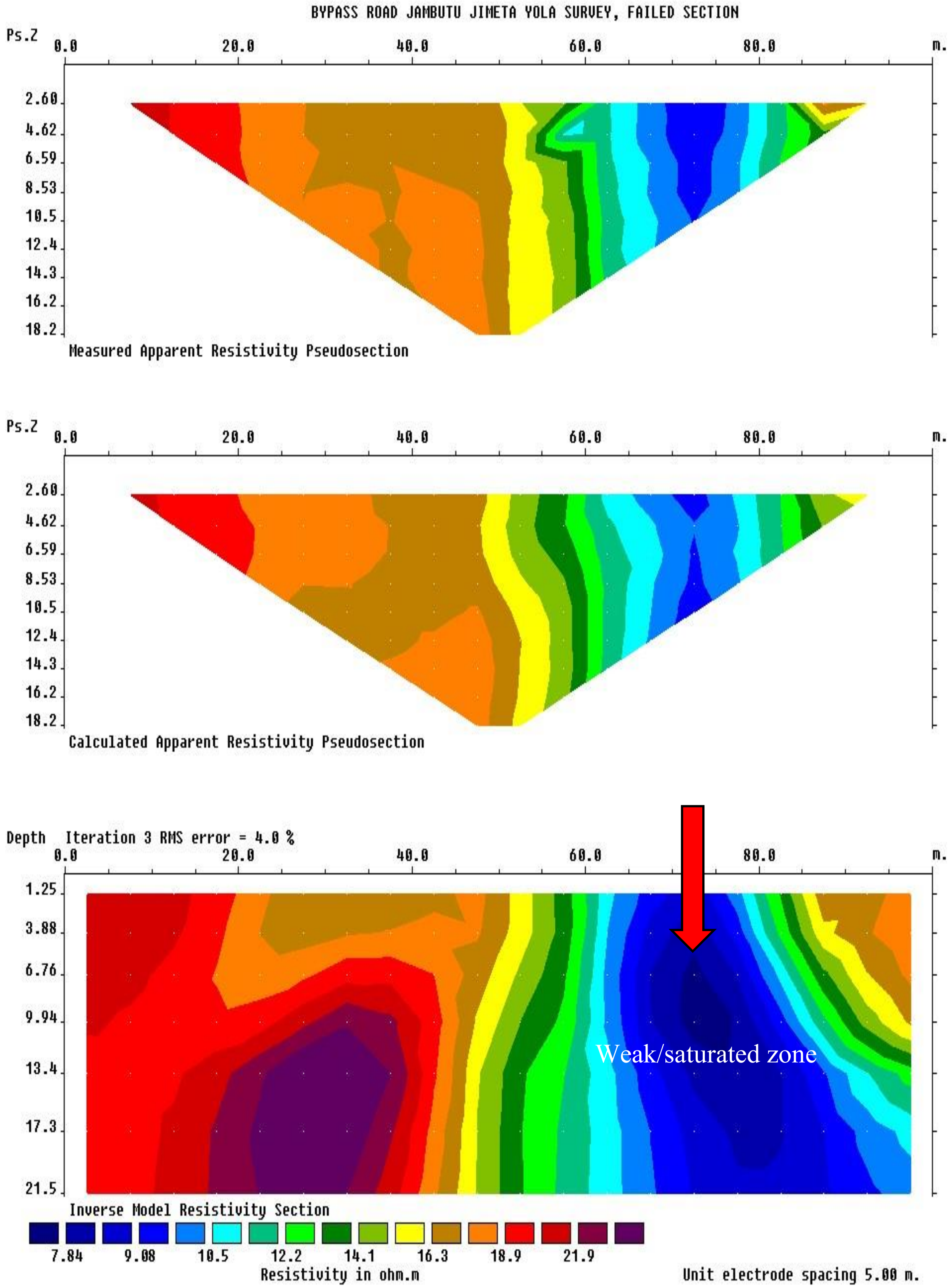

Figure 7: Pseudo-section plots showing the measured apparent resistivity, calculated apparent resistivity and inverse model resistivity section for the Failed Section 3 (FS3)

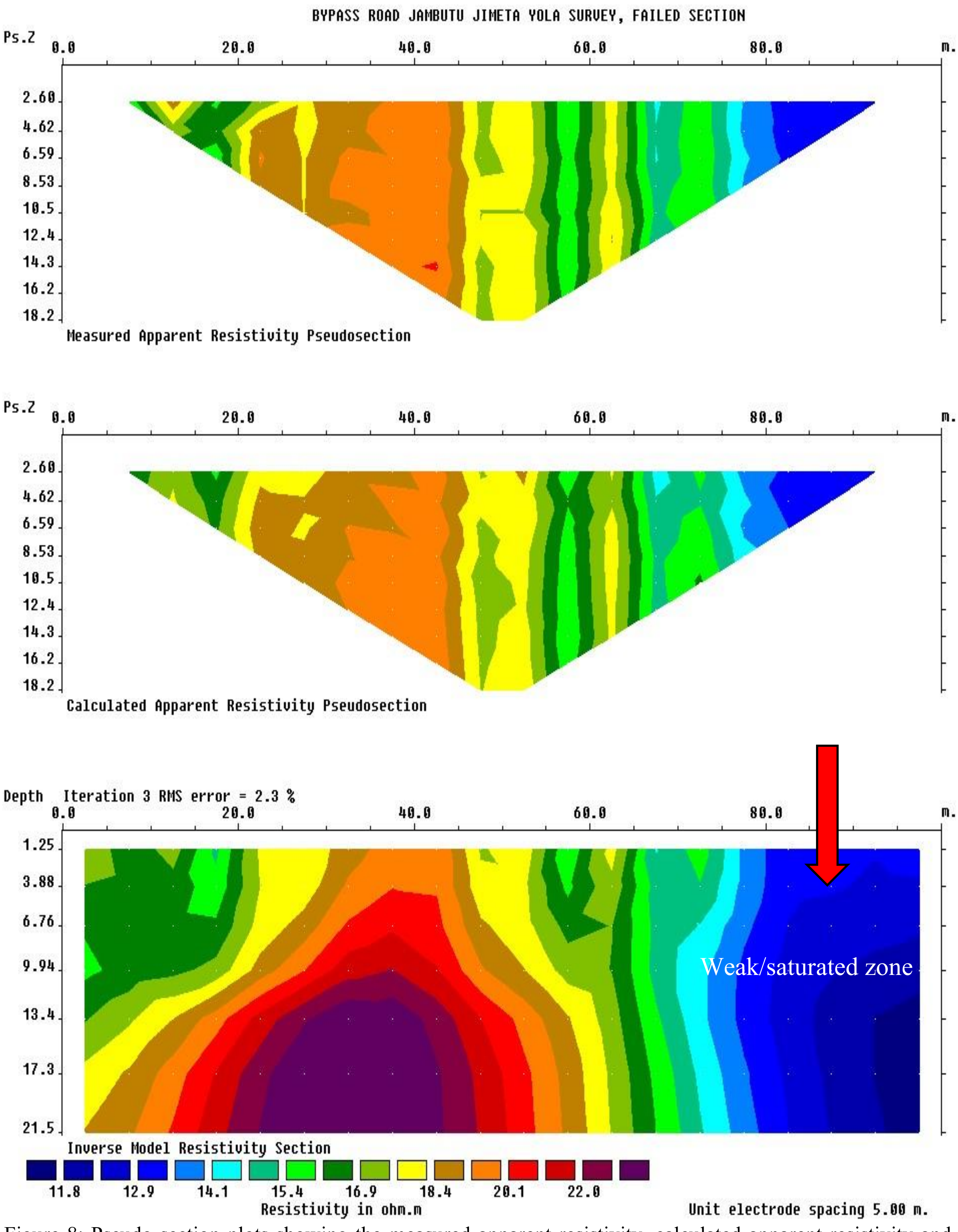

Figure 8: Pseudo-section plots showing the measured apparent resistivity, calculated apparent resistivity and inverse model resistivity section for the Failed Section 4 (FS4)

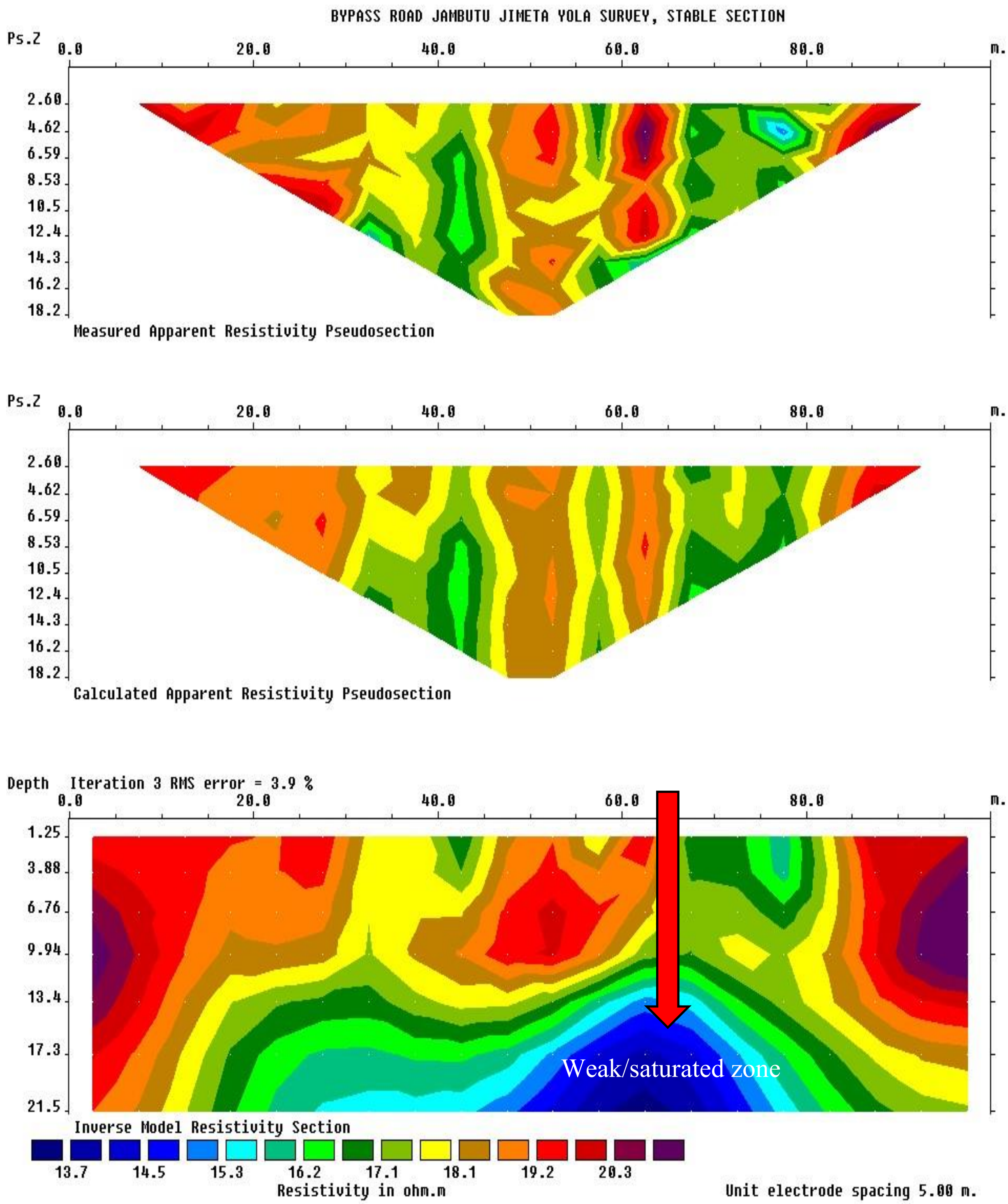

Figure 9: Pseudo-section plots showing the measured apparent resistivity, calculated apparent resistivity and inverse model resistivity section for the Stable Section 3 (SS3)

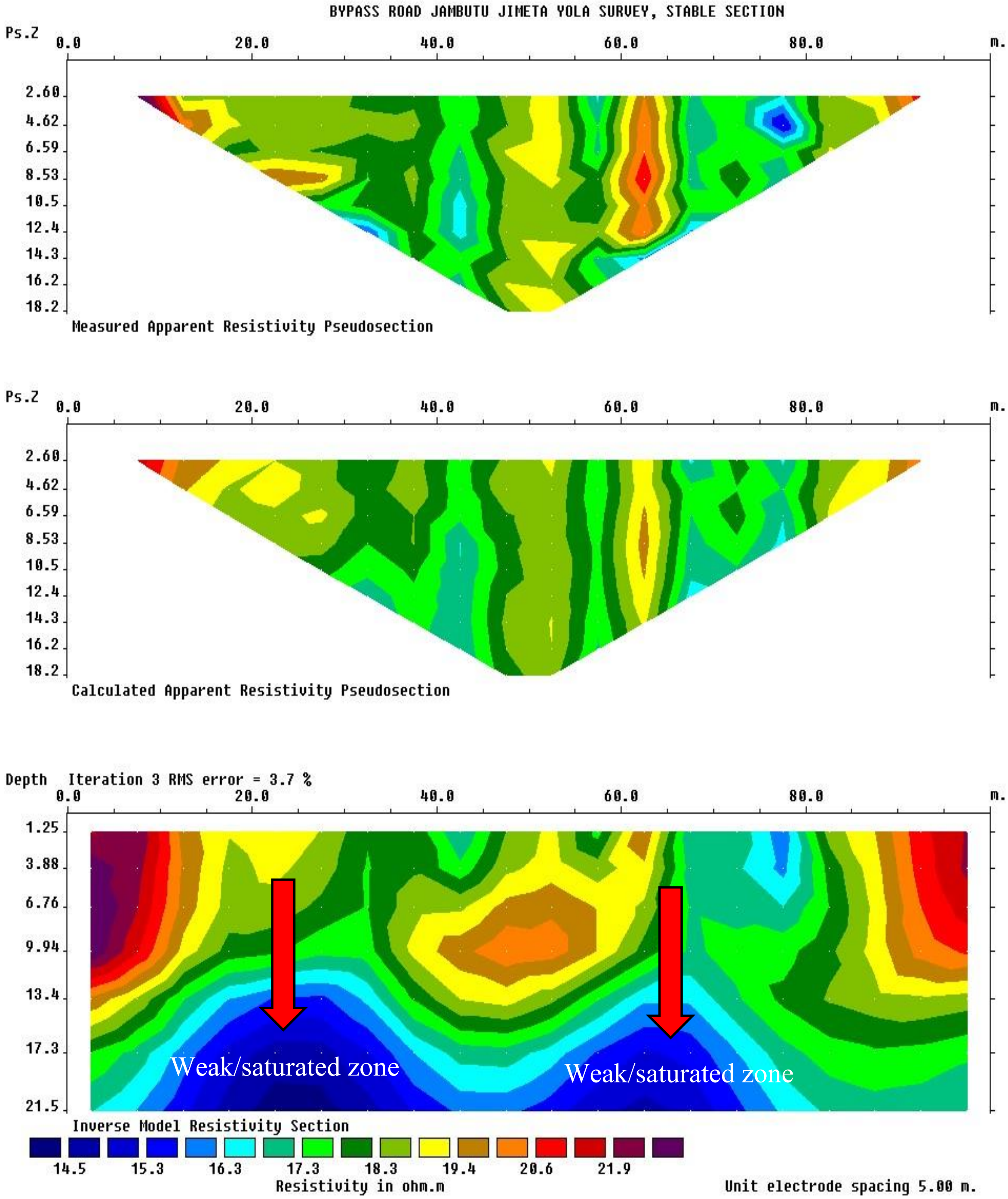

Figure 10: Pseudo-section plots showing the measured apparent resistivity, calculated apparent resistivity and inverse model resistivity section for the Stable Section 4 (SS4)

Figure 3 and Figure 4 shows the resistivity pseudo-sections for the stable section 1 (SS1) and stable section 2 (SS2) respectively. The figures show resistivity values ranging between 38.9 - 138 Ωm and 28.2 - 121 Ωm respectively. These ranges of resistivity values indicate that the road sections are underlain by very hard clay, sandy clay and/or sandstone (Amos-Uhegbu & John, 2017; Oguntade, 2022; Reynolds, 1998; Telford *et al.*, 1990) and are adjudged to be moderately competent (Idornigie *et al.*, 2006). The resistivity of the stable road sections 1 (SSS1) ranging between 38.9 - 138 is typical of soils with low to moderate moisture content, high density and low porosity, good stability and load-bearing capacity. Whereas, resistivity of the stable road sections

2 (SSS2) ranging between 28.2 - 121 Ωm is typical of soils with moderate moisture content , moderate density and porosity, fair stability and fair load-bearing capacity (Lowrie, 1997; Reynolds, 1998). This no doubt accounts for the relative stability of these sections of the road. We can therefore deduce that the influence of sandy clay and sandstone intercalation which are not really water bearing zones (Rafiu *et al.,*, 2020) increases the shear strength of the soils and the load bearing capacity (Amos-Uhegbu & John, 2017). However, though there was no failure observed at these control road sections (SS1 and SS2), the sections are underlain by saturated clay layer (Figures 3 and 4) which are weak zones and have moderate resistivity values suggesting that they are vulnerable to failure in future.

Figure 5 reveals the resistivity pseudo-section for failed section 1 (FS1), showing a much lower resistivity value than the stable sections 1 (SS1) and 2 (SS2), ranging between 28.5 - 82.7 Ωm. This range of resistivity is indicative of an underlying layer of clay and sandy clay (Brian, 1978; Fang & Daniels, 2006; Idornigie *et al.,*, 2006) which are considered to be incompetent as pavement foundation materials, because they have the capacity to retain water as result of the high porosity and low permeability (Fang & Daniels, 2006; Ike *et al.*, 2024; Ike *et al.*, 2023; Santamarina *et al.*, 2001). The underlying material is therefore not good enough as subgrade course material, since it absorbs water, swells and exhibits low bearing capacity, causing differential settlement of the overlying pavement leading to road collapse (Aderemi & Adeola, 2021; Bisong *et al.,*, 2023). Resistivity of this failed road section (FS 1) ranging between 28.5-82.7 Ωm is typical of soils with high moisture content (poor drainage), poor compaction, high porosity and poor stability, low load-bearing capacity and subsequent failure with increased risk of erosion and deformation (Adeyemi & Wahab, 2008; Akpoyiboa *et al.*, 2025; Fang & Daniels, 2006). According to Akpoyiboa *et al.,* (2025), a substantial quantity of clay or clayey soils in the subbase or subgrade course material ensures that lateritic soil stability, strength, and integrity are not guaranteed especially when water is present.

Figures 6, 7 and 8 shows the resistivity pseudo-section for the failed section 2 (FS 2), 3 (FS 3) and 4 (FS 4) respectively. Their resistivity values ranges between 9.81 - 29.7 Ωm, 7.84 - 21.9 Ωm, 11.9 - 21.5 Ωm respectively. These ranges of low resistivity values signify the presence of weak zones of saturated moist clay, silty sand/sandy clay (Momoh *et al.,*, 2008; Reynolds, 1998; Telford *et al.*, 1990) and are known for poor stability, risk of erosion and deformation.

According to Bisong *et al.,* (2023) and Rafiu *et al.,* (2020), any resistivity value as low as less than 30 Ωm is considered a weak zone, this section of the road is therefore situated on an incompetent foundation material, hence can be adjudged to be responsible for the damages on the road pavement. Adesola *et al.,* (2017) further added that low resistivity zones are consistent with geologic features such as fractures, faults, clay materials and weak/saturated zones which are inimical to the strength and stability of road pavement.

Figure 9 shows the resistivity pseudo-section for stable section 3 (SS3), with a layer of resistivity value ranging between 13.7 – 20.3 Ωm overlying a weak zone. Figure 10 on the other hand, reveals resistivity pseudo-section for stable section 4 (SS4), with layer of resistivity value ranging between 14.5 – 21.9 Ωm, overlying a weak zone. These range of resistivities 13.7 – 20.3 Ωm and 14.5 – 16.3 Ωm for the SS3 and SS4 respectively are typical of clay, silty or sandy clay which has the tendency to retain moisture due to high porosity and low permeability (Aderemi & Adeola, 2021). Though there was no visible failure observed on the pavement surface, the low resistivity of the underlying material makes the pavement vulnerable to failure in future. Results of the geophysical survey of our study are in agreement with those of Adiat *et al.* (2017); Eebo and Abiodun (2021); Nnamdi *et al.* (2019); Ademila (2017); Ademila and Olayinka (2020); Akpoyiboa *et al.,* (2025); Avwenaghegha *et al.* (2021); and Jekayinfa and Osinowo (2021), whose studies extensively proved the troublesome influence of clay or clayey underlying earth material as one of the common causes of road pavement failure having low resistivity value. Such layers are saturated and weak zones, hence cannot support vehicular loads. In particular, clays expands and contracts seasonally, resulting in several cracks and deformations on the road as a result of its low shear strength and compressibility (Adeyemi & Wahab, 2008; Akpoyiboa *et al.,*, 2025; Egwuonwu *et al.*, 2011). According to Nnamdi *et al.,* (2019), moderate, high and low resistivity soils are indicative of partially stable, very stable and failed sections of the road respectively. The overlap in the resistivity of different rocks and soils is because their resistivities are dependent on factors like porosity, clay content, degree l of saturation and the concentration of electrolytes/dissolve salts (Lowrie, 1997). Most of the resistivities were less than 100 Ωm (Figure 5, Figure 6, Figure 7, Figure 8, Figure 9 and Figure 10) while a few others were slightly above 100 Ωm (Figure 3 and Figure 4). Groundwater usually has resistivity between 10 Ωm to 100 Ωm (Reynolds, 1998; Telford *et al.,*, 1990) which were observed in Figure 5, Figure 6, Figure 7, Figure 8, Figure 9, and Figure 10. The geo-electrical resistivity method of investigation is therefore effective in mapping the subsurface.

CONCLUSION

This study successfully employed geophysical methods, specifically, the Wenner electrical resistivity tomography (ERT) to evaluate subsurface conditions and their relationship to road pavement failures in the study area. The findings reaffirm the effectiveness of ERT in investigating the underlying causes of pavement and other infrastructure failures, given its ability to differentiate subsurface materials based on their varying resistivity values. A functional road pavement requires a competent subgrade or subbase capable of supporting vehicular loads without deformation. The failed sections (FS1–FS4) were found to be underlain by materials with low electrical resistivity (<100 Ωm), indicative of clay and clayey mixtures. In particular, the weak or saturated clay layers were observed to have reached the surface in the failed segments (FS), thereby compromising structural integrity. Conversely, the stable sections (SS1 and SS2) were underlain by very hard clay, sandy clay, and sandstone materials that are considered moderately competent. The stable sections (SS) 3 and 4 were found to overlay dry clay, silty, and sandy clay layers, with some underlying weak saturated zones. Clay-rich soils are generally unsuitable as subgrade materials due to their low permeability and high moisture retention, which leads to seasonal expansion and contraction. These cyclic changes severely weaken the pavement structure over time. The tendency of clay to retain moisture and deform under repeated vehicular loads makes it an incompetent foundation material. It is therefore obvious that the primary factors contributing to the pavement failures in the study area are the presence of clay and clayey subgrade materials, poor drainage conditions, the low-lying, flood-prone nature of the area and proximity to the Benue River. Additional contributing factors may include inadequate maintenance strategies, insufficient pavement thickness, and the use of substandard construction materials. To mitigate these issues, the implementation of effective drainage systems, soil stabilization measures, and improved construction practices is essential.

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