Studia Quaternaria, vol. 37, no. 2 (2020): 101–107 DOI: 10.24425/sq.2020.133754

ELECTRICAL RESISTIVITY TOMOGRAPHY FOR GEO-ENGINEERING INVESTIGATION OF SUBSURFACE DEFECTS: A CASE STUDY OF ETIORO-AKOKO HIGHWAY, ONDO STATE, SOUTHWESTERN NIGERIA

Adedibu Sunny Akingboye*, Isaac Babatunde Osazuwa, Muraina Zaid Mohammed

Department of Earth Sciences, Adekunle Ajasin University, P.M.B. 001 Akungba-Akoko, Ondo State, Nigeria; e-mail: adedibu.akingboye@aaua.edu.ng

** corresponding author*

Abstract:
The durability of roads is dependent on the proper screening of the variations in subsurface geological characteristics and conditions through geo-engineering investigations and good construction practices. In this study, electrical resistivity tomography (ERT) technique was used to investigate the subsurface defects and potential failures along the substrate of Etioro-Akoko highway, Ondo State, southwestern Nigeria. Results of the inverse model resistivity sections generated for the two investigated traverses showed four distinct subsurface layers. The shallow clayey topsoil, weathered layer, and partially weathered/fractured bedrock have resistivity values ranging from 4–150 ohm-m, 10–325 ohm-m, and 205–800 ohm-m, with thickness values of 0–2 m, 0.5–12.5 m, and less than few meters to > 24 m, respectively. The fresh bedrock is characterised by resistivity generally in excess of 1000 ohm-m. The bedrock mirrored gently to rapidly oscillating bedrock troughs and relatively inclined deep penetrating multiple fractures: F1–F'1, F2–F'2 and F3–F'3, with floater in-between the first two fractures. These delineated subsurface characteristic features were envisaged as potential threats to the pavement of the highway. Pavement failures in the area could be attributed to the incompetent clayey sub-base/substrate materials and the imposed stresses on the low load-bearing fractured bedrock and deep weathered troughs by heavy traffics. Anticipatory construction designs that included the use of competent sub-base materials and bridges for the failed segments and fractured zones along the highway, respectively, were recommended.

Key words: electrical resistivity tomography (ERT), geo-engineering, deep weathered troughs, multiple fractures, pavement failure, highway, Etioro-Akoko

Manuscript received 25 November 2019, accepted 20 January 2020

INTRODUCTION

The use of non-invasive geophysical techniques for geo-engineering investigations provide rapid, reliable and cost effective insights into the nature of the subsurface geological strata on which civil engineering structures are founded. Electrical resistivity imaging is one of the widely used geophysical methods for geo-engineering investigations besides the conventional seismic refraction method and single point geotechnical probing. However, over the last two decades, advancement in geoelectrical imaging using electrical resistivity tomography (ERT) technique has greatly improved the confidence and quality of acquired data. The accuracy of imaged subsurface features of interest, particularly in complex terrains is also improved (Loke *et al.*, 2013; Merritt, 2014; Akingboye and Ogunyele, 2019).

In pre- and post-foundation studies, ERT provides insights into groundwater regimes (Maślakowski *et al.*, 2014), seepage zones (Abu-Zied, 1994; Osazuwa and Chii, 2009), sinkhole (Yassin *et al.*, 2014), bedrock structures (Storz *et al.*, 2000; Ganerød *et al.*, 2006; Egwuonwu *et al.*, 2011). ERT technique can provide information on continuous profilling of depth to competent bedrock/formations and thickness of overburden covers (Robineau *et al.*, 2007; Ngan-Tillard *et al.*, 2010; Fadele *et al.*, 2013; Nordiana *et al.,* 2018). The technique can delineate undulating interfaces and boundary conditions. It can also be used for resolving difficulties associated with some geophysical conditions such as mapping of discrete bodies like boulders and cavities through its improved and robust 2- and 3-dimensional (2D and 3D) inversion results (Loke *et al.*, 2013).

The impeding factors to constructing long lasting and stable foundations for roads and other civil engineering works are attributed to subsurface geologic features, such as fractured bedrock, unconsolidated/incompetent sub-grade and sub-base soils, as low-bearing capacity materials (Aigbedion, 2007; Wisén *et al.,* 2008; Osazuwa and Chii, 2010; Osinowo *et al.,* 2011; Ayolabi *et al*., 2012). These features are usually prone to subsidence or instability and thus, weaken the foundations of engineering structures. On the other hand, grains sizes and shapes, and pore spaces determine the amount of water retaining and draining capacities of soils. These factors have direct effects on overlying road pavements. The expansion and shrinkage of clayey soils, for instance, constitute a threat to foundation/pavement. In addition, the development of cracks is envisaged due to differential settlement arising from the responses of fractured boulders (floaters) and saturated weathered troughs to external forces, like vibrations from heavy traffics along roads.

Failures of highway segments are not limited to a particular terrain, but are evident in both basement and sedimentary terrains. However, the future states of roads and other civil works are dependent on detailed and adequate subsurface information, which include variations in soils properties and water contents, bedrock topography and structures. These information are highly essential to civil engineers for suitable foundation design practices to arrest both immediate and future failures.

The roads in Akoko areas of Ondo State are in devastating conditions due to severe cracks, potholes, depressions and gully created along many sections of the roads. The deteriorating conditions of these roads hinder smooth movement of vehicles, cause wearing of vehicles parts and accidents. The conditions of the roads worsen every day particularly in rainy season despite rehabilitation/palliative efforts to put them in good shape for road users. Etioro-Akoko road segments are not exempted. Hence, the states and conditions of the roads require detailed and inexpensive geophysical investigations. The study tends to understand the nature of the subsurface geological characteristics and conditions responsible for such failures aside causative factors, such as poor drainage and construction designs which are associated with road surfacing with thin asphalt coating.

In this study, we used ERT to investigate the nature of subsurface defects along the substrate of Etioro-Akoko highway. This is aimed at delineating the nature of the subsurface soil constituents, weak zones – fractures and conduits, and saturated/seepage zones which pose threats to the pavement of the highway. The information derived from this study would be useful for future rehabilitation and construction of new roads in the area and other places with similar subsurface geological conditions.

LOCATION AND GEOLOGICAL SETTING

Etioro-Akoko is located in the northern part of Ondo State, southwestern Nigeria, between latitudes 07^{o}26’ and 07^{o}27’ N and longitudes 005^{o}43’ and 005^{o}44’ E (Fig. 1a). The area is underlain by rocks of the Migmatite-Gneiss Complex of the Precambrian Southwestern Basement rocks of Nigeria (Rahaman, 1989) (Fig. 1b). The rocks in the area include granite gneiss, which is the widely spread rock and other minor intrusives, such as aplite, pegmatite and vein quartz. The basement rocks outcropped in few places across the area and have undergone at least two episodes of tectonic deformation, which have helped in the development of series of simple and complex structures in the rocks.

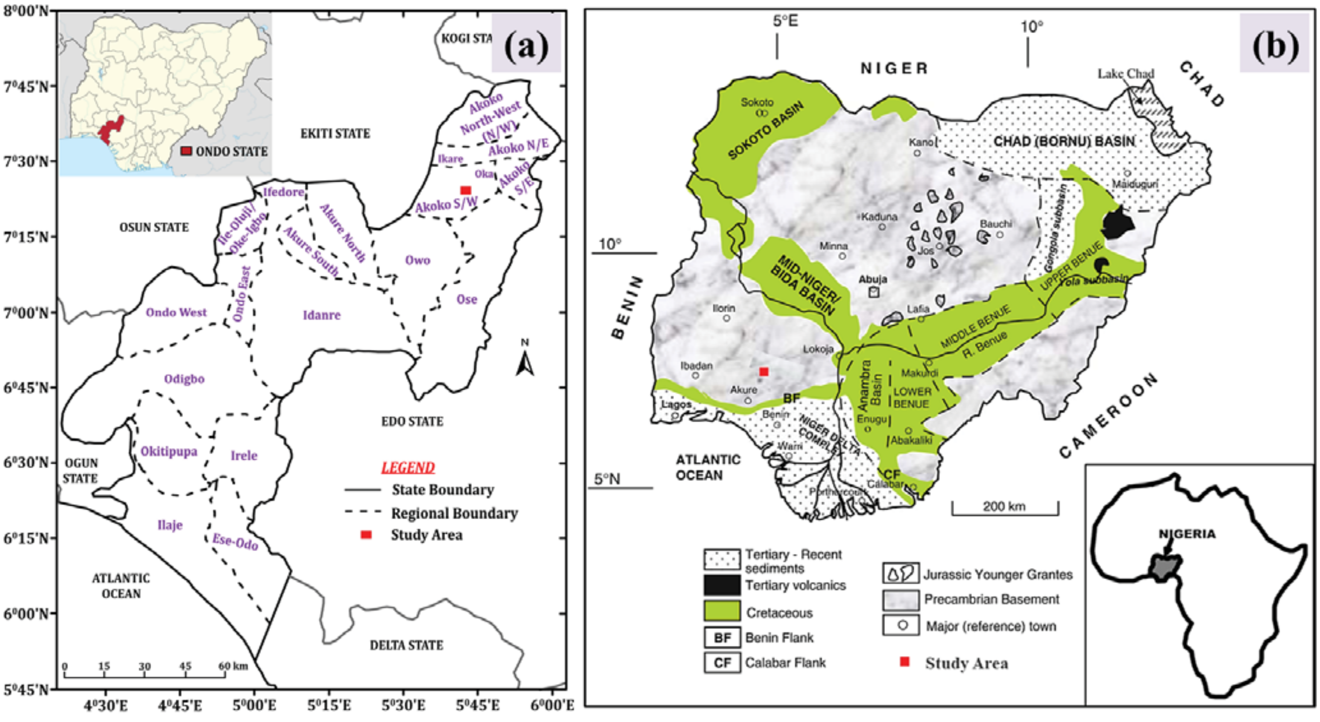

Fig. 1. (a) Location map of Ondo State showing the study area. Inset: Location map of Nigeria showing Ondo State. (b) Geological map of Nigeria showing the study area (modified after Obaje, 2009).

Fig. 2. Parts of failed sections along the highway in the study area.

The highway segment investigated is the failed segments in Etioro-Akoko community along Owo – Oba-Akoko – Akungba – Ikare-Akoko highway (Fig. 2). The highway constitutes one of the busiest major highways in Akoko areas of Ondo State. It runs through the study area and divides it into approximately two halves. Akingboye *et al.* (2019) reported in the study conducted in the study area that the depth of near surface strata to the bedrock is generally thin except for few places with localised depressions/troughs.

MATERIALS AND METHODS

The study involved a reconnaissance survey to identify both the stable and unstable sections of the highway in the study area. Geophysical traverses were established few distances away from the highway along the eastern shoulder of the identified segments of interest. The ABEM Lund Resistivity Imaging System employing the Wenner array protocol, with electrode spacing of 5 m, was used for the tomographic survey.

Measurements were acquired along two traverses (TRs 1 and 2) in the study area (Fig. 3a and b). TRs 1 and 2 were established approximately in NS direction along the shoulder of the highway to cover a total spread length of 400 m, with a spacing of 5 m between respective electrodes. A single traverse of 200 m each without a roll-along technique was employed to enhance signal-to-noise ratio and for better vertical resolution profile without smeared structures from artifacts. This practice was adopted because of the nature and complexity of the subsurface geology of the area, and reduction in amount of penetrating current due to increasing electrode distance and probing depths. Usually, the depth of road pavement rarely exceeds the first near surface strata; therefore, smaller electrode spacing is usually required for such investigation. To achieve this, cell widths of half electrode spacing in the inversion software was employed to derive half of the unit electrode spacing for the 2D resistivity models.

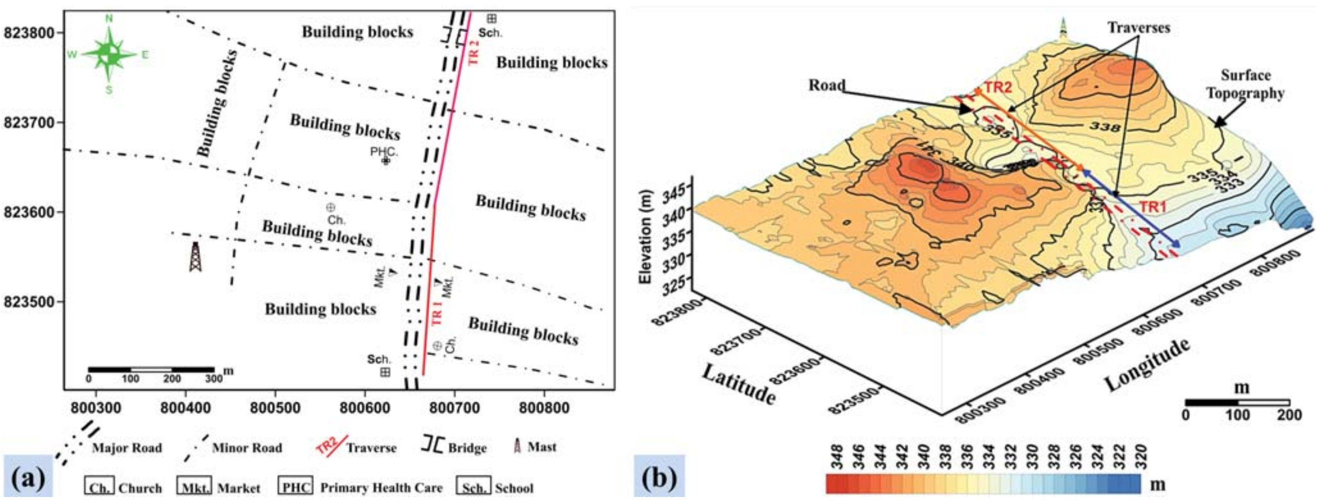

Fig. 3. (a) Data acquisition map of the study area showing the geophysical traverses (TRs 1 and 2). (b) 3D topographic map of the study area showing the surface topographic relief and the two investigated traverses (TRs 1 and 2) in NS direction at the eastern shoulder of the highway.

Data processing, inversion and interpretation of results were similar to that employed in the work of Akingboye *et al.* (2019). The converted field data sets in RES2DINVx64 software format were processed and inverted sequentially after the extermination of bad data points. The Least-square inversion modelling with modified change and inversion parameters was used to determine the subsurface apparent resistivity distribution of the sections investigated. The inversion software uses a mathematical inverse problem that determines the subsurface distribution of resistivity from measurements of apparent resistivity data sets. This inversion technique produces a subsurface inverted model that agrees mostly with the field apparent resistivity measurements based on predefined numbers of iterations for convergence. The 2D model apparent resistivity and Jacobian matrix values were calculated using a mathematical link between the model parameter and the response model for finite-element method described by Silvester and Ferrari (1996).

Cell widths of half electrode spacing were used to achieve half unit electrode spacing of 2.5 m for each cell blocks instead of the original field electrode spacing of 5 m. This technique was adopted for optimum result in order to derive detailed information about the subsurface strata at near surface depths. Finite-element method of 4 nodes and L_1-norm were also employed for more accurate calculated apparent resistivity and stable inversion models. The vertical/horizontal flatness ratio filter and damping factor were set to 0.5 and 0.1 with minimum of 0.02 (one-fifth of the initial value), respectively. These parameters were employed to stabilise the inversion process for better resolution of anomalies appearance and to increase the certainty that the identified anomalies actually exist. Inverse model convergence (RMS error) limit below 10% was chosen for a maximum of 10 iterations.

RESULTS AND DISCUSSION

Results

The subsurface inverse model resistivity section of TR 1 is shown in Fig. 4. The inverse resistivity model is characterised by four distinct subsurface layers of varying resistivity responses. The first layer is characterised by surficial clayey topsoil with resistivity generally below 150 ohm-m and depth extent of about 2 m. The topsoil is interspersed by discontinuous pockets of highly resistive material denoted as lateritic/hard-pan clay in few places. The second layer is characterised by constituents of the weathered materials typically of saturated clayey sand/sandy clay, with resistivity ranging from 10–203 ohm-m and thickness ranging from 0.5–11.5 m at stations 105 m and 15 m, respectively**.** This layer is discontinued by a third layer, which is the partially weathered/fractured bedrock, with resistivity response in the range of 205–700 ohm-m and depth greater than 25 m. The third layer peaks to the near top layer at stations 65 m, 105 m, 122–132 m and 170 m, giving the weathered layer a curve to lenticular shapes particularly from station 170 m to the end of the traverse.

Stations 47–55 m and 60–85 m witnessed two contemporaneous multiple fractures: F1–F'1 and F2–F'2, respectively. These are partially inclined deep penetrating fractures with similar trending direction. F2–F'2 is a late phase fracture, which further fractured and displaced the earlier fractured bedrock by F1–F'1 downwardly, leaving a leaning-fractured resistive bedrock within. This leaning bedrock slab was later weathered due to infiltrating soil water and seepages from beneath to form a resistive boulder as floater at depth range of 5–15 m. An arc-like structure was also formed at its base arising from the resultant effect of continuous weathering. The fresh bedrock (B), the basal unit, depicts resistivity that is generally greater than 1000 ohm-m. The fresh bedrock is characterised by axial planes dipping in the direction of the fractures around stations 45 m and 87 m, and gentle undulating surface. It is segmented into northern and southern sections by the extensive partially weathered/fractured zone.

The inverse model resistivity section of TR 2 presented as Fig. 5 shows similar features in terms of overburden and underlying bedrock characteristics to that observed in TR 1. The inverse model shows four distinct subsurface layers of varying resistivity responses. The topsoil with resistivity response pattern generally below 150 ohm-m is interspersed by discontinuous multiple pockets of resistive lateritic/hard-pan clay. This response pattern extends to depth of about 1.9

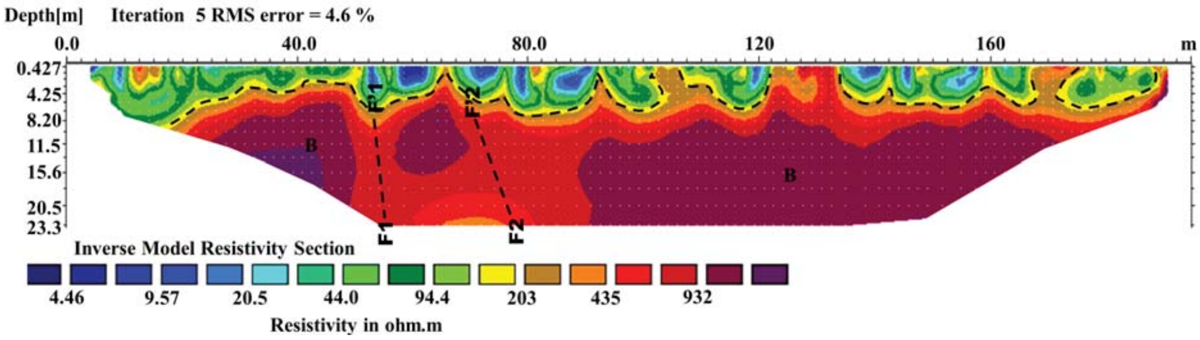

Fig. 4. 2D inverse model resistivity section of traverse 1. The subsurface geology is characterised by thin overburden which is underlain by gentle oscillating bedrock surfaces separated by an extensive partially weathered/fractured bedrock zone produced from two contemporaneous fracture systems (F1–F'1 and F2–F'2). The black broken lines with varying amplitudes mark the surface of the weathered bedrock.

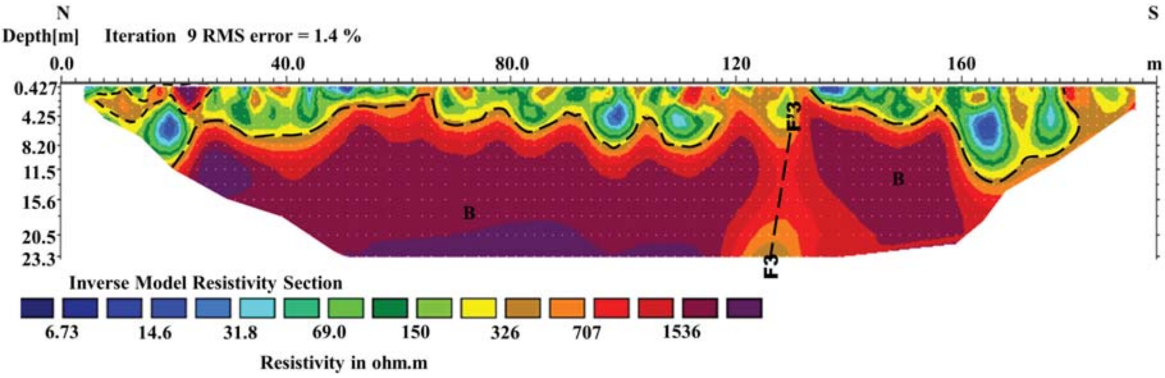

Fig. 5. 2D inverse model resistivity section of traverse 2. The deep penetrating fracture (F3 - F'3) discontinued the consistently high resistivity bedrock to produce a conductive pathway for water.

m. The second layer, weathered layer, is characterised by resistivity and thickness ranging from 10–325 ohm-m and 0.5–12.5 m, respectively. This layer consists of weathered bedrock materials typically of clay to sandy soil compositions with water saturation. The bedrock underlying the weathered layer is marked by relatively gentle to rapid oscillating partially weathered surfaces and fracture. These two features formed the third layer, which is the partially weathered/fractured bedrock with resistivity values in the range of 330–800 ohm-m. The fourth layer is the fresh bedrock (B) with resistivity generally in excess of 1000 ohm-m.

The bedrock topography along this traverse mirrored deep and elongated bedrock troughs between stations 12–23 m, 32–44 m and 156–178 m. At near surface depth, the foundation floor of the existing bridge between stations 19 m and 22 m is mapped to be resting on fairly weathered to resistive thin bedrock. Stations 70–110 m are zones with continuously oscillating and increasing bedrock depressions. Within stations 122 m and 135 m, an X-shaped structure produced by fracture (F3–F'3), is envisaged. This fracture segmented the bedrock into two: wide bedrock unit extending from station 120 m to extreme northern end, and tooth-like shape bedrock with partially weathered base at the southern section.

Discussion

The two inverse model resistivity sections (Figs. 4 and 5) show four distinct subsurface layers. The shallow clayey topsoil, uppermost layer, is characterised by resistivity generally less than 150 ohm-m and thickness value of about 2 m. The saturated clayey to sandy weathered layer (second layer) has resistivity and thickness values in the range of 10–325 ohm-m and 0.5–12.5 m, respectively. The partially weathered/fractured bedrock, third layer, depicts resistivity values ranging from 205–800 ohm-m and thickness ranging from the near surface to greater than 24 m. The fresh bedrock is characterised by resistivity generally in excess of 1000 ohm-m.

Figure 6 shows the subsurface litho-section underlying the investigated segments along the highway in the study

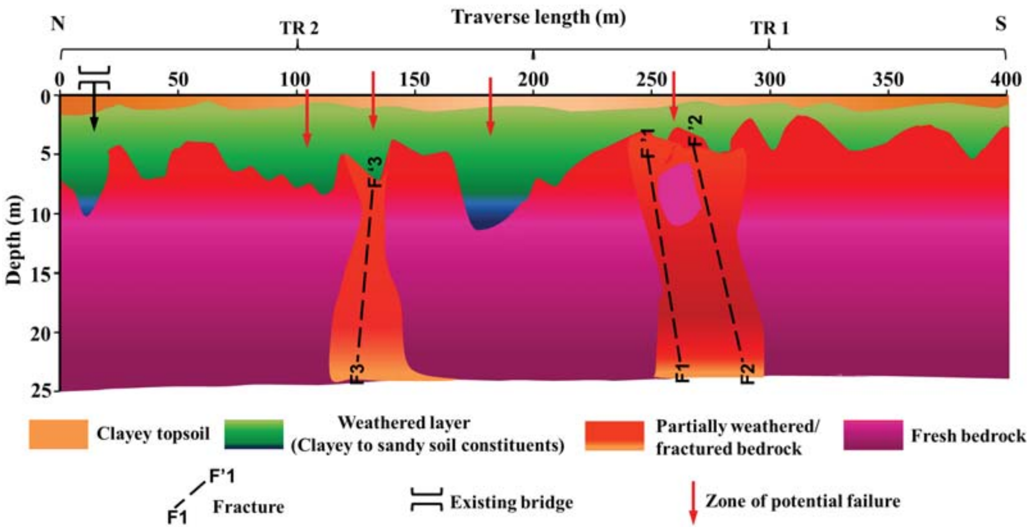

Fig. 6. Litho-section of the total traversed length along the Etioro-Akoko highway. The image shows the nature and thicknesses of the topsoil and weathered layer. The gentle to rapid undulating bedrock topography which is occasioned by deeply weathered and elongated troughs, and the fractured bedrock and zones of potential failures along the highway are also clearly imaged.

area. It shows that the overburden covers are generally less than 4 m, except for few places with deep weathered and elongated bedrock troughs extending to depth of about 15 m. The bedrock underlying the road is characterised by three deep penetrating fractures: F1–F'1, F2–F'2 and F3–F'3, trending in two major directions, and gently to rapidly oscillating topography. F1–F'1 and F2–F'2 are in opposite direction to F3–F'3 with approximately the same angle of displacements. These fracture systems compartmentalised the fresh bedrock into three segments: northern flank segment extending to station 120 m, stations 135–248 m segment, and southern flank segment extending from station 290 m. The fractured zones within the compartmentalised bedrock and deep bedrock troughs are possible conduits for groundwater/seepage zones along the investigated road segment. These major features are inimical to the substrate of the highway. The highway situation is further compounded by the clayey nature of the first two near surface strata. This nature is suggestive of a constant swelling and shrinking potentials of the sub-base/substrate materials that subsequently cracks the pavement of the road.

Along the deeply weathered and elongated bedrock troughs, possibilities of potholes are imminent. Both the constant vibrations from heavy traffics and declining bearing capacity of the floaters (boulders) and fractured bedrock may have provoked differential settlement and consequent failures of road sections in the area.

CONCLUSIONS

A non-invasive geophysical method employing the ERT technique was used for the geo-engineering investigation of the substrate of Etioro-Akoko highway, Ondo State, southwestern Nigeria. The study was aimed at delineating the subsurface geological defects posing threats to the pavement of the highway.

The results show the clayey and saturated sections within the overburden constituents, and partially weathered/fractured bedrock and fresh resistive bedrock. The zones of potential pavement failures underlying the investigated highway in the study area are envisioned mainly along the fractured and weathered bedrock troughs. These zones are the possible conduits for groundwater seeps that saturate the substrate near surface clayey strata aside the water retained from precipitation along the failed road sections.

It can therefore be concluded that the failures experienced along Etioro-Akoko highway may be attributed to the incompetent characteristics of the sub-base/substrate soil materials. Failures are also premised on differential settlement of the unstable floating boulders and the declining load-bearing capacity of the fractured bedrock caused by the stresses from heavy traffics. Therefore, anticipatory construction designs that include bridge construction via reinforcement of concrete materials to the top of stable ground across the fractured zones are proposed, while the use of competent sub-base materials along the failed segments of the highway in the area are upheld.

Acknowledgements

The authors wish to thank the anonymous reviewers for their comments that have made the manuscript more readable.

REFERENCES

Abu-Zeid, N., 1994. Investigation of channel seepage areas at the existing Kaffrein dam site (Jordan) using electrical-resistivity measurements. Journal of Applied Geophysics 32, 163–175.

Aigbedion, I., 2007. Geological and geophysical evidence for the road failures in Edo state, Nigeria. Environmental Geology, 101–103.

Akingboye, A.S., Ogunyele, A.C., 2019. Insight into seismic refraction and electrical resistivity tomography techniques in subsurface investigations. The Mining-Geology Petroleum Engineering Bulletin (MGPB) 34 (1), 93–111. https://doi.org/10.17794/rgn.2019.1.9

Akingboye, A.S., Osazuwa, I.B., Mohammed, M.Z., 2019. Electrical resistivity tomography for sustainable groundwater development in a complex geological area. Materials and Geoenvironment 66 (2), 121–128. https://doi.org/10.2478/rmzmag-2019-0004

Ayolabi, E.A., Folorunso, A.F., Jegede, O.E., 2012. An Application of 2D Electrical Resistivity Tomography in Geotechnical Investigation of Foundation Defects: A Case Study. Journal of Geology and Mining Research 3 (12), 142–151. http://doi.org/10.5897/JGMR12.002

Egwuonwu, G.N., Ibe, S.O., Osazuwa, I.B., 2011. Geophysical Assessment of Foundation Depths around a Leaning Superstructure in Zaria Area, Northwestern Nigeria using Electrical Resistivity Tomography, The Pacific Journal of Science and Technology 12 (1), 472–486.

Fadele, S.I., Jatau, B.S., Goki, N.G., 2013. Subsurface Structural Characterization of Filatan Area, Zaria-Kano Road, using the 2D Electrical Resistivity Tomography. Journal of Earth Sciences and Geotechnical Engineering 3 (1), 73–83.

Ganerød, G.V., Rønning, J.S., Dalsegg, E., Elvebakk, H., Holmøy, K., Nilsen, B. Braathen A., 2006. Comparison of geophysical methods for sub-surface mapping of faults and fracture zones in a section of the Viggja road tunnel. Norway. Bulletin of Engineering Geology and the Environment 65, 231–243. https://doi.org/10.1007/s10064-006-0041-6

Loke, M.H., Chambers, J.E., Rucker, D.F., Kuras, O., Wilkinson, P.B., 2013. Recent developments in the direct-current geoelectrical imaging method. Journal of Applied Geophysics 95, 135–156.

Maślakowski, M., Kowalczyk, S., Mieszkowski, R., Józefiak, K., 2014. Using electrical resistivity tomography (ERT) as a tool in Geotechnical investigation of the subsurface of a highway. Studia Quaternaria 31 (2), 83–89. https://doi.org/10.2478/squa-2014-0008

Merritt, A.J., 2014. 4D Geophysical Monitoring of Hydrogeology Precursors to Landslide Activation. PhD Thesis, School of Earth and Environmental, University of Leeds, UK. 276 p.

Ngan-Tillard, D., Venmans, A., Slob, E., Mulder, A., 2010. Total engineering geology approach applied to motorway construction and widening in the Netherlands: Part II: Pilot site in tidal deposits. Engineering Geology 114, 171–180. https://doi.org/10.1016/j.enggeo.2010.04.015

Nordiana, M.M., Bery, A.A., Taqiuddin, Z.M., Jinmin, M., Abir, I.A., 2018. 2-D Electrical Resistivity Tomography (ERT) Assessment of Ground Failure in Urban Area. IOP Conf. Series: Journal of Physics: Conf. Series, 995 012076. https://doi.org/10.1088/1742-6596/995/1/012076

Obaje, N.G., 2009. Geology and Mineral Resources of Nigeria. Heidelberge, Berlin: Springer-Verlag. 221 p. https://doi.org/10.1007/978-3-540-92685-6

Osazuwa, I.B., Chii, E.C., 2009. A two-dimensional electrical resistivity imaging of an earth dam, Zaria, Nigeria. Journal of Environmental Hydrology 17 (28), 1–8.

Osazuwa, I.B., Chii, E.C., 2010. Two-dimensional electrical resistivity survey around the periphery of an artificial lake in Precambrian Basement Complex of Northern Nigeria. International Journal of Physical Sciences 5 (3), 238–245.

Osinowo, O.O., Akanji, A.O., Akinmosin, A., 2011. Integrated geophysical and geotechnical investigation of the failed portion of a road in Basement Complex terrain, Southwest Nigeria. Materials and Geoenvironment 58 (2), 143–162.

Rahaman, M.A.,1989. Review of the Basement Geology of South-Western Nigeria. In: Kogbe, C.A. (Ed.), Geology of Nigeria (2nd eds.). Rockview Nige Limited, Jos. pp. 39–56.

Robineau, B., Join, J.L., Beauvais, A., Parisot, J.C., Savin, C., 2007. Geoelectrical imaging of a thick regolith developed on ultramafic rocks: groundwater influence. Australian Journal of Earth Sciences 54 (5), 773–781. http://dx.doi.org/10.1080/08120090701305277

Silvester, P.P., Ferrari, R.L., 1996. Finite elements for electrical engineers (3rd ed.). Cambridge University Press. 514 p. http://doi.org/10.1071/CBO9781139170611

Storz, H., Storz, W., Jacobs, F., 2000. Electrical resistivity tomography to investigate geological structures of the Earth's upper crust. Geophysical Prospecting 48 (3), 455–471.

Wisén, R., Christiansen, A., Dahlin, T., Auken, E., 2008. Experience from two resistivity inversion techniques applied in three cases of geotechnical site investigation. Journal of Geotechnical and Geoenvironmental Engineering 134, 1730–1742. https://doi.org/10.1061/(ASCE)1090-0241(2008)134:12(1730)

Yassin, R.R., Muhammad, R.F., Taib, S.H., Al-Kouri, O., 2014. Application of ERT and Aerial Photographs Techniques to identify the Consequences of Sinkholes Hazards in Constructing Housing Complexes Sites over Karstic Carbonate Bedrock in Perak, Peninsular Malaysia. Journal of Geography and Geology 6 (3), 55–89.