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Troubled roads: Application of surface geophysics to highway failures of the sedimentary terrain (Iruekpen-Ifon Road) of Edo State, Nigeria

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As part of effort to examine the factors responsible for highway failure in the sedimentary terrain, geophysical survey involving Very Low Frequency Electromagnetic (VLF-EM), Schlumberger Vertical Electrical Sounding (VES), and dipole-dipole electrical resistivity techniques were carried out along Iruekpen-Ifon highway. This was aimed at using surface geophysics to characterize and identify the factors responsible the for road failures along Iruekpen-Ifon highway. ABEM WADI instrument was used to obtain electromagnetic-Very Low Frequency (VLF) field data, while ABEM resistivity meter was used to obtain electrical resistivity field data. The VLF-EM data were interpreted using the VLF Graphic software, VELFAN 1.0 double plot of filtered real and filtered imaginary against distance. The VES data obtained were interpreted using IP 2 Win software. Geoelectric parameters were used to generate the Dar Zarrouk second order parameters. 2-D inversion modeling of the dipole-dipole data was carried out using ZONDRES window software. VLF-EM result suggested varying degree of conductivity in the area and the wide spread of clay/metallic ore and water in the study area. Results show that the topsoil generally varies in composition from clay to clayey and laterite with resistivity values varying from 89 to 400 Ωm and thickness between 0.2 and 4.0 m. The fractured layers composed of clay and compacted clayey sand which represents the recent alluvial deposits with resistivity values of 2 to 89 Ωm and the thickness between 1.5 and 11 m. The fresh water zone is characterized by low resistivity ranging from 0.5 to 23 Ωm, which is diagnostic of saline water saturated with clay formation, fresh water ingression, and marls. The values of co-efficient of anisotropy (λ) range from 1.03 to 2.19. The relatively higher values of *λ* (1.30 to 2.19) suggest that the subsurface rocks in these areas are likely to be more intensely fractured and more permeable. The saline water saturated with clay formation, fresh water ingression, fracture and marls clearly limit the lithological contacts and enhance high swelling potential which might be responsible for the road pavement failures in the studied area.

Key words: Highway, resistivity, troubled roads, Dar Zarrouk, anisotropy.

INTRODUCTION

A road is a thoroughfare, way, or route on land between two places, which in general has been paved or otherwise, enhanced to allow travel by some transportation. However, the presence of discontinuities such as cracks, surface deformation (rutting, etc.), disintegration (potholes, etc.), surface defects (ravelling, etc.) on a road network is regarded as road failure. Accordingly, roads are constructed with detailed information obtained from geological, geophysical and geotechnical investigations of the construction site because information obtained play important role in the design, stability, economical construction and maintenance of the roads. Such investigations are capable of delineating structures such as unconsolidated soil formations with varying resistivity and expansiveness, naturally occurring underground water channels which may expedite discontinuities. Degradation of many highway pavements is traceable to the surface water ingress through cracks and joints. These have resulted to frequent motor accidents leading to loss of lives and properties in Nigeria. However, some major Nigerian highways are known to fail shortly after construction and well before their design ages and this unfortunately has become an embarrassing stigma to the road users and nation at large. Furthermore, one of the main consequences of many rackety vehicles on the Nigerian roads is due to its failure. It has been shown that vehicles wear down faster in less developed countries of Africa like Nigeria than is obtainable in civilized economies. This is evident in secondhand vehicles that are shipped from developed economies to Africa which are in most cases here considered as new vehicles.

In particular, three main sections of the Iruekpen-Ifon highway have experienced recurrent failure after rehabilitations. In recognition of the devastating effects of these highway problems in recent years, it has become imperative to use surface geophysics to investigate these failed sections in order to identify the causes of the failures along this highway. Surface geophysics provides economic, non-destructive and rapid tools for the detection of discontinuity in road network resulting in cracks, disintegration, bulges and depressions. There are numerous case studies all over the world showing the effectiveness of geophysical methods in the detection of highway failures (Olorunfemi and Mesida, 1987; Adesida and Omosuyi, 2005; Ozegin et al., 2007; Momoh et al., 2008; Ojo et al., 1990; Soupios et al., 2007; Akintorinwa and Adeusi, 2009; Ofomola et al., 2009); and the methods have been established to play complementary roles in geotechnical studies, besides the fact that they are less expensive and non-invasive.

Road failure is an inevitable consequence of man's activities and a natural phenomenon as well. Road failure can be of these patterns, namely, (i) Alligator cracking, (ii) Rutting, (iii) Chuck holes (Potholes), (iv) Ravelling, and (v) Shear failures (Block cracking).

Alligator cracking

This is described by interconnected cracks forming a series of small polygons resembling an alligator's skin (Figure 1a). This could result from the fatigue effect of repetitive heavy truck loads or ageing in combination with exponential loss of pavement thickness. It can occur with or without surface distortion and pumping.

Rutting

A rut is a longitudinal deformation at wheel tracks mainly associated with shoving along the road (Figure 1b). This is caused by heavy loads and high tyre pressure, subgrade settlement caused by saturation, poor construction methods, or asphalt mixtures of inadequate strength.

Chuck holes (Potholes)

Potholes are irregularly shaped holes of various sizes. These most often result from wear or destruction of the wearing course, sometimes from the presence of foreign bodies in the surfacing (Figure 1c). They can also be caused by water penetrating the surface and causing the base and/or subgrade to become wet and unstable. They are small when they first appear. In the absence of maintenance, they grow and reproduce in rows.

Ravelling

This is progressive loss of pavement material. The possible cause for ravelling could be separation of bituminous film from aggregates through stripping caused by deficiency of bonding or ageing of surface due to variations in climatic and loading conditions (Figure 1d). It can also occur due to the inconsistent deformation of the lower pavement layers.

Shear failures (Block cracking)

This is block cracking leading to chipping of pavement surfacing and/or upheaval outside the tyre cracks with associated cracking. This could result from deficiency in cohesion and internal friction in pavement base structure due to ageing and fatigue (Figure 1e).

MATERIALS AND METHODS

Two geophysical methods were adopted; Very Low Frequency electromagnetic method and electrical resistivity method. ABEM

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Figure 1. (a) Alligator cracking; (b) Rutting at wheel path; (c) Potholes; (d) Ravelling; (e) Block cracking.

WADI instrument was used to obtain electromagnetic-Very Low Frequency (VLF) field data, while ABEM resistivity meter was used to obtain electrical resistivity field data. The use of electromagnetic method was preliminary survey along the three locations with traverses measuring 210, 600 and 140 m, respectively. The EM-VLF data were interpreted using the VLF Graphic software, VELFAN 1.0 double plot of filtered real and filtered imaginary against distance. For the electrical resistivity method, two techniques were used, namely, the Vertical Electrical Sounding (VES) using Schlumberger configuration with AB/2 (AB/2 = Current electrode spacing) varying from 1 to 100 m. A total of 42 VES stations were occupied, which include 10, 25 and 7 VES stations at the three studied locations, respectively. 2-D Electrical Resistivity Tomography (ERT) using dipole-dipole configuration with inter station separation (a) of 10 m, an expansion factor (n) that varied from 1 to 5 was also carried out. The VES data obtained were interpreted using IP 2 Win Software and layer parameters such as true resistivity and thickness were determined. The geoelectric parameters were used to generate the concept of Dar Zarrouk second order (Maillet, 1974) parameters (transverse unit resistance, longitudinal conductance and resistivity ρ (Ω-m) for the co-efficient of anisotropy (λ) in porous media). 2-D inversion modeling of the dipole-dipole data was carried out using ZONDRES window software. It should be emphasized that 2 D Electrical Resistivity Tomography (ERT) is a method by which 2 Dimensional images of subsurface resistivity distribution are generated. Using this method, features with electrical properties differing from those of the surrounding material may be located and characterized in terms of electrical resistivity, geometry and depth of burial.

Location and geological setting of the study area

The study area is bounded by Longitudes 5°50' and 6°39'E and Latitudes 6°55' and 7°37'N (as shown in Figure 2). The study area is underlain by the Imo Eusterine and Marine Shale which comprise grey-black shale at the basal region of the section of about 100 m, graded upward into alternation of thin beds of fissile dirty-light shale and gypsum of about 2 to 5 cm. The section passes on into light yellow-brown sandy mudstone with lateral variation in faces from

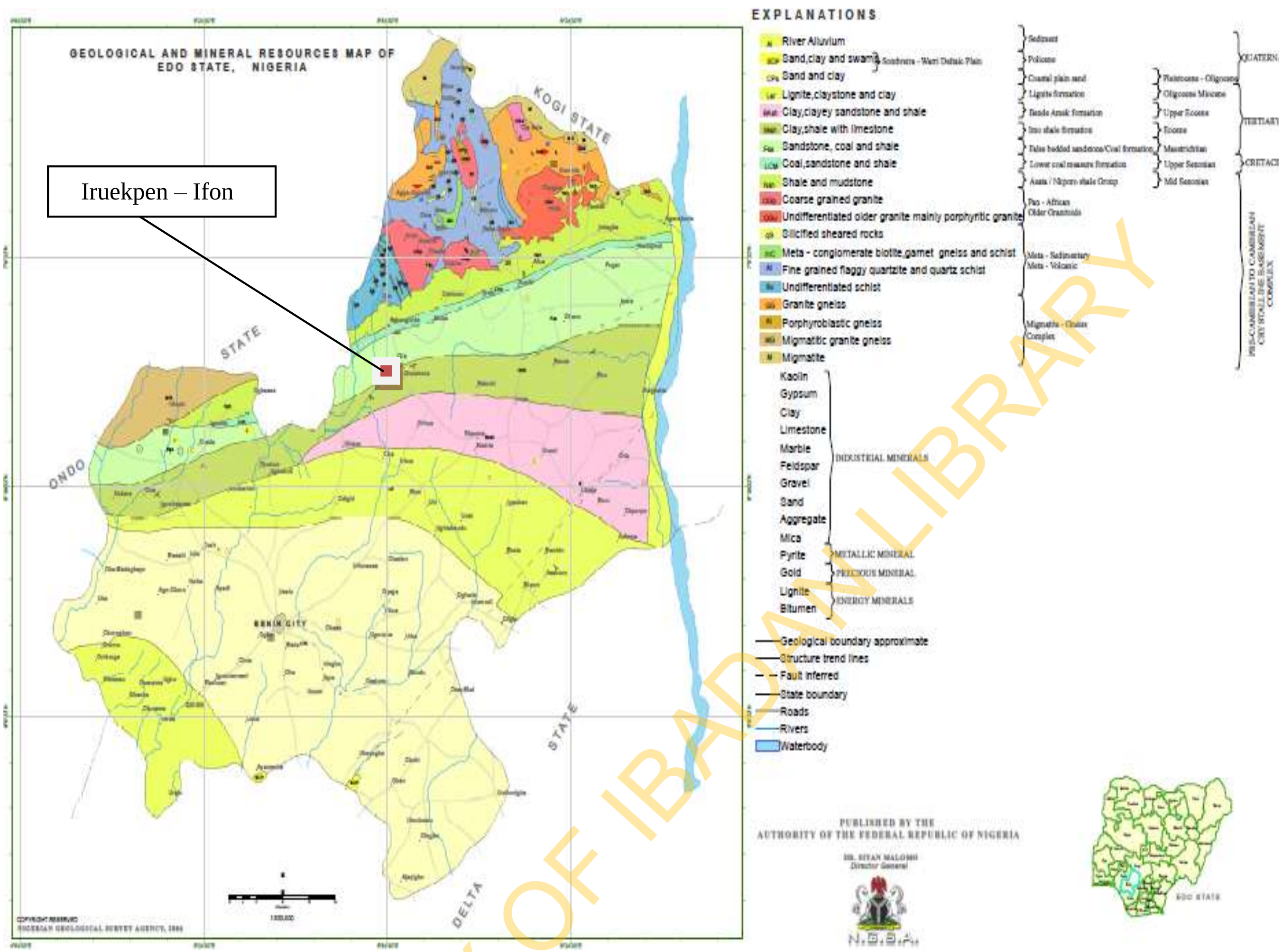

Figure 2. Geological and mineral resources map of Edo State, NGSA 2006.

sandy mudstone to clay. The shale is generally hard at Uhonmora and the section is more of shale and intercalation of gypsum and shale towards the top of the section. However, the Ozalla section of the Imo Shale does not have intercalation of gypsum bed with shale rather it comprises mudstone, clay and shale (Plate 1). The two sections of Imo Shale in the study area exhibit similar unique characteristic of ferruginous nature within the sandy mudstone unit. This unique characteristic in the study area strengthening the load carrying capacity of the lithology except for the area with faces variation from ferruginous sandy mudstone to clay. The mudstone is well laminated with imbedded clay clast (Obaje, 2009).

Sedimentation in the Lower Benue Trough commenced with the marine Albian Asu River Group, although some pyroclastics of Aptian-Early Albian ages have been sparingly reported (Ojoh, 1992). The Asu River Group in the Lower Benue Trough comprises the shales, limestones and sandstone lenses of the Abakaliki Formation in the Abakaliki area and the Mfamosing Limestone in the Calabar Flank (Petters, 1982). The marine Cenomanian–Turonian Nkalagu Formation (black shales, limestones and siltsones) and the interfingering regressive sandstones of the Agala and Agbani Formations rest on the Asu River Group. Mid-Santonian deformation in the Benue Trough displaced the major depositional axis westward which led to the formation of the Anambra Basin. Post-deformational sedimentation in the Lower Benue Trough, constitutes the Anambra Basin. Sedimentation in the Anambra Basin, thus commenced with the Campanian-Maastrichtian marine and paralic shales of the Enugu and Nkporo Formations, overlain by the coal measures of the Mamu Formation (Reijers and Nwajide, 1998). The fluviodeltaic sandstones of the Ajali and Owelli Formations lie on the Mamu Formation and constitute its lateral equivalents in most places. In the Paleocene, the marine shales of the Imo and Nsukka Formations were deposited, overlain by the tidal Nanka Sandstone of Eocene age. Down dip, towards the Niger Delta, the Akata Shale and the Agbada Formation constitute the Paleogene equivalents of the Anambra Basin.

RESULTS AND DISCUSSION

The approaches adopted for data interpretation are of two types, namely qualitative approach which involves visual inspection of Electromagnetic curves and quantitative approach which involves depth calculation of VES, dar Zarrouk parameters etc. The localities studied are variously shown in (Plate 2a to c).

The purpose of Very Low Frequency – Electromagnetic

Plate 1. Geological setting showing beddings and faults of the rock exposures.

Method (VLF – EM) is to qualitatively delineate the conductive zones and non-conductive zones in the study area. Graphic software, VELFAN 1.0 developed by Alberg Services Nigeria Limited (Geophysical Consulting Services), in MATLAB graphical user interface was used to plot the filtered imaginary and real Very Low Frequency- Electromagnetic curves. High positive values indicate presence of conductive subsurface structures while low or negative values are indicative of resistive formations, (Sharma and Baranwal, 2005).

The positive peak anomalies P1, P2, P3 and P4 on the filtered real curve, revealed vertical and/ or near vertical conductors (Figure 3a).

In Figure 3b, the filtered real curve indicates conductors with positive peaks. P1, P2, P3, P4, P5, P6, F1, F2 and F. These conductors are 80, 175, 212, 245, 380, 420, 500, 522 and 550 m from the starting station (zero mark) of the survey profile.

In Figure 3c, the positive peaks anomalies P1, P2, P3 , P4 and P5 indicated on filtered real curve, show locations of vertical and/or near vertical conductors. These anomalies are 42, 102, 143, 169 and 200 m from the starting station (zero mark) of the survey profile.

Estimating Dar Zarrouk (D-Z) parameters from (VES) results

The analysis of the D-Z parameters longitudinal unit conductance (S), transverse unit resistance (T), also, longitudinal resistivity (ρ_l) provides a very convenient and easily applicable solution to understand the geophysical behavior of saline and fresh water aquifers. (Maillet, 1947) termed the Dar Zarrouk (D-Z) parameters. The secondary parameters (longitudinal conductance (S_i), transverse resistance (T_i), longitudinal resistivity (ρ_L), transverse resistivity (ρ_t) and coefficient of anisotropy (λ)) were determined from the layers' resistivities and thicknesses using the mathematical relations (Zohdy et al., 1974):

$$S_i = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \qquad (1)$$

$$T_i = \sum_{i=1}^{n} h_i \rho_i \text{ (Ohm.m}^2\text{)} \qquad (2)$$

$$\rho_L = \sum_{i=1}^{n} \frac{h_i}{s_i} \quad (\rho_l = H/S) \qquad (3)$$

$$\rho_t = \sum_{i=1}^{n} \frac{T_i}{h_i} \quad (\rho_t = T/H) \qquad (4)$$

$$\lambda = \sqrt{\frac{\rho_t}{\rho_L}} \qquad (5)$$

The concept of Dar Zarrouk parameters were first introduced by Maillet (1974) to explain the problem of non-uniqueness in the interpretation of resistivity depth sounding curves. As resistivities of clay with sand and saline water interfere with each other, the data

Plate 2. (a) Failed Section at Locality 1; (b) Failed Section at Locality 2; (c) Failed Section at Locality 3.

interpretation becomes a difficult task. Such situation requires the formulation of better analysis technique of interpretation for the existing data to yield useful and easily understandable solution to differentiate among fresh and saline aquifers.

The geoelectric parameters were used to generate the concept of Dar Zarrouk second order parameters. The coefficient of anisotropy *(λ)* has been shown to have

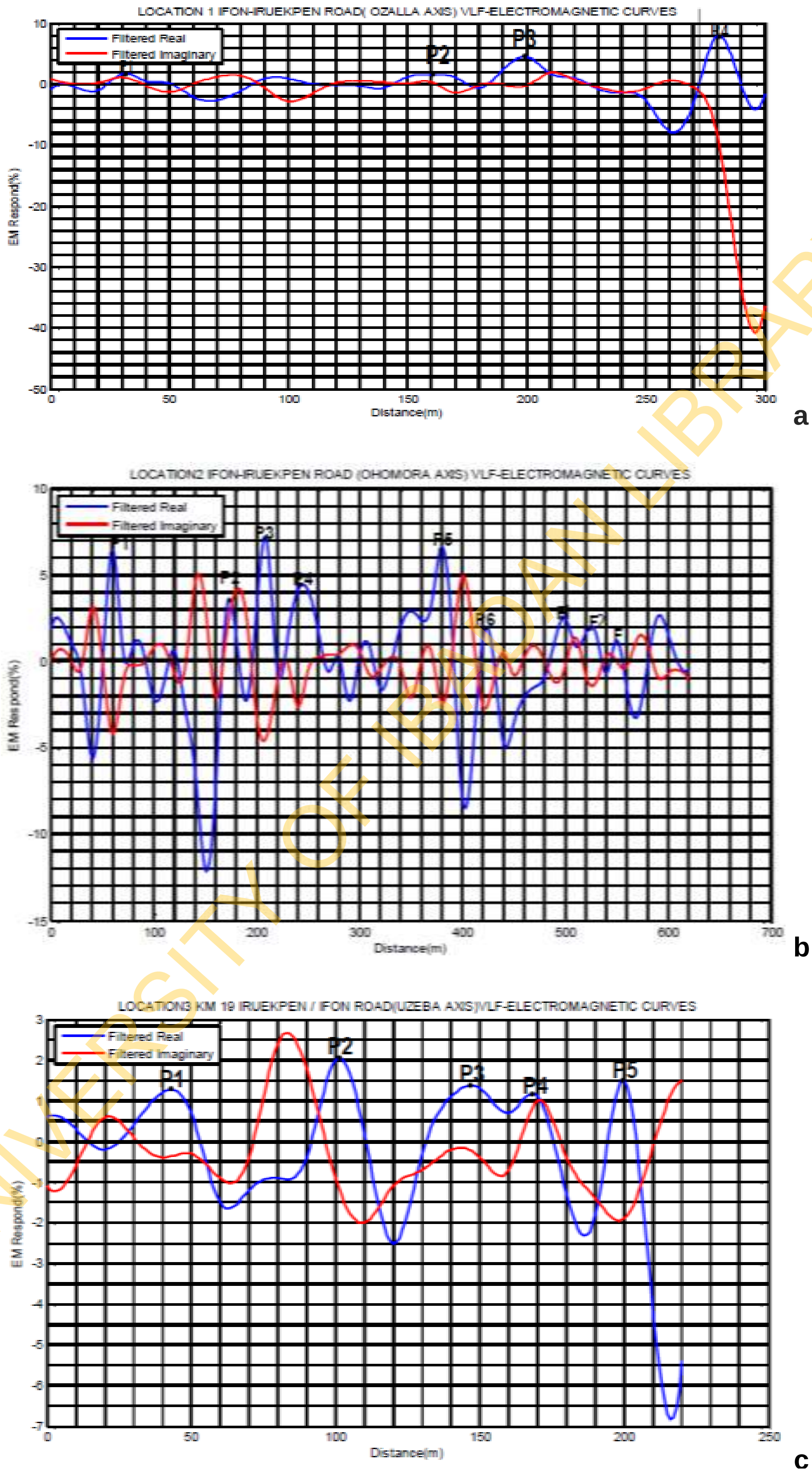

Figure 3. (a) VLF-EM Curves in locality 1; (b) VLF-EM Curves in locality 2; (c) VLF-EM Curves in locality 3.

Table 1. Dar Zarrouk parameters results.

VES No.	Total resistance (T)	Total conductance (S)	Co-efficient of anisotropy (λ)
1	115.40	0.017	1.03
2	274.73	0.063	1.20
3	87.31	0.027	1.07
4	654.08	0.144	1.05
5	114.21	0.015	1.24
6	226.13	0.068	1.13
7	102.79	0.128	1.51
8	153.28	0.019	1.38
9	376.84	0.013	1.15
10	851.87	0.007	1.29
11	284.50	0.057	1.16
12	548.80	0.019	1.36
13	583.52	0.024	1.31
14	380.82	0.036	1.31
15	289.81	0.067	1.22
16	279.80	0.070	1.21
17	190.99	0.037	1.12
18	564.75	0.013	1.61
19	181.87	0.081	1.24
20	223.41	0.061	1.14
21	191.51	0.033	1.42
22	175.93	0.033	1.42
23	158.91	0.050	1.33
24	193.62	0.022	1.22
25	230.88	0.030	1.17
26	235.05	0.066	1.28
27	200.85	0.028	1.22
28	414.04	0.023	1.28
29	380.38	0.026	1.29
30	425.75	0.022	1.16
31	245.12	0.026	1.11
32	225.23	0.118	1.12
33	454.77	0.121	1.50
34	353.53	0.047	1.37
35	273.82	0.020	1.06
36	2212.63	0.008	1.53
37	1313.04	0.015	1.43
38	533.34	0.035	1.84
39	163.94	0.070	1.24
40	196.27	0.083	1.33
41	330.10	0.022	2.19
42	150.45	0.019	1.09

the same functional form as permeability anisotropy. Thus, a higher coefficient of anisotropy *(λ)* implies higher - permeability anisotropy. The values of co-efficient of anisotropy (λ) ranges from of 1.03 to 2.19 (Table 1). The relatively higher values of *λ* (1.30 to 2.19) suggest that the subsurface rocks in these areas are likely to be more intensely fractured and more permeable. These clearly limit the lithological contacts and enhance high swelling potential.

The dipole-dipole profiling involving the combination of horizontal profiling and vertical electrical sounding was adopted as a means of mapping vertical discontinuities

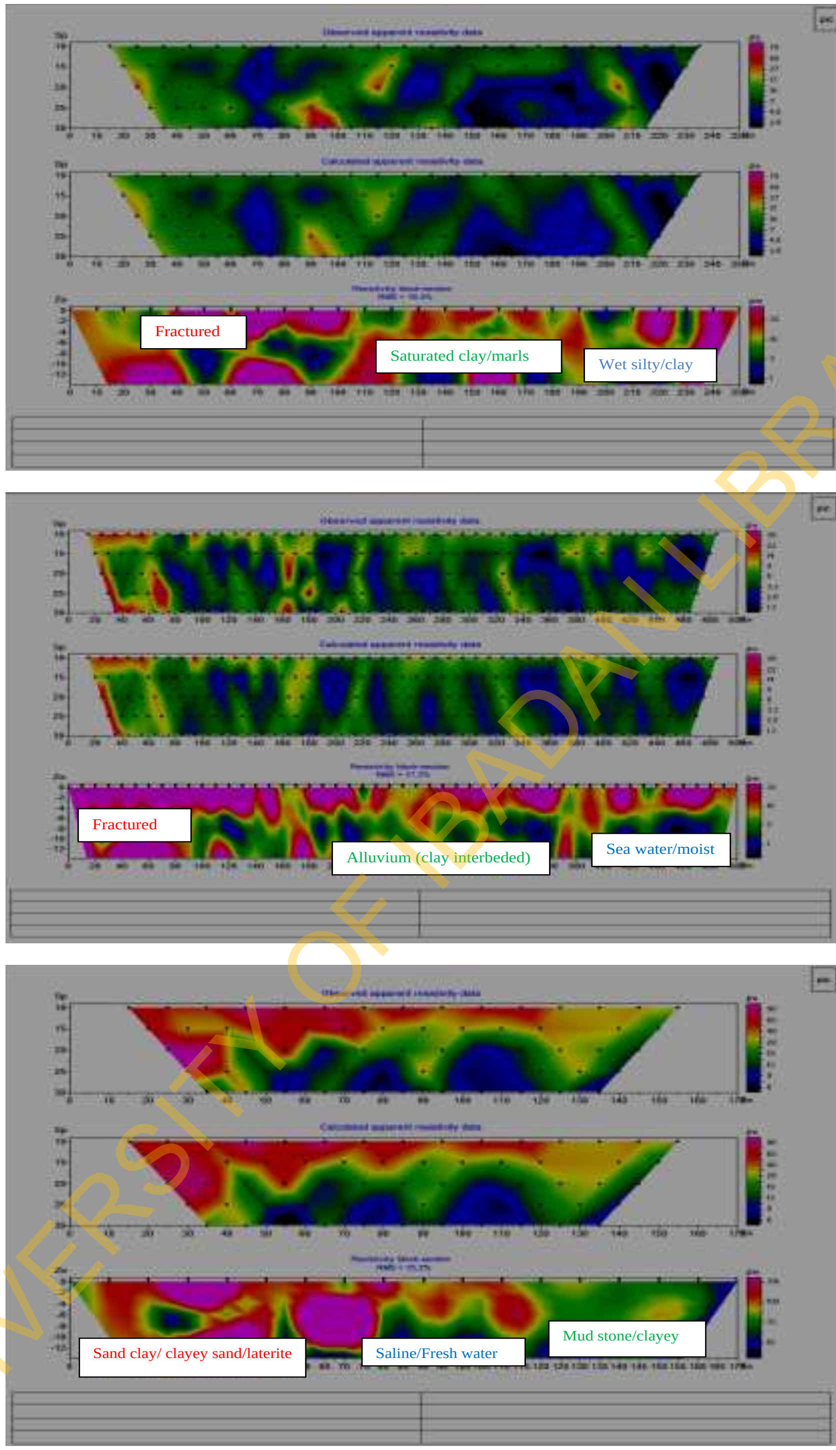

Figure 4. (a) 2-D Modelling of Dipole-Dipole Data at Locality 1; (b) 2-D Modelling of Dipole-Dipole Data at Locality 2; (c) 2-D Modelling of Dipole-Dipole Data at Locality 3.

typical of jointed, fractured and faulted zones. The dipole-dipole field data were inverted to 2-D resistivity structure using 'ZONDRES for Window' software. The dipole-dipole pseudo-sections and the 2-D resistivity structures are variously shown in Figure 4a, b and c.

The dipole-dipole pseudo-sections and the 2-D resistivity structure at locality 1 are as shown in Figure 4a. The 2-D resistivity structure shows a subsurface sequence with very thin topsoil which is virtually unrepresented on the 2-D resistivity structure, a nearly uniform weathered layer and nearly filled entire structure with wet silty/clay and saturated clay/marls. The dipole-dipole pseudo-sections (field and theoretical) and 2-D resistivity structure at locality 2 (as shown in Figure 4b), shows a fracture/weathered basement, moist clay and alluvium that are predominately observe with depth varying from 1 to 12 m. Figure 4c shows the dipole-dipole pseudo-sections and 2-D resistivity structure profile at locality 3. The 2-D resistivity structure shows a subsurface sequence that is composed of thin topsoil (unrepresented), a variably thick clayey sand/laterite layer, soils and waters (containing fresh water, clayey sand, saline and mud stone).

Conclusion

From the engineering geophysical site investigation undertaken at the study areas (locations 1, 2 and 3), it can be inferred that the possible causes of highway pavement failure in the studied highway are near-surface linear (geological) features such as lithological contact beneath the highway pavements. This feature act as zone weakness that enhances the ingression (accumulation) of water and hence leading to pavement failure portions at all the locations, which is secondary salinity. Marls and clay topsoils/sub-grade soils (with characteristic low layer resistivity less than 100 Ωm) which are encased in alluvium have the tendency of absorbing water as a result of intense fracture hence exhibit high swelling potential and collapse under imposed traffic load stress which subsequently lead to translational failure. This fracture could also be said to be non-systematic and first order. This was majorly observed in failed portion 2. Excessive cut into the conductive water absorbing clayey substratum (weathered layer) that is montmorillonite (clay that undergoes expansion and contraction by virtue of change in moisture contents) as observed at locations 1 and 3. Potential to degrade the pavement material is the presence of water (permanent or seasonal) in the road environment, may have a far more deleterious impact on the road formation than salts present in the water. This was visibly seen in location 2.

Conflict of Interests

The authors have not declared any conflict of interests.

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