Integrated geophysical and geotechnical investigation of the failed portion of a road in basement complex Terrain, Southwest Nigeria

Povezane geofizikalne in geotehnične preiskave poškodovanega dela ceste na ozemlju metamorfne podlage v Jugozahodni Nigeriji

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Abstract: Several efforts by the local authority to fix the bad portions of Ijebu-Ode–Erunwon road, southwest Nigeria have yielded no meaningful result, as the road often get deteriorated shortly after repairs. Geophysical investigation integrated with geotechnical studies were undertaken to determine causes of the consistent failure of the highway. Very Low Frequency Electromagnetic (VLF-EM) and Electrical Resistivity (ER) methods were employed to map sections of the road with anomalous electrical responses and interpreted in-terms of structures, lithology and water saturation.

VLF-EM plots identified positive peaks of filtered real amplitudes greater than 30 % which correspond to major and minor linear fractures within the basement rocks. High current density >30 and low resistivity <10 Ω m delineated rock units underlying the failed pavement to be water saturated. Liquid limit, linear shrinkage and plastic limit index results; 24.0–48.5 %, 2.1–12.9 %, 7.5–27.4 % respectively, indicate excellent to good engineering index properties. However, soaked and unsoaked CBR results; 70.3–83.9 %, and 12.9–31.6 % respectively, indicate percentage reduction in strength with wetness up to 80 %.

Original scientific paper

This study implies that integrated geophysical and geotechnical investigation offers very useful approach for characterizing near surface earth which could be helpful in site preparation prior to construction.

Izvleček: Vrsta poizkusov krajevnih oblasti, da bi popravili slabe odseke ceste Ijebu-Ode–Erunwon v jugozahodni Nigeriji ni bila uspešna, ker se je navadno stanje ceste poslabšalo kmalu nato, ko so jo popravili. Da bi ugotovili vzroke za ponavljajoče se propadanje ceste, so opravili geofizikalne raziskave v povezavi z geotehničnimi študijami. Z zelo nizkofrekvenčno elektromagnetno metodo (VLF-EM) in metodo specifične električne upornosti (ER) so preiskali odseke ceste z anomalnimi električnimi lastnostmi in jih interpretirali z ozirom na zgradbo, litologijo in nasičenost z vodo.

Na diagramih VLF – EM so ugotovili pozitivne vrhove filtriranih realnih amplitud večjih od 30 %, ki ustrezajo večjim in manjšim linearnim razpokam v kamninah podlage. Visoka gostota toka >30 in nizka specifična upornost <10 Ω m sta značilni za zemljine, nasičene z vodo, ki leže pod poškodovanim cestnim površjem. Vrednosti meje tečenja 24.0–48.5 %, meje krčenja 2.1–12.9 % in indeksa meje plastičnosti 7.5–27.4 % nakazujejo od odlične do dobre inženirske indeksne lastnosti. Toda rezultati preskusa CBR v nasičenem in nenasičenem stanju, 70.3–83.9 % in 12.9–31.6 %, kažejo, da se zmanjša nosilnost pri vlagi do 80 %. Raziskava priča o tem, kako uporabno je povezati geofizikalne in geotehnične preiskave za karakterizacijo pripovršinskih tal, kar utegne biti smotrno pri preiskavi terena pred samo gradnjo.

Keywords: electromagnetic, resistivity, geotechnical, basement complex, Ijebu-Ode

Ključne besede: elektromagnetna metoda, specifična upornost, geotehnične metode, kamnine podlage, cesta Ijebu-Ode, Nigerija

Introduction

Flexible highway aids easy and smooth vehicular movement, and has been very useful for transportation of people, goods and services from one point to another, especially in developing countries where other means of transportation such as rail, underground tube, air and water transport system have remained largely undeveloped. However, bad portions of road, many of which result from poor construction or being founded on incompetent sub-grade and sub-base materials had been found to do more harm than good. They have been responsible for many fatal accidents, wearing down of vehicles and waste of valuable time during traffic jams. The various types of road failure identified in the study area include failure of the black top surfacing, especially along wheel cracks, pitting or minor dent, shear or massive failure (pot-holes) extending through the pavement occasionally to the sub-grade. (Plate 1)

The integrity of near surface geophysical investigation methods to complement geotechnical studies in some foundation engineering problems cannot be overemphasized. This research therefore integrates Electromagnetic, Electrical Resistivity and geotechnical techniques to study the causes of consistent failure of Luba–Erunwon axis of Ijebu-Ode–Erunwon road. It involves lateral and vertical probe of the failed, fairly stable, fairly failed and stable portion of the road in order to characterize the near surface geologic materials that constitute the sub-grade, sub-base and the foundation upon which the pavement was founded.

The study area is situated within the southwestern part of Nigeria, it lies between longitudes $6^{0}49'$ N and 6°52’ N, latitude $3^{0}56'$ E and $3^{0}58'$ E and the studied portion of the pavement is about 2

Plate 1. Failed section of Luba–Erunwon axis of Ijebu-Ode–Erunwon road

km in length. The road was initially constructed in 1983 and have since suffered major failures, especially in the northeastern end, towards Erunwon axis of the road. The road has been repaired severally, the repairs usually include minor repair of the road element and resurfacing. However the northeastern part of the road always starts to deteriorate barely six months after reconstruction.

Geological setting

Ijebu-Ode and environ lies within the transitional zone between the Precambrian Basement Complex rocks of the southwestern Nigeria and the Cretaceous sediments of Abeokuta Group in eastern part of Dahomey Basin. The basement rocks occur predominantly in the north, northwest and northeastern parts of the field and it is predominantly a Migmatite Gneiss Complex of biotite granite gneiss, biotite-hornblende gneiss with varying degrees of fracturing (Olayinka and Osinowo, 2009). The southern part of the field is overlain by Ise Member of Abeokuta group that unconformably overlies the basement rocks. Litho-stratigraphically, Abeokuta Group comprise of

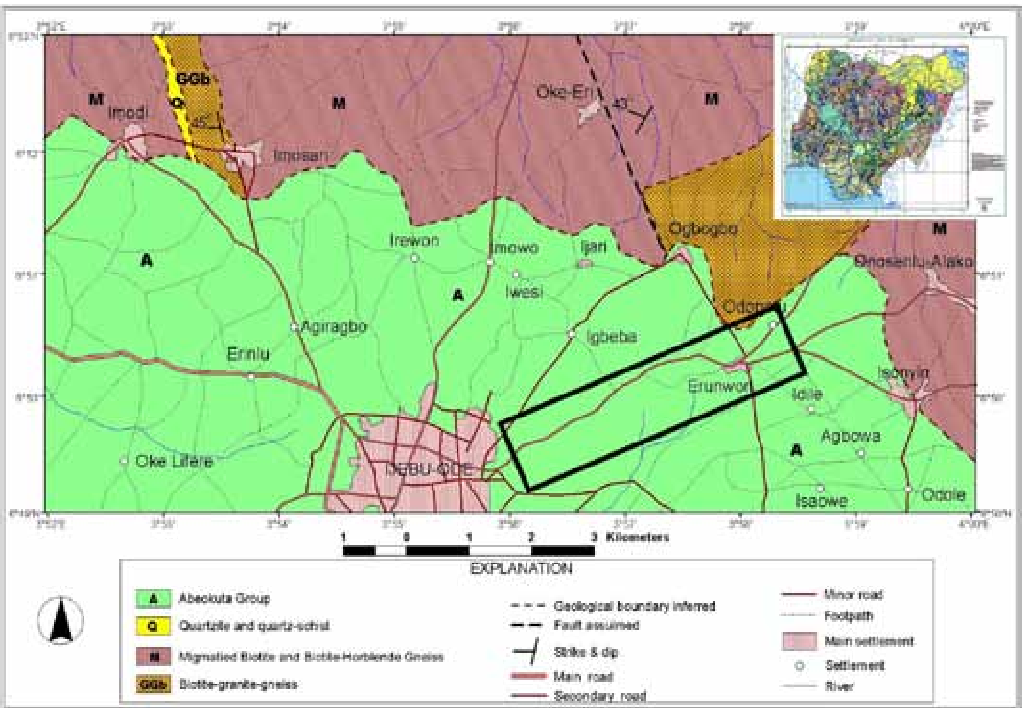


Figure 1. Geological map of Ijebu-Ode and its environ with geological map of Nigeria inserted

grits, arkosic sandstones, siltstones and clay with occasional conglomerate of predominantly arenaceous materials (Omatsola and Adegoke, 1981). Figure 1 shows the geology of Ijebu-Ode and its environ.

Materials and methods

Electromagnetic method is one of the geophysical methods commonly used in foundation investigation and environmental studies (Olorunfemi & Mesida, 1987; Sharma, 1997). The principle is based on induction of a secondary magnetic field H_s in the subsurface conductor of conductivity σ due to effect of an artificially generated primary field H_P. Electromagnetic measurements are usually presented as the mutual impedance ratio Z/Z_0 or relative charge in the impedance over a conductor which has ability to provide clear information about the subsurface conductivity and structure.

$$Z/Z_0 - 1 = \frac{H_s^z(\omega, \sigma, h, s)}{H_p^z(s)}$$

ABEM WADI was used for VLF-EM measurements, it uses military transmitters as the source of primary electromagnetic waves H_P which is located several kilometers away at the high powered military communication transmission stations. The transmitter's antenna transmits signals continuously at low radio frequency range of 15–30 kHz. The signals generated can travel long distance and able to penetrate the subsurface to induce eddy current in buried conductors. The technique measures the components of Very Low Frequency EM field which are related to the geoelectric structure of the subsurface. (Chouteau et al, 1996). Five VLF-EM profile stations were occupied with the profile length ranging from 250 m to 850 m. Readings were taking at station interval of 3 m and 6 m. Measurements such as raw real, raw imaginary, station's latitude and longitude and the signal strength were recorded against station interval.

Electrical resistivity investigation of the subsurface involved determination of the distribution of ground resistivity based on its response to the flow of electric current injected during surface measurement. True ground resistivity of the subsurface can be estimated and can further be employed to interpret the subsurface qualitatively and quantitatively ((Loke, 2001). Georesistivity survey involved measurement of potential difference generated by the current electrodes adapted to Wenner and Schlumberger electrode configurations.

$$\rho_a = \Delta V/I \cdot K$$

K is the geometric factor.

Two measurement methods were adopted; 1-D Vertical Electrical Sounding (VES) and 2-D resistivity measurement using Electrical Resistivity Traversing (ERT) technique. The 1D VES measurements aimed at determining the variation in the geoelectric parameters with depth at the probed stations while 2D method mapped resistivity continuity useful to delineate structurally weak zones that could be responsible for continuous failure of the road. Geopulse Tigre resistivity meter was used to measure ground resistance. Current electrodes for 1D measurement were spread from AB/2 of 1 m to 133 m for VES measurement. Two dimensional measurements was made by increasing the electrode spacing along the levels. Ten levels along profiles were covered with electrode spacing range from 3 m to 30 m at incremental step of 3 across 100 m long profile.

Geotechnical studies to determine some engineering index properties of sub-grade and sub-base materials employed to corroborate the geophysical measurements involved collection of twelve disturbed bulk samples from four pits each drilled to depth of 1 m and at sampling depths of 0–0.3 m, 0.3–0.6 m and 0.6–1.0 m from each pit. Sample recovering pits were constructed at the failed, fairly stable, fairly failed and stable parts of the road at 80 m, 247 m, 300 m and 470 m on the road. Mechanical sieving helped determined particle size distribution of gravel and sand proportions of dried coarse fraction. Consistency Limit Tests generally known as the Atterberg limits gave the plasticity characteristics of the cohesive fraction of the sieved samples. The consistency limit test includes; liquid limit, plastic limit and linear shrinkage test. The difference between the liquid and plastic limits gave the plasticity index, which is the range of moisture contents over which the soil remains plastic.

California Bearing Ratio (CBR) test, widely used to characterize and select sub-grade materials for use in road construction was carried out. The test was devised by the California Highway Association and it is simply the ratio of the load that cause a penetration of 2.5 mm or 5.0 mm material to a standard load that causes similar penetration on a standard California sample, notably 13.24 kN and 19.96 kN respectively.

$$CBR = \frac{\text{Load that caused a penetration of 2.5/5.0 mm} \times 100\ \%}{13.24/19.96\ (\text{kN})}$$

Both soaked and unsoaked CBR tests were carried out and swelling of samples was carefully monitored during the 96 h of soaking period to assess the likely effect of water ingress on the swelling of base material. The samples were compacted at the modified AASHTO level as described under procedure for compaction test in a standard *CBR* mold.

Data processing

The obtained raw real (in-phase) and raw imaginary (quadrature) components contain valuable diagnostic information of the subsurface but in a complex pattern that cannot directly and easily be related to the causative body. They contain noise, the raw real/imaginary data are also often wrongly located on the source along the profile. To correct the above effects and obtain profiles or pseudo-section/images that are easy to interpret, two different data processing techniques were applied. Fraser (1969) and Karous & Hjelt (1977, 1983) filtering operators. Fraser filter is a linear high-frequency band-pass filter that yields semi-quantitative interpretation of data. It transforms the in-phase components into contourable data with noise reduced to the best possible minimum. VLFPROS MATLAB code for processing VLF-EM data developed by Sundararajan et al. (2006) was employed to carry out both the Fraser and the Karous and Hjelt filtering operations.

Electrical resistivity data processing involved cleaning the data to remove spurious readings. Resultant VES data were plotted on bi-log paper and partial curve matched using standard two layer curves and auxiliary curves; Cagniard graph (Koefoed, 1979), to obtain some geoelectrical parameters such as layer depth/thickness and layer resistivity values (Orellana & Mooney, 1966). The obtained geoelectrical parameters from partial curve matching were used as initial model parameters to interpret the geoelectrical sounding curves using inversion model software RESIST (Vander Velpen, 1988) and WinGLink. The inversion algorithm involves the calculation of curves for observed data by convolving the resistivity transform with appropriate filter coefficient, (Ghosh, 1971 and O'Neill, 1975). The inversion algorithm filters spurious data, enhance signal as well as correct depth matched for obtained geoelectric layers.

Data Quality Check (QC) was carried out on the obtained ERT data for spurious data. The resultant data were inverted using the DIPRO inversion software based on the inversion principle presented by Yi & Kim, (1988). The software is a $2\frac{1}{2}$ dimensional inversion subroutine designed based on the Least Square inversion algorithm and uses two different modeling and smoothening approaches. The FDM Inversion performs smoothness constrained least square inversions based on the finite difference modeling assuming flat topography, while the FEM performs smoothness constrained least square inversion based on finite element modeling. The software automatically determines a two dimensional resistivity model of the subsurface for the obtained data. A forward modeling subroutine is applied to calculate theoretical apparent resistivity values and a non-linear least squares optimisation techniques was used for the inversion subroutine, (DEGROOT-HEDLIN & CONSTABLE, 1990 and SASAKI, 1989).

RESULTS

PALACKY et al. (1981), DE ROOY et al. (1986), HAZELL et al. (1988) and other authors have shown the relevance of EM method to be in overburden thickness estimation and basement fracture delineation. Figures 2 (a–f) present the VLF-EM plot of raw real and filtered real components against the profile distance in meters. Two basic anomaly types were identified using characteristic feature curves of coincident inflections on real component anomaly curves as well as the amplitude of the filtered real anomaly. The sign 'F' indicates point with positive peak filtered real anomaly with amplitude ranging between 30–60 %. It characterizes regions or points along the profile with major linear displacement at depth <5 m which may represent a fractured or sheared zone. The sign 'f' indicates positive filtered real anomaly of amplitude <30 % and characterizes zones or points with loose materials at depth <5 m.

Five major linear features F_1–F_5 were delineated at 87 m, 178 m, 298 m, 657 m and 810 m of the profile. Features F_1, F_2 and F_5 were identified at the failed portion while features F_4 and F_3 were found at the fairly failed part of the road respectively. This shows that 60 % of the identified major features underlie the intensely failed portion while 40 % underlies fairly failed portion. Also, features f_1–f_8 were detected around locations 203 m, 330 m, 410 m, 482 m, 553 m, 578 m, 848 m, 1040 m of the profile length.

Figure 3 is the current density plot along profile 1 which traversed the failed, fairly stable and stable portions of the road from NE-SW. The profile indicates relatively high conductive zone as evident by high current density (up to 30) close to the surface in the north-eastern end and central part of the profile. These zones coincide with the failed portion of the road, it also coincides with the highly fractured part. The high conductivity is likely due to high water filled fractures in the basement rock. Similarly, low resistivity section at the north-eastern end of the road (high conductivity) was identified on the 2-D inverted section obtained from the ERT profile (Figure 4) and resistivity section (Figure 5) constructed from VES data around the study area. The stable portion has a relatively thick and dry sandy unit upon which the pavement rests directly. Vertical Electrical Soundings (VES) identified three to four layered earth interpreted as top soil, loose saturated clayey sand unit and highly saturated fractured basement at the failed section of the road. Figure

6 (a and b) present the representative curves and interpreted log of VES data around the stable and failed portion of the road.

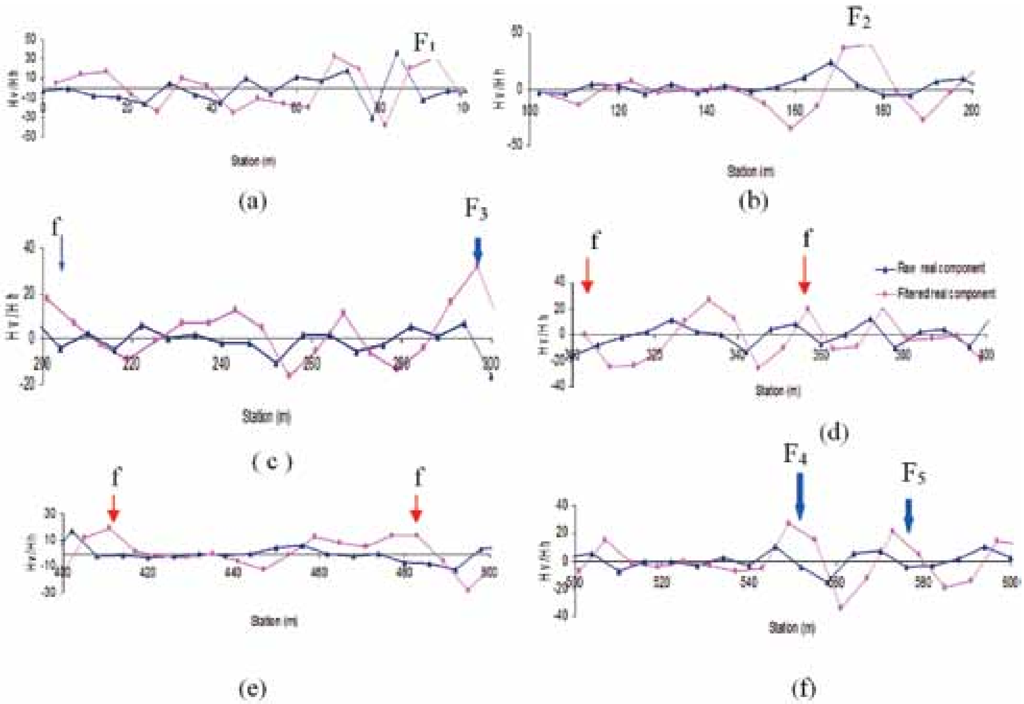


Figure 2. VLF – EM Curve of Raw real and Filtered real Components.

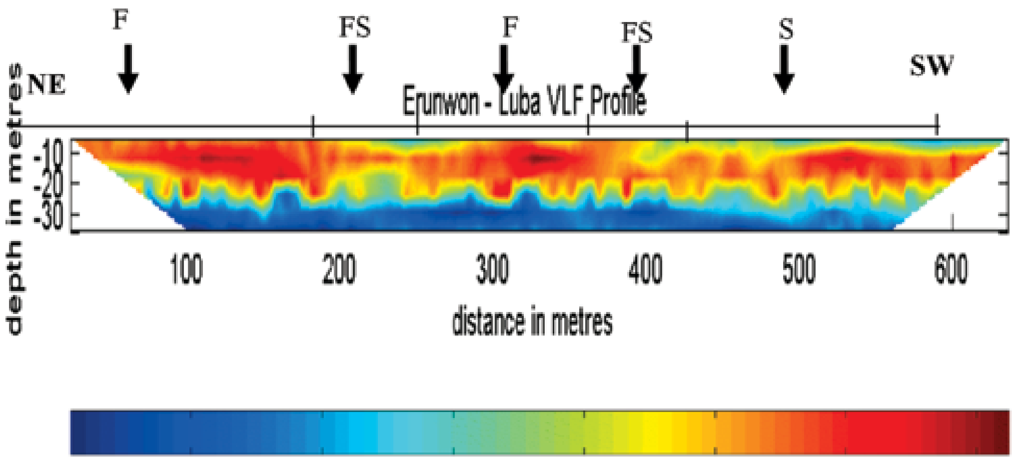


Figure 3. Current density plot along VLF – EM Profile 1 (F = Failed, S = Stable, FS = Fairly Stable)

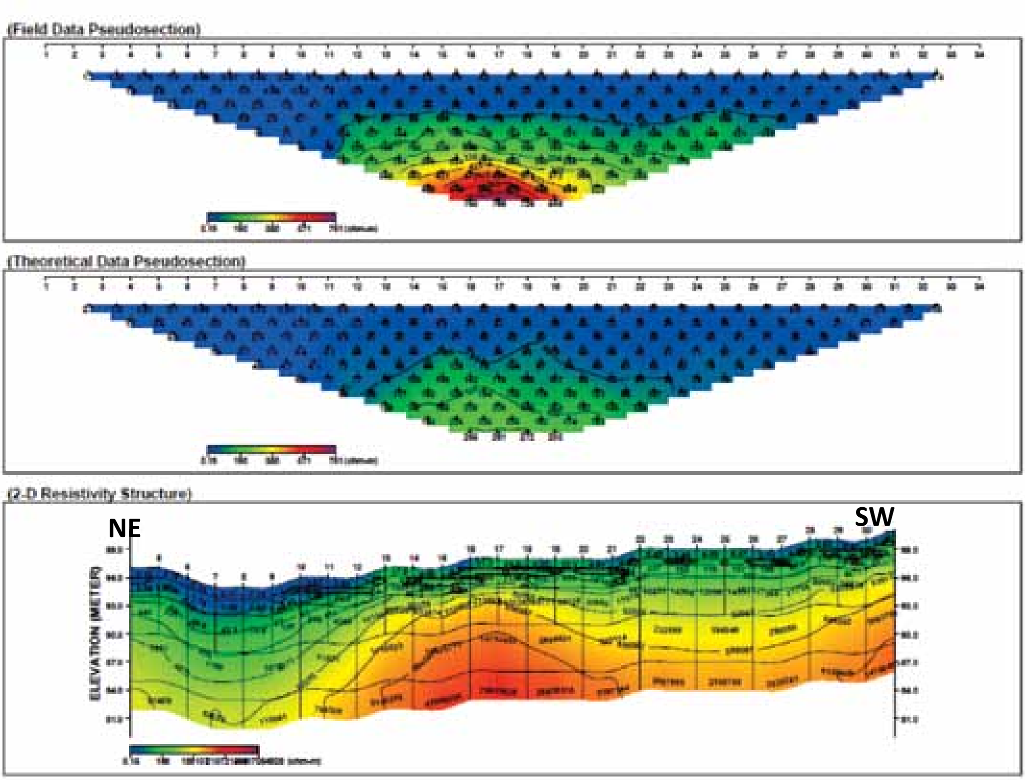


Figure 4. Field data pseudo section, theoretical pseudo section and ERT sections along Ijebu-Ode–Erunwon road.

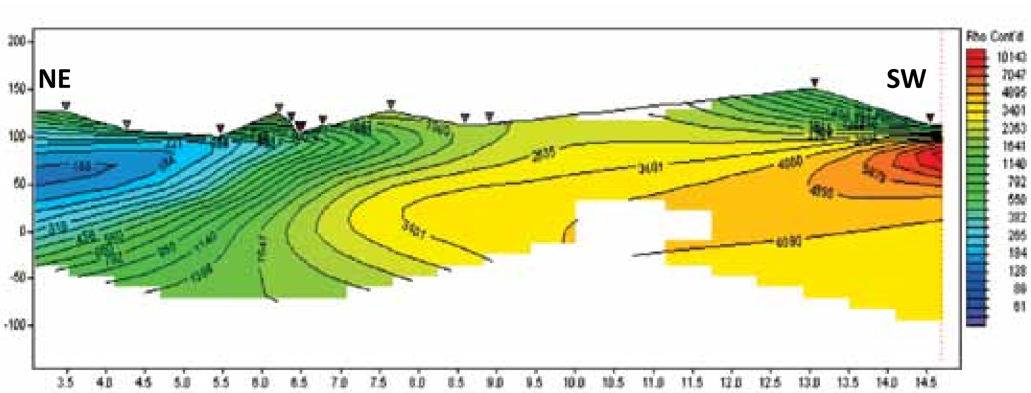
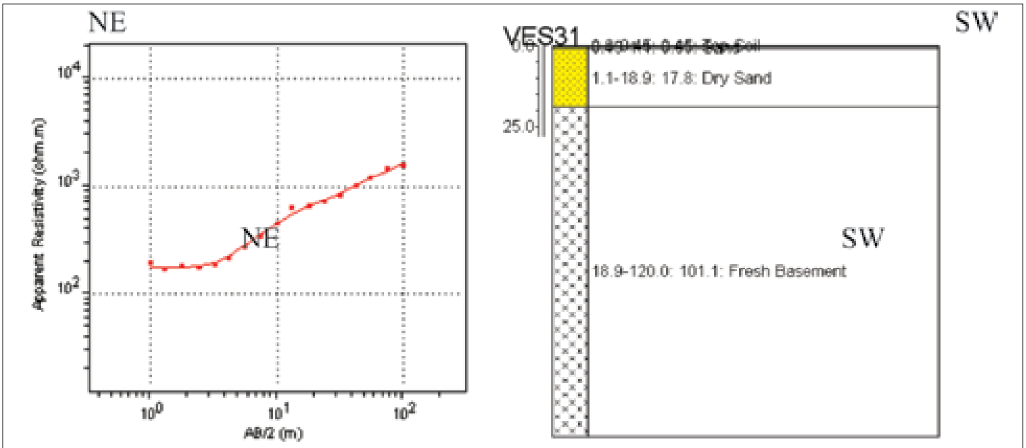
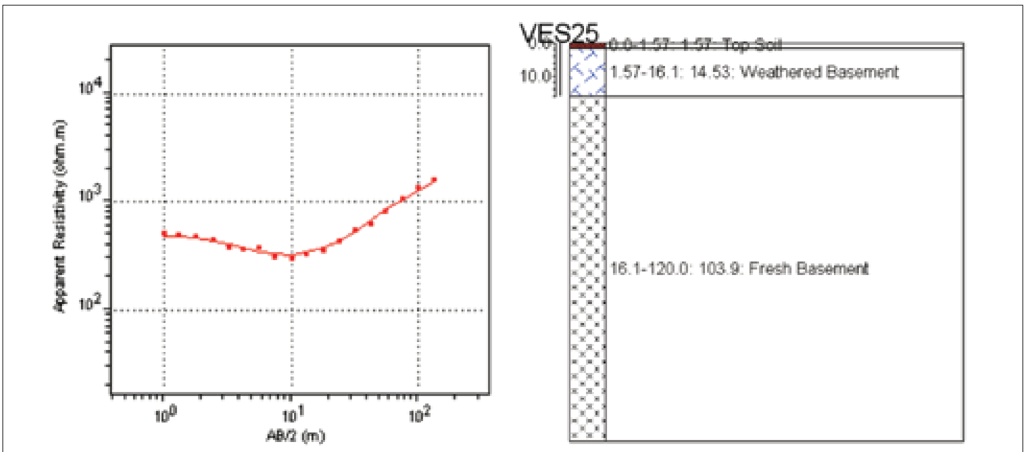


Figure 5. Inverted Electrical Resistivity section from VES data around the study area.



VES 31				
Layers	1	2	3	4
Resistivity (Ω m)	311	77.1	808	2813
Depth (m)	0.45	1.1	18.9	-
Interpretation	Top soil	Sandy clay	Unsaturated sand	Fresh basement rock

Figure 6a. Representative VES curve and interpreted log around stable part of the Ijebu-Ode–Erunwon road



VES 25					
Layers	1	2	3	4	5
Resistivity (Ω m)	516	283	4144		
Depth (m)	1.57	16.1	-		
Interpretation	Top soil	Fractured basement rock	Fresh basement rock		

Figure 6b. Representative VES curve and interpreted log around failed part of the Ijebu-Ode–Erunwon road

Results of Geotechnical analysis

Geotechnical investigation of the highway is aimed at ascertaining geotechnical bases for the road failure. Table 1 presents a description of the recovered samples.

Grain size distribution

Table 2 presents the summary of the grain size distribution. Samples 2C, 3B, 3C, 4B and 4C have higher fines constituent than other samples. The percentage of fines ranges from 22–26 %, 23–45 %, 21–37 % and 24–46 % for samples from failed, fairly stable, fairly failed and stable parts of the road respectively. The result indicates that the soil units below the stable parts of the road exhibit better engineering properties than those of the failed, fairly failed and fairly stable portions.

Table 1. Soil profiles in the study area

Depth Range (m)	Road condition	Pit No	Sample code	Colour	Name
0-03	Failed	1	1A	Brown	Clayey sand
0.3-0.6		1	1B	Brown	Clayey sand
0.6-1.0		1	1C	Very brown	Clayey sand
0.0-3	Fairly stable	2	2A	Brown	Clayey sand
0.3-0.6		2	2B	Brown	Sandy clay
0.6-1		2	2C	Reddish brown	Sandy clay
0-0.3	Fairly failed	3	3A	Brown	Sandy clay
0.3-0.6		3	3B	Reddish brown	Silty clay
0.6-1		3	3C	Reddish brown	Silty clay
0-0.3	Stable	4	4B	Reddish brown	Silty clay
0.3-0.6		4	4B	Reddish brown	Silty clay
0.6-1		4	4C	Reddish brown	Silty clay

Table 2. Grain size distribution of the studied soil samples

Sample	Depth (m)	Medium Gravel/%	Fine Gravel %	Coarse Sand/%	Medium Sand/%	Fine Sand %	Fines (Clay and Silt)/%
1A	0–0.3	7.0	7.0	19.0	27.0	14.0	26.0
1B	0.3–0.6	2.0	4.0	20.0	37.0	14.0	23.0
1C	0.6–1.0	1.0	1.5	17.5	38.0	20.0	22.0
2A	0–0.3	0.1	0.1	16.9	42.0	17.0	23.9
2B	0.3–0.6	0.1	0.1	20.8	45.0	13.0	21.0
2C	0.6–1.0	0	0	12.5	40.0	10.5	37.0
3A	0–0.3	3.0	2.0	19.5	39.5	13.0	23.0
3B	0.3–0.6	0.1	1.9	16.0	33.5	10.5	37.0
3C	0.6–1.0	0	0.1	15.9	30.5	8.5	45.0
4A	0–0.3	2.0	1.5	17.5	41.5	13.5	24.0
4B	0.3–0.6	0	0	21.0	27.0	14.5	37.5
4C	0.6–1.0	0	0	15.0	29.5	9.5	46.0

Table 3. Atterberg Limit result of the clay fraction of the recovered samples

Sample	Depth (m)	Road Condition	Liquid Limit (%)	Plastic limit (%)	Plasticity Index	Linear Shrinkage
1A	0–0.3	Failed	27.0	15.6	11.4	6.4
1B	0.3–0.6		26.8	15.0	11.3	7.8
1C	0.6–1.0		24.0	14.7	9.3	6.4
2A	0–0.3	Fairly Stable	24.0	16.1	7.9	2.1
2B	0.3–0.6		26.0	18.5	7.5	5.7
2C	0.6–1.0		50.0	29.4	20.6	12.9
3A	0–0.3	Fairly Failed	24.0	13.7	10.3	2.1
3B	0.3–0.6		48.5	21.1	27.4	9.3
3C	0.6–1.0		56.0	26.2	29.8	12.1
4A	0–0.3	Stable	26.0	13.1	12.9	2.1
4B	0.3–0.6		36.0	17.7	18.3	8.6
4C	0.6–1.0		51.0	25.3	25.7	10.4

According to the American Association of State Highway and Transportation Official (AASHTO) classification system, samples from failed portions, samples 1A,1B and 1C fell into A-2-6, A-2-6 and A-2-4 groups which are excellent to good materials for sub-grade soil in rating, while samples 3A, 3B and 3C of the fairly failed portions fell into A-2-4, A-7-6, and A-7-6 groups which corresponds to excellent to good and fair to poor soils respectively for sub-grade material. Also, samples 4A, 4B and 4C of the stable portion of the road fell into A-2-6, A-6 and A-4 groups which corresponds to excellent to good and fair to poor soils respectively. Samples 2A, 2B and 2C fell into A-2-4, A-2-4 and A-7-6 groups and also correspond to excellent to good and fair to good soils respectively for sub-grade materials.

Table 3 presents the plastic limit test results, the range and mean values range from 14.7–15.6 % and 15.1 %; 13.7–26.2 % and 20.3 %; 16.1–29.4 % and 21.3 % and 13.1–25.3 % and 18.7 % at the failed, fairly failed, fairly stable and stable portions respectively. The respective plasticity indexes which is the difference between the liquid limits and plastic limits range and mean of 9.3–11.4 % and 10.7 % respectively for failed portion, 10.3–29.8 % and 22.5 % respectively for fairly failed portion, 7.5–20.6 % and 12.0 % respectively for fairly stable portion and 12.9–25.7 % and 19.0 % respectively for stable portion.

Linear Shrinkage

The linear shrinkage at the failed, fairly failed, fairly stable and stable portions have range and mean of 6.4–7.8 % and 6.9 %; 2.1–12.1 % and

7.8 %; 2.1–12.9 % and 6.9 %, and 2.1–10.7 % and 7.1 % respectively. MADEDOR (1983) and ADEYEMI (1992) gave the maximum value of 8 % as linear Shrinkage for highway sub-base materials and maximum of 10 % was specified for sub-grade materials. It can therefore be concluded that at the failed portions the liquid limits, plasticity index and linear shrinkage for samples 1A, 1B and 1C satisfied all the required standards for highway sub-base and while at the fairly failed portion sample 3A satisfied all the require standards for sub-base materials, but samples 3B and BC failed the requirements for sub-grade material. At the stable portions, samples 4A and 4B satisfied the required standard by FMWH (2000) for sub-base and sub-grade soils respectively while samples 4C has slightly higher liquid and plasticity index. At the fairly stable portion, samples 2A and 2B also satisfied the requirements for sub-base and sub-grade materials for highways but samples 2C has slightly higher liquid and linear shrinkage values.

From the Casagrande chart (Figure 7), the classification of the soil samples 1A, 1B, 1C, 3A, 2A, 2B and 4A plotted within the region of low plasticity while samples 2C, 3B, and 4B, 4C plotted within

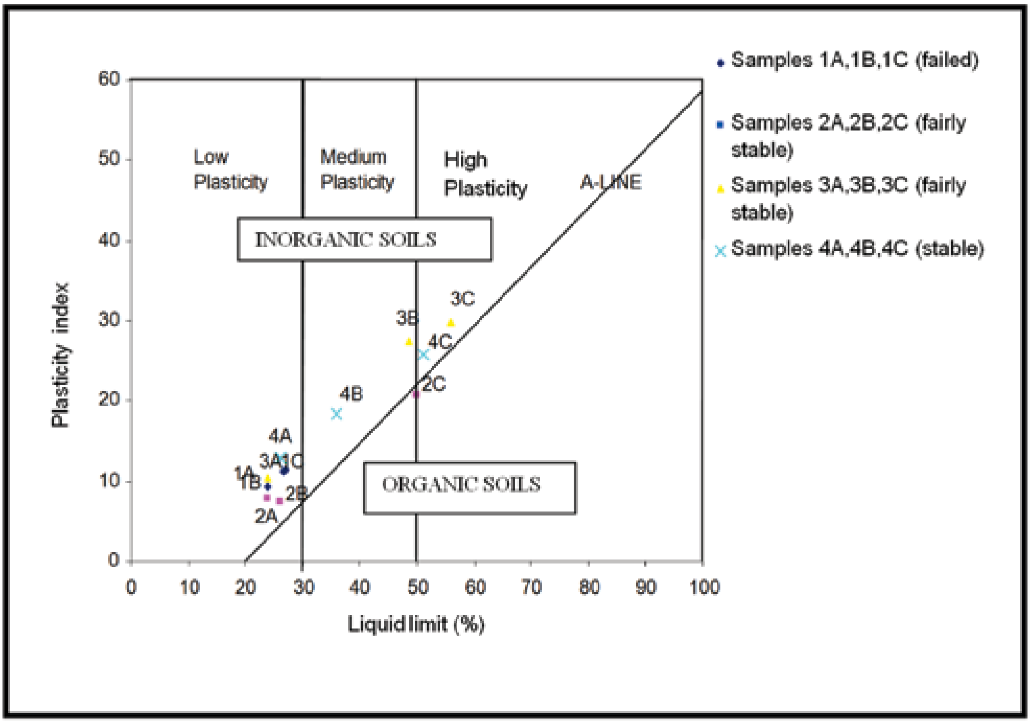


Figure 7. Casagrande Chart Classification of studied samples

region of medium plasticity. Sample 3C plotted completely within region of high plasticity. The result indicates that samples 1A, 1B and1C (of failed portion) 2A, 2B (of fairly stable portion), 3A (of fairly failed portion) 4A, 4B and 4C (of the stable portion) are good sub-base and sub-grade materials while samples 3C of fairly failed portion is unsuitable for sub-grade material.

California Bearing Ratio Strength

The dry density of the soils and optimum moisture content of the soils compacted at the modified AASHTO is shown in the Table 4. It shows percentage reduction in strength as a result of soaking of the compacted samples and it ranges between 55–83 %. Figures 8 (a–e) present the unsoaked and soaked *CBR* curves of the studied samples. Most of the analyzed samples have the required 80 % unsoaked *CBR* value recommended for highway sub-base and sub-grade soils by the FMWH (2000) but only sample 1B satisfied the required unsoaked *CBR* value of 30 %.

Table 4. Maximum dry density and optimum moisture content of the samples compacted at the modified AASHTO level.

Sample	Depth (m)	Road condition	Maximum dry density (kg/m)	Optimum moisture content (%)
1B	0.3–0.6	Failed	1970	10.95
1C	0.6–1.0		1910	10.6
3B	0.3–0.6	Fairly failed	1730	12.4
4B	0.3–0.6	Stable	1830	12.0
4C	0.6–1.0		1780	14.0

Table 5. CBR result

Sample	unsoaked *CBR* (%)	Soaked *CBR* (%)	Percentage Reduction in strength (%)
1B	71.3	31.6	55.68022
1C	83.9	15.3	81.764
3B	76.7	12.9	83.18123
4B	70.3	19	72.97297
4C	77.6	17	78.09278

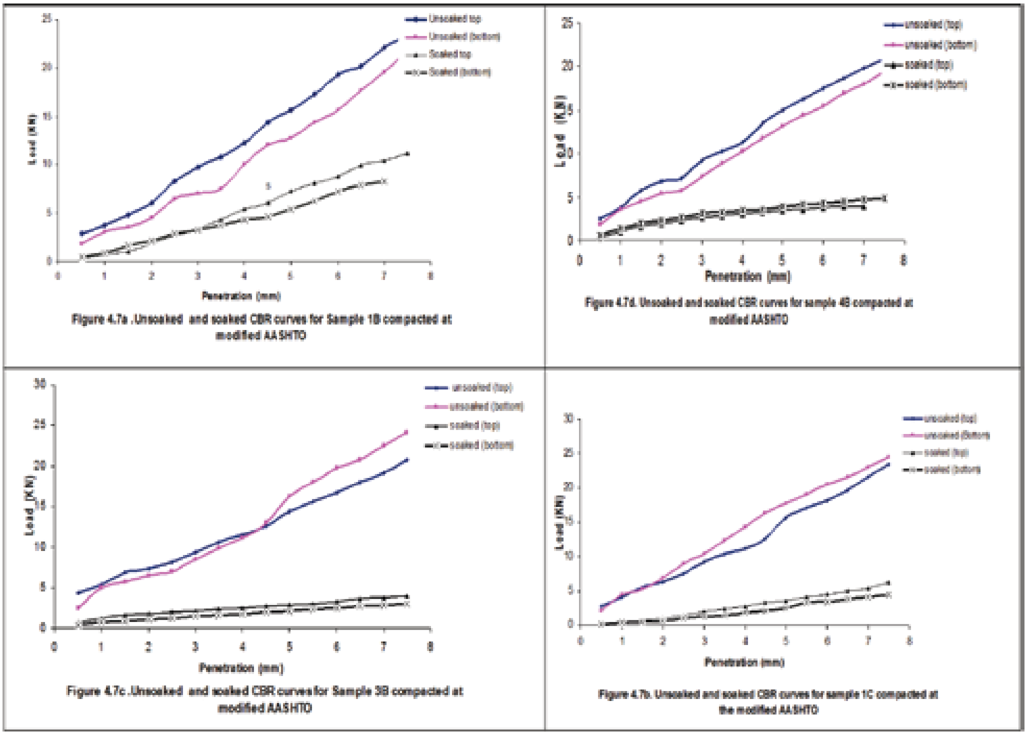


Figure 8. California bearing ratio of the studied soils compacted at the optimum moisture content of the modified AASHTO

DISCUSSION

The geophysical investigation results gave horizontal variation in conductivity of the subsurface materials underlying the flexible highway pavement at different portions in view of ascertaining geophysical bases if any for the causes of the highway failure. The interpretation of the plots of real and filtered real curves of the geophysical survey showed that majority of the identified major and minor linear features which represent zones of anomalously high conductivity were detected at the intensely failed portions of the road. These features are suspected to be numerous fractures in the underlying basement rocks and hence, conductive discontinuity in the shallow overburden.

The geotechnical analysis of the twelve bulk soil samples collected at different portions of the highway helped determined the variation in engineering index properties of the sub-base and sub-grade soils. Geotechnical results revealed that the sub-base and sub-grade soils in the depth range of 0-1.0m of the failed portions satisfied all the requirements of liquid limits, plasticity index, linear shrinkage, grain size distribution characteristics specified by the Federal Ministry of Works and Housing. These soils also plot within the region of low plasticity on Casagrande chart classification and under AASHTO classification into groups A-2-6, A-2-6 and A-2-4 which indicate that the soils are excellent to good materials for sub-grade soils.

In terms of shear strength most of the analyzed samples have adequate values of unsoaked *CBR*. However, they suffered very high reduction in shear strength of up to 80 % in soaked condition. The numerous major and minor linear fractures mapped in the shallow basement as delineated by VLF – EM methods have tendency to increased the permeability of the portion and thus cause the it to be highly saturated. This is evident in high current density and low resistivity values associated with the failed region. This has particularly made the excellent to good sub-base and sub-grade materials to perpetually remain in soaked condition. The geotechnical implication of this is that the highway pavement is resting on sub-grade, sub-base and foundation materials that lost as high as 80 % of shear strength as a result of ingress of water.

Conclusion

Both geophysical and geotechnical investigation methods have been used to characterize different portions of the flexible highway in the study area. The highway was reported to always fail barely six months after reconstruction. Geophysical investigation delineated numerous anomalously high current density and low resistivity zones as well as identified some major and minor linear fractures in the shallow underlying basement rocks. Also, the geotechnical investigations although showed that the samples collected generally displayed excellent to good engineering index properties as sub-base and sub-grade materials, but suffers up to 80 % reduction in strength with wetness. The interaction of the sub-grade and sub-base soils with water from numerous fractures in the basement rocks has greatly reduced shear strengths and therefore incessant failure of the overlying pavement.

Removal and replacement of the sub-grade and sub-base materials upon which the flexible pavement rests (up to 1 m) or soil stabilization / treatment that would improve materials shear strength under wet condition is suggested as well as construction of proper drainage system to drain the whole length of the road. This will address consistent highway pavement failure associated with Erunwon – Ijebu-Ode road.

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