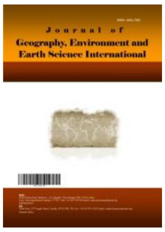

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Engineering Geophysical Investigation of Road Failure in a Basement Complex Terrain, Southwestern Nigeria

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Authors' contributions

This work was carried out in collaboration between both authors. Author IAA designed the study, managed the literature searches and wrote the first draft of the manuscript. Author COA acquired the field data and carried out the initial analyses. Both authors read and approved the final manuscript.

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ABSTRACT

Geoelectrical and geotechnical investigations were conducted to determine factors responsible for pavement failure in some segments of Adebayo Alao-Akala road in Ibadan, southwestern Nigeria. The geoelectrical investigation employed Schlumberger vertical electrical sounding conducted at fifteen stations occupied along two failed segments and one stable segment of the road, using station spacing of 25 m and maximum electrode spread of 100 m. 2D electrical resistivity survey was also conducted using the dipole-dipole electrode array with electrode spacing, a, of 1 m and expansion factor, n varied from 1 to 5 m. The VES data were interpreted quantitatively by partial curve matching and computer iteration technique and geoelectric sections were generated while 2D resistivity structures of the subsurface were produced from the inverted 2D resistivity data. The geotechnical investigation involved Grain size distribution, Atterberg limits, Compaction and California Bearing Ratio tests conducted on subsoils collected beneath the segment. The failed segments are underlain by low-resistivity clayey subgrade of resistivity mostly less than 100Ωm

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while the stable segment overlies sandy clay/clayey sand mixture of relatively higher resistivity, ranging from 200Ωm to 530Ωm. The subsoils of the failed segments comprise high-plasticity sandy clay and sandy gravelly clay while those of the stable segment are medium plasticity sandy clayey gravel. The values of maximum dry density are 1.46 Mg/m^3-1.73 Mg/m^3, 1.71 Mg/m^3-1.86 Mg/m^3 and 1.75 Mg/m^3-1.82 Mg/m^3 respectively, with corresponding optimum moisture content of 7%-8%, 11%-20% and 10%-17% and California bearing ratio under soaked condition for 48 hours of 7%-8%, 17%-20% and 11%-17% respectively. The failure of the road pavement is attributable to the clayey nature of the subgrade, and poor drainage. The stable segment is underlain by excellent-to-good subgrade materials. Ingress of surface water into the clayey subgrade occasioned by poor drainage of run-off resulted in deformation of the road pavement in response to vehicular load.

Keywords: Deformation; geoelectrical; geotechnical; poor drainage; road pavement; subgrade; vehicular load.

1. INTRODUCTION

The rate at which Nigerian roads fail in recent times has become worrisome, as it brings untold economic hardship on the citizenry, on the one hand, and all the tiers of government, on the other. Vehicles consume more fuel for trips on failed roads than they would on stable roads. Apart from losing quality times, motor parts wear faster while road users are physically stressed as they are jolted in their vehicles along failed roads everyday with consequent health implication and raised medical bills. Lives and goods are also often lost as a result of auto crash occasioned by bad roads.

Nigerian roads hardly last one year after construction because standards are usually compromised prior to, during and after construction. Road failure is economically retrogressive since huge resources are spent to rehabilitate or even reconstruct, where most of the road stretch is damaged. Rehabilitation and reconstruction usually cost more since prices of materials and services might have soared, especially in an unstable economy. Failed roads portend failed economy.

Although road failures have more often been attributed to poor design; substandard construction materials; poor drainage system, bad usage and poor maintenance [1,2,3,4,5], geological factors play primary role but are usually taken for granted and rarely considered in road design and construction [6,7,8]. The geological factors include near-surface geologic sequence, characteristics and behaviour of the subgrade soils and existence of concealed geological structures such as fractures, ancient stream channels and shear zones [9,7,10,11]. The failure to understand and give due consideration to the geology and geotechnical characteristics of the soils and/or rocks underlying the routes along which roads are constructed is a major cause of the failure of road pavements [12,13].

Conventional geotechnical methods of investigating causes of road failure are expensive and time-consuming. Geophysical surveys are, however, efficient and cost-effective in providing geotechnical information since they combine high speed and appreciable accuracy in providing subsurface information over large areas [14,15]. They are therefore capable of providing distinctive subsurface information from which reliable geotechnical deductions can be made about the subgrade and the underlying rock(s) beneath road pavements. If properly constrained with carefully supervised borehole logs, geophysical surveying can provide critical subsurface information, maximize rate of ground coverage and minimize the need for drilling [16,17]. Geophysical methods reveal subsurface properties underlying road pavements such that minimum geotechnical tests are required at zones of interest requiring further detailed investigation.

The study area, Adebayo Alao-Akala Way, lies between Wofun and Alegongo, Ibadan southwestern Nigeria, within latitude 7º 25'-7º 26' N and longitude 3º 57' and 3º 59' E (Fig. 1) with elevation varying from 197 m to 259 m above sea level. The 2 km long road was constructed in 2009 with pavement width of about 7.5 m and shoulder widths of 2.0 m and has failed at several portions along its length shortly after it was commissioned for use. The area lies within the basement complex terrain of southwestern Nigeria [18,19] and is mainly underlain by undifferentiated gneiss (Fig. 2). The road accesses an area in its development phase and is plied by heavy trucks hauling building materials to construction sites. It is therefore expected to be geotechnically stable and capable of bearing the magnitude of vehicular load imposable on it, without compromising the integrity of the pavement, if adequate preconstruction consideration had been taken.

In view of anticipated plans to rehabilitate the road, an investigation of the subsoil underlying the road pavement is imperative in order to serve as useful guide in the repair work. Most road pavement failures have been attributed to problems associated with the subgrade [20]. The subgrade is the receiving platform for the weight of the wheel load exerted on the road pavement. This study therefore integrates geophysical and geotechnical methods to characterize the near-surface geologic materials that constitute the subgrade upon which the road pavement was laid in order to determine possible causes of its failure. The objectives are to delineate the geoelectric sequence; determine the nature of the subsoils; determine depth to the bedrock; identify geological features within the bedrock (e.g. fractures and buried cavity) which may have constituted threat to the stability of the road pavement; evaluate the engineering properties of the subsoils and appraise their suitability, or otherwise, for stable road pavement.

2. MATERIALS AND METHODS

The study entailed geophysical and geotechnical investigations conducted along two selected Failed segments (A and B), and one Stable segment of the road (Fig. 3). The geophysical investigation employed the electrical resistivity method which utilized Schlumberger vertical electrical sounding (VES), and dipole-dipole profiling in order to detect both the vertical and lateral variations in resistivity. The VES was conducted at fifteen stations with station spacing of 25 m and maximum electrode spacing of 100 m while the dipole-dipole profiling was carried out using electrode spacing, a = 1 m and expansion factor n, varied from 1 to 5. The resistivity measurements were made with the aid of an ABEM SAS 1000 Terrameter and its accessories. The VES data were interpreted quantitatively by partial curve matching and computer iteration technique using WinRESIST Version 1.0 [21] and the results presented as VES curves and geoelectric sections. The dipole-dipole apparent resistivity data were inverted by using 2D inversion procedures run in Dipro for Windows, Version 4.01, [22].

The geotechnical investigation involved collection of disturbed and undisturbed soil samples with the aid of soil auger at 0.5 m, 1.0 m and 1.5 m depths from two test pits established 50 m apart on each of the traverses. Grain size analysis, Atterberg limits, Standard Proctor Compaction and California bearing ratio (CBR) tests were conducted on the soil samples by using set of sieves (0.063 µm-2.00 mm), Casagrande's equipment, Compaction mould and Penetration plunder respectively, and in accordance with the procedures of the British standard code for site investigations (BS 1377-2, 1990). The CBR test was performed under soaked condition for 48 hours. The soil samples were classified and rated based on the American Association of State Highway Transportation Officials (AASHTO) Standard Specifications for Transportation Materials and Methods of Sampling and Testing (2020), and the Federal Ministry of Works and Housing (FMWH) General Specifications for Road and Bridges (2016).

3. RESULTS AND DISCUSSION

The vertical electrical sounding data are presented as geoelectric sections while the 2-D dipole-dipole resistivity data are presented as inverted 2-D sections. Failed segment A is underlain by three geoelectric layers defined as topsoil, clay and bedrock (Fig. 4). The resistivity and thickness of the topsoil is 28-153 ohm-m and 0.9-1.6 m respectively. The clay layer has resistivity ranging from 8 Ωm to 30 Ωm and is 2.9 m to 4.9 m thick. Resistivity of the bedrock ranges from 587 Ωm to 889 Ωm while depth to bedrock is 3.9-5.7 m.

The geoelectric section beneath Failed segment B (Fig. 5) shows four geoelectric layers defined as topsoil, sandy clay, clay and bedrock. The topsoil has resistivity values ranging from 24 Ωm to 46 Ωm and thickness from 0.5 m to 1.1 m. The resistivity of the sandy clay layer is 178-193 Ωm and is 0.8-1.0 m thick. The resistivity and thickness of the clay layer are 5-18 Ωm and 1.9-10.8 m respectively. The bedrock resistivity is 410-770 Ωm while depth to the bedrock is 2.7-11.6 m. The geoelectric section beneath the Stable segment (Fig. 6) reveals three geoelectric layers defined as topsoil, clay and bedrock. The topsoil has resistivity ranging from 92 Ωm to 179 Ωm and is 0.8 m to 1.9 m thick. It is underlain by clay layer of resistivity 22-77 Ωm and thickness 2.9 m to 11.1 m. Bedrock resistivity and depth to bedrock range from 303 Ωm to1104 Ωm and 2.9

m to 11.1 m respectively. The failure observed along the Failed segments cannot be attributed to bedrock fracturing as the values of reflectivity coefficients, R, at subsoil-bedrock interface, computed with saprolite resistivity, ρ_w and bedrock resistivity, ρ_b, range from 0.93 to 0.98, indicating fresh bedrock. A bedrock is suspected to be fractured when R is less than 0.7 [23].

The 2-D resistivity section beneath Failed segment A (Fig. 7) reveals that the subgrade is characterized by low-resistivity soil material typically clay with resistivity, ρ ranging from 2.46 Ωm to 99.0 Ωm. Lenses of sandy clay (ρ = 101 Ωm to 201 Ωm) and clayey sand (ρ = 254 Ωm-320 Ωm) occur in places within the predominantly clay overburden. The reisistivity generally decreases with increasing depth.

The 2-D resistivity section beneath Failed segment B (Fig. 8) shows that the subgrade is predominantly clay with resistivity ranging from 0.83 Ωm to 97.4 Ωm. Sandy clay (ρ = 102 Ωm–245 Ωm), clayey sand 265 Ωm – 823 Ωm and sand (ρ = 1633 Ωm) occur as lenses in places and at various depths within the subsoil. Since clay is porous but impermeable, it swells as rain water enters the subgrade through openings in the surface, and shrinks as it loses moisture in the dry season, causing differential settlement and eventual failure of the road pavement as it yields to vehicular load [12,15].

The 2-D resistivity section beneath the Stable segment (Fig. 9) reveals subgrade from station 1 to station 50 is predominantly sandy clay with resistivity ranging from 100 to 247 Ωm. The subgrade beneath stations 51 – 98 is characterized by relatively more resistive clayey sand, about 1 m thick, underlain by sandy clay. The resistivity of the clayey sand layer ranges from 258 Ωm to 530 Ωm. The predominance of the relatively higher resistivity materials beneath this portion is indicative of competence and stability of the subgrade against vehicular load [15,11].

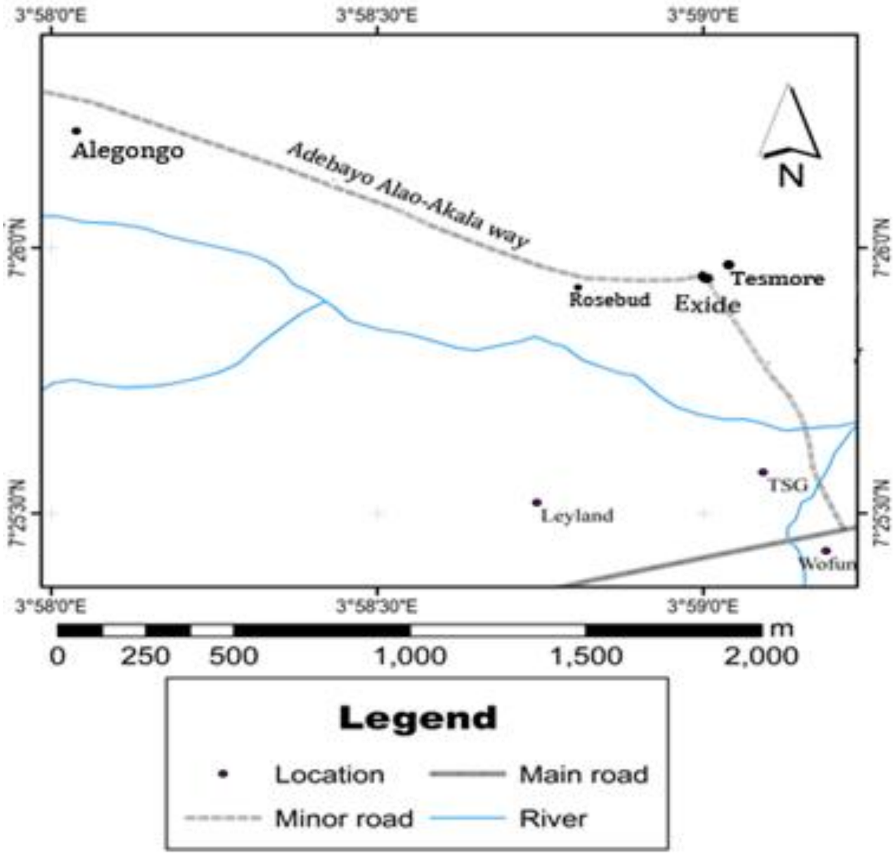

Fig. 1. Location map of the study area

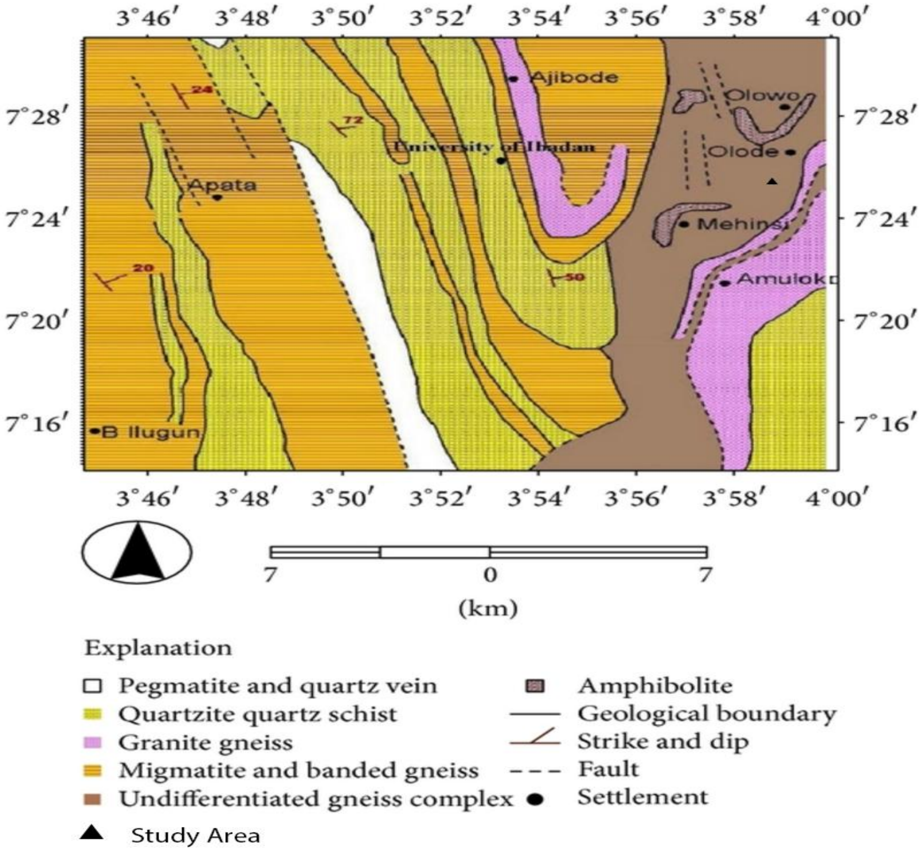

Fig. 2. Geological map of the study area (adapted after Okunlola et al. [24])

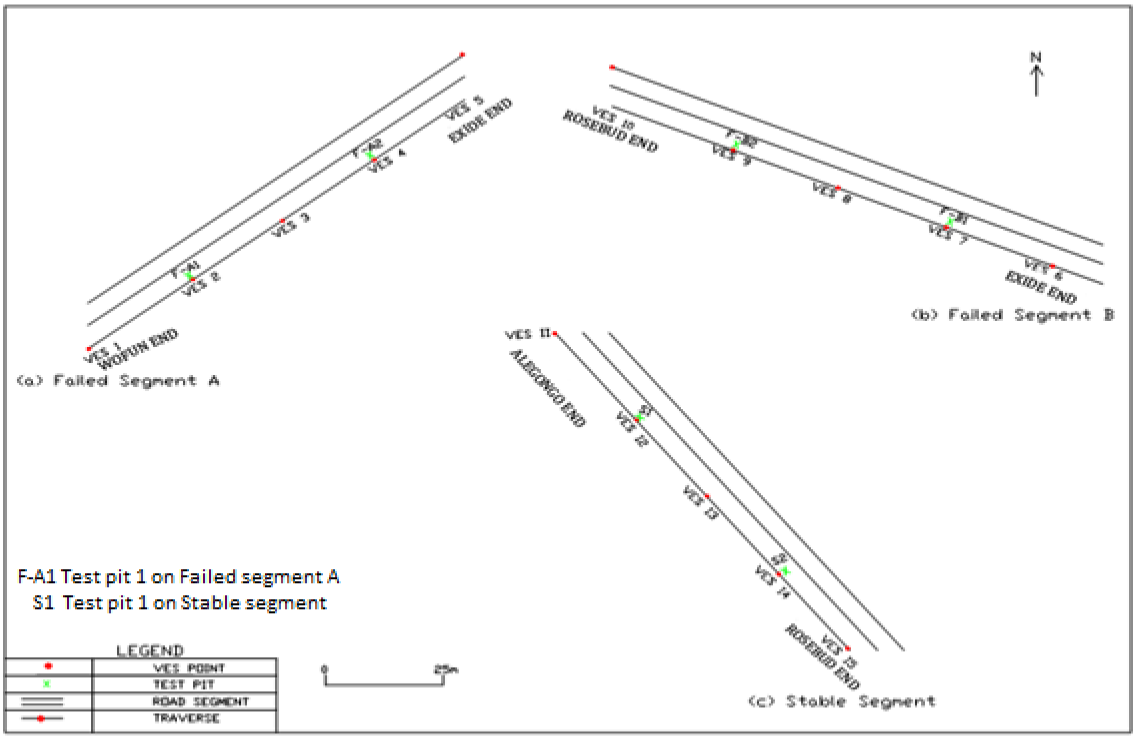

Fig. 3. Field layout showing the road segments investigated

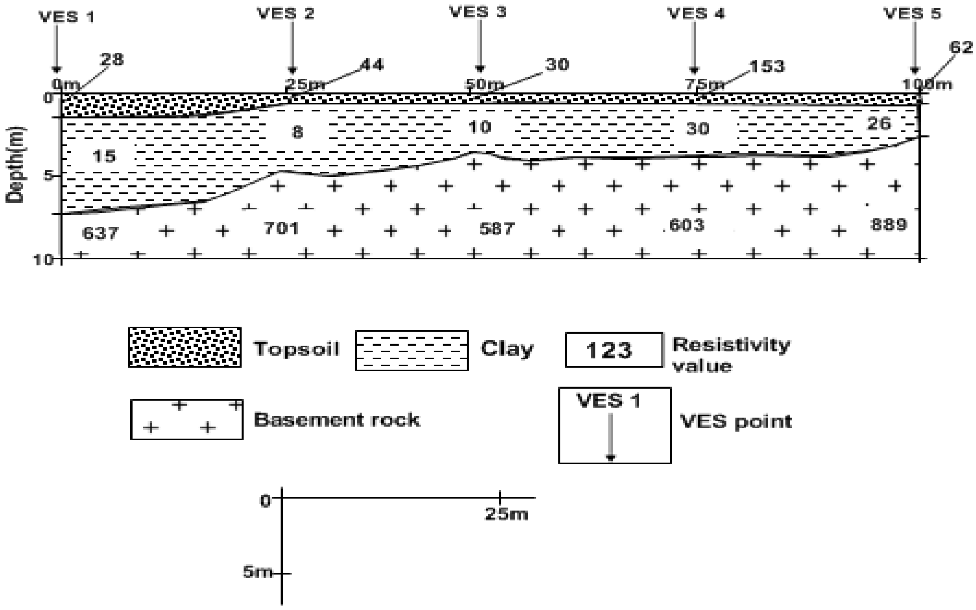

Fig. 4. Geoelectric section beneath Failed segment A

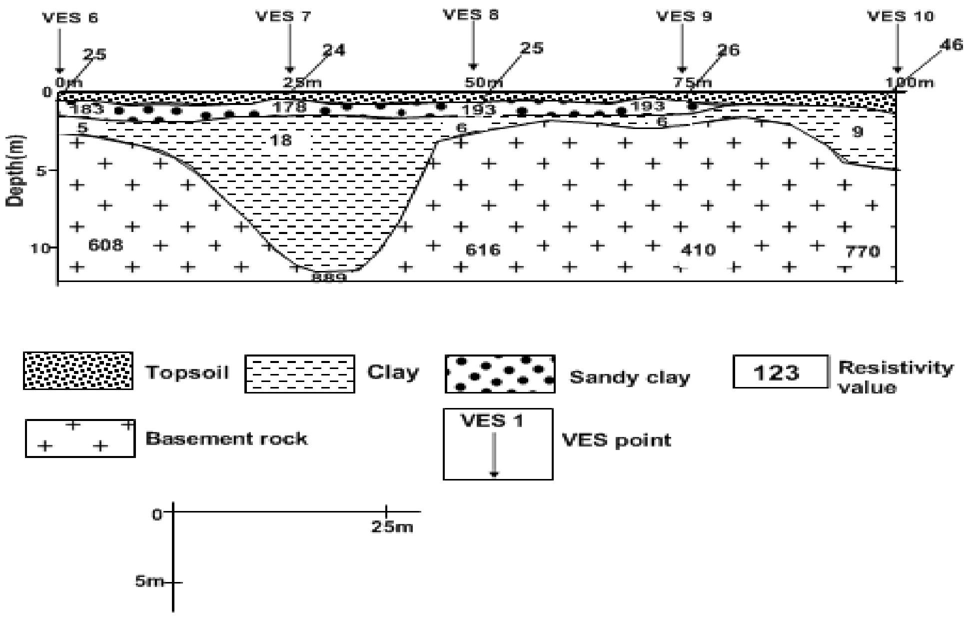

Fig. 5. Geoelectric section beneath Failed segment B

The results of classification tests conducted on soil samples from the study area are presented in Table 1. The results of sieve analysis reveal that the amount of fines in the subgrade sampled beneath Failed segment A ranges from 39% to 66%. %Sand ranges from 18% to 31% while the amount of gravel increases from 3% to 42%. The soil samples from Failed segment B consist of fines ranging from 22% to 64%, sand varying from 12% to 35% and gravel increasing from 3% to 66%. %Fines ranges from 20% to 32% in the soils from the Stable segment while the amounts of sand and gravel range from 13% to 22% and 48% to 65% respectively.

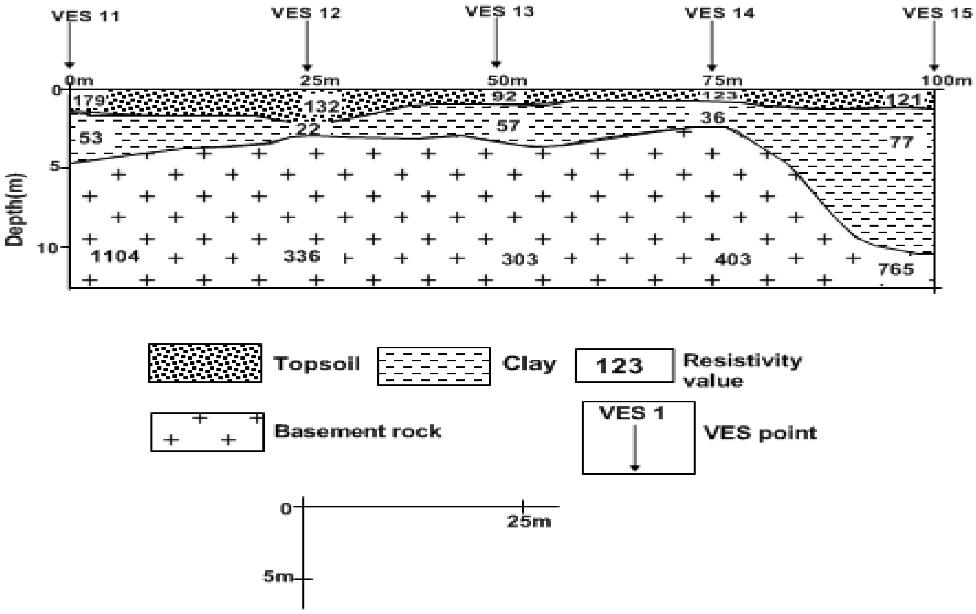

Fig. 6. Geoelectric section beneath the Stable segment

Table 1. Grain size distribution and Atterberg limits of soils from the study area

Sample no.	Depth (m)	Atterberg limits			% Fines	% Sand	% Gravel	Soil description
		LL (%)	PL (%)	PI (%)				
Failed A1/1	0.5	70	31	39	66	31	3	Sandy Clay
" A1/2	1.0	66	28	38	49	18	33	Sandy Gravelly Clay
" A1/3	1.5	60	24	36	39	19	42	Sandy Gravelly Clay
Failed A2/1	0.5	68	30	38	65	30	5	Sandy Clay
" A2/2	1.0	64	27	37	48	20	32	Sandy Gravelly Clay
" A2/3	1.5	58	22	36	40	22	38	Sandy Gravelly Clay
Failed B1/1	0.5	59	23	36	62	35	3	Sandy Clay
" B1/2	1.0	40	18	22	30	19	51	Sandy Clayey Gravel
" B1/3	1.5	54	28	26	62	33	5	Sandy Clay
Failed B2/1	0.5	56	20	36	64	32	4	Sandy Clay
" B2/2	1.0	42	20	22	22	12	66	Sandy Clayey Gravel
" B2/3	1.5	31	14	17	28	17	55	Sandy Clayey Gravel
Stable 1/1	0.5	49	24	25	20	18	62	Sandy Clayey Gravel
" 1/2	1.0	48	25	23	28	14	58	Sandy Clayey Gravel
" 1/3	1.5	42	21	21	32	13	55	Sandy Clayey Gravel
Stable 2/1	0.5	47	24	23	22	13	65	Sandy Clayey Gravel
" 2/2	1.0	44	22	22	28	20	52	Sandy Clayey Gravel
" 2/3	1.5	41	20	21	30	22	48	Sandy Clayey Gravel

The subgrade beneath the Failed segments can be described as sandy clay within the top 0.5 m and sandy gravelly clay within the depth interval 0.5 m to 1.5 m. The fines are clay since the LL-PI values plot above the A-line on the Cassagrande (1948) chart (Fig. 10). The soils from Failed segment A have high plasticity and high compressibility while those from Failed segment B have medium-to-high plasticity and medium-to-high compressibility. High Plasticity soils are known to display excessive shrinkage and settlement in response to seasonal variations [25,26] and this may have been the cause of the failure along these segments. The soils from the Stable segment are well-graded sandy clayey gravel of medium plasticity and medium compressibility.

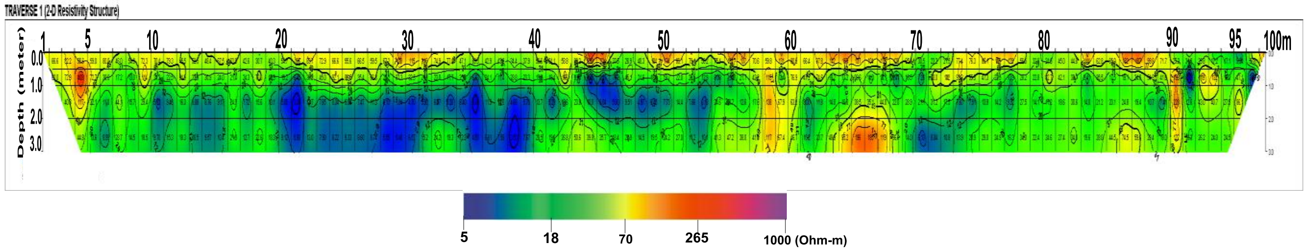

Fig. 7. 2D Resistivity section beneath Failed segment A

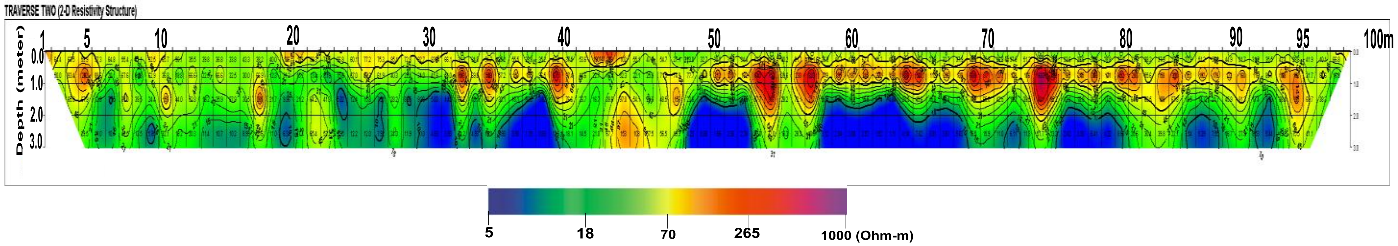

Fig. 8. 2D Resistivity section beneath Failed segment

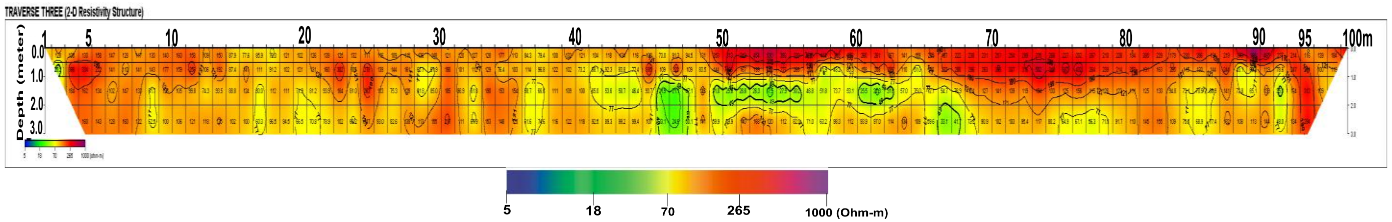

Fig. 9. 2D Resistivity section beneath the Stable segment

The AASHTO Standard Specifications [27] classifies the sandy clay and sandy gravelly clay of the Failed segments as A-7-6 and A-7-5 respectively, which are generally rated as fair-to-poor subgrades. Soils having Liquid limit (LL) greater than 50% and Plasticity index (PI) greater than 35% is not suitable subgrade materials (BS 5930, [28]). The strength of such soils can be significantly reduced by ingress of water. Clays are known to possess high porosity and low permeability, and hence retain surface water which enters it for a long time, resulting in high pore pressure, swelling and weakening of the soils, and consequently, failure of the overlying road pavement in response to vehicular load.

The General/Standard Specifications for Road and Bridges (FMWH, [29]) and Standard Specifications for Transportation Materials and Methods of Sampling and Testing (AASHTO, [27]) specify amount of fines less than 35% in a soil to be suitable subgrade. The subsoils beneath Stable segment belong to this group and are thus classified as A-2-6 soils and rated as excellent- to-good subgrade.

The Maximum Dry Density (MDD) of soil samples from Failed segment A ranges from 1.46 Mg/m^3 to 1.73 Mg/m^3 while the Optimum Moisture Content (OMC) ranges from 16% to 29%. The MDD and OMC of soils from Failed segment B range from 1.71 to 1.86 Mg/m^3 and 11% to 20% respectively. Based on the General/Standard Specifications (FMWH, [29]; AASHTO, [27]) which set a minimum of 1.76 Mg/m^3 as Maximum Dry Density (MDD) and a maximum of 18% as Optimum Moisture Content (OMC) for suitable subgrade materials, the soils from the Failed segment A are not suitable subgrade materials. The top 0.5 m beneath Failed segment B is unsuitable subgrade and is underlain by suitable materials at depth. The soils from the Stable segment have MDD and OMC values ranging from 1.75 Mg/m^3 to 1.82 Mg/m^3 and 10% to 17% respectively and are therefore adjudged suitable subgrade materials.

The General/Standard Specifications (FMWH, [29]; AASHTO, [27]) recommend a minimum value of 10% for California Bearing Ratio (CBR) of subgrade soils under soaked condition for at least 48 hours. On this basis, the CBR values ranging from 5% to 7% obtained beneath Failed segment A indicate poor and unsuitable subgrade, and may have caused the failure of the road pavement. The soil from the top 0.5 m of Failed segment B is equally poor subgrade material with CBR values of 7-8%, but is underlain by suitable subgrade soils of CBR in the range 17% to 20%, within the depth interval 0.5 -1.5 m. The subsoils beneath the Stable segment have CBR values ranging from 10% to 17%, suggestive of Excellent-to-Good subgrade materials and laying credence to the better load carrying capacity and stability of the road pavement. The summary of the soil classification, subgrade rating and results of strength tests are presented in Table 2.

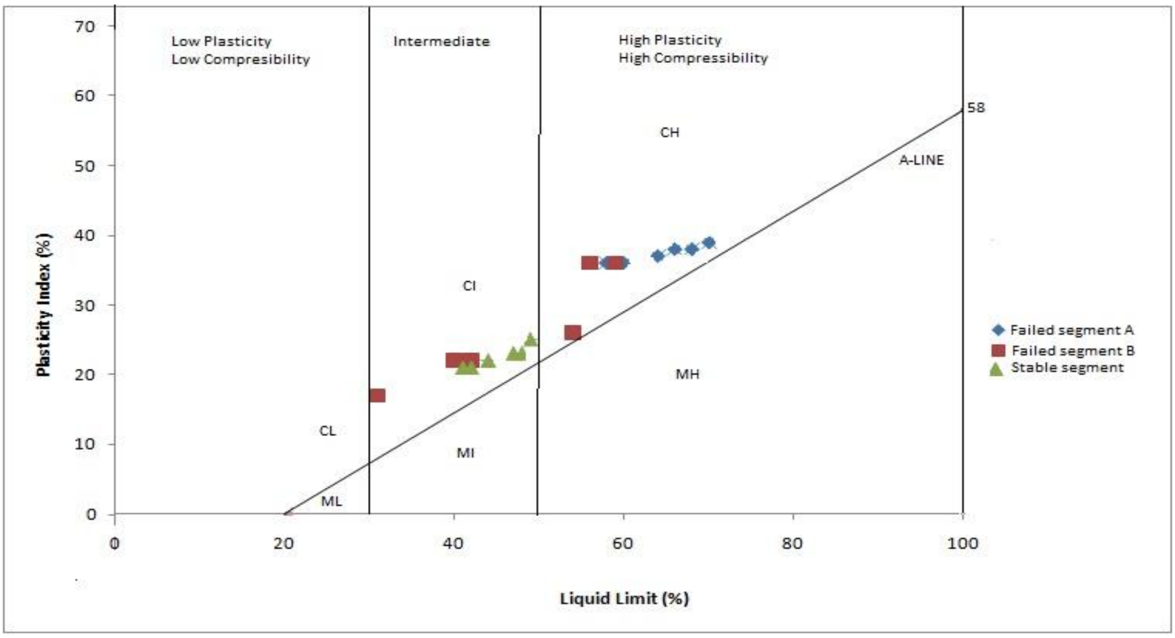

Fig. 10. Cassagrande chart of the soil samples

Table 2. Soil Classification, CBR and Subgrade rating of soils from the study area

Sample no.	Depth (m)	LL (%)	PI (%)	Soil Group (USCS)	Soil Class AASHTO	MDD (%)	OMC (%)	CBR (%)	Subgrade Rating
Failed A1/1	0.5	70	39	CS	A-7-6	1.60	25	5	Fair-to-Poor
" A1/2	1.0	66	38	CG	A-7-5	1.67	23	6	Fair-to-Poor
" A1/3	1.5	60	36	CG	A-7-5	1.73	16	8	Fair-to-Poor
Failed A2/1	0.5	68	38	CS	A-7-6	1.53	25	6	Fair-to-Poor
" A2/2	1.0	64	37	CG	A-7-5	1.48	28	6	Fair-to-Poor
" A2/3	1.5	58	36	CG	A-7-5	1.46	29	7	Fair-to-Poor
Failed B1/1	0.5	59	36	CS	A-7-6	1.71	23	7	Fair-to-Poor
" B1/2	1.0	40	22	GC	A-2-6	1.76	17	17	Excellent-to-Good
" B1/3	1.5	54	26	CS	A-7-6	1.75	20	8	Fair-to-Poor
Failed B2/1	0.5	56	36	CS	A-7-6	1.72	21	8	Fair-to-Poor
" B2/2	1.0	42	22	GC	A-2-6	1.78	14	17	Excellent-to-Good
" B2/3	1.5	31	17	GC	A-2-6	1.86	11	20	Excellent-to-Good
Stable 1/1	0.5	49	25	GC	A-2-6	1.76	16	10	Excellent-to-Good
" 1/2	1.0	48	23	GC	A-2-6	1.79	14	11	Excellent-to-Good
" 1/3	1.5	42	21	GC	A-2-6	1.81	12	17	Excellent-to-Good
Stable 2/1	0.5	47	23	GC	A-2-6	1.78	16	11	Excellent-to-Good
" 2/2	1.0	44	22	GC	A-2-6	1.81	15	15	Excellent-to-Good
" 2/3	1.5	41	21	GC	A-2-6	1.82	10	17	Excellent-to-Good

CS = Sandy Clay, CG = Gravelly Clay, GC = Clayey Gravel (well-graded gravel-sand-clay mixture)

4. CONCLUSION

The failure of the road pavement along the failed segments is attributable to geotechnically poor properties associated with the clayey nature of the subgrade and poor drainage. The Failed segments are underlain by low-resistivity clay-rich subgrade. The subsoils beneath the Stable segment are characterized by relatively higher resistivity comprising sandy clay/clayey sand mixture whose index properties and strength parameters are capable of bearing vehicular load transmissible through the overlying road pavement. Poor drainage of run-off from topographic highs to the toes of the road pavement resulted in flooding and subsequent weakening and erosion of the asphaltic road surface which subsequently allowed ingress of surface water into the clayey subgrade and caused failure of the road pavement in response to vehicular load. The results of this study will guide in the rehabilitation/reconstruction programme for the road.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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