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Integrated geophysical investigation for pavement failure along a dual carriage way, Southwestern Nigeria: a case study

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Abstract

An integrated geophysical investigation was carried out on some portions of Ogbomoso-Ilorin dual carriage way located within the basement complex area of Southwestern Nigeria, with a view to delineating the cause(s) of road pavement failure observed along the road. Three failed portions and one control stable segment of the road pavement were investigated within the southwestern flank of the road. This study integrated very-low-frequency (VLF) electromagnetic (EM), ground magnetic and electrical resistivity (ER) geophysical prospecting methods for detailed study of the terrain. Two (2) VLF-EM and ground magnetic traverses were established per studied location. A total of fifty three (53) vertical electrical sounding (VES) using Schlumberger array was occupied. 2-D resistivity imaging using dipole-dipole electrode array were employed along the established traverses. Qualitative interpretation of the VLF-EM and ground magnetic profiles suggest typical fracture zones. The results obtained from the VES and 2-D resistive image of the subsurface showed major geologic features, which are typical of fractures, faults, joints, cavities and voids. The near surface subsoil on which the road pavement is founded within the failed and stable segments is predominantly characterized by low resistive materials (<100 Ωm) and (<150 Ωm) respectively. Therefore, the geological factors responsible for the susceptibility of the road to failure are clayey subgrade soil beneath the road pavement, lateral inhomogeneity, near surface geological structures and changes in elevations due to fluctuation in the saturated zone.

Keywords: Geological structures; lateral inhomogeneity; pavement failure, resistivity imaging; subgrade.

1. Introduction

The availability of good highway infrastructures in any society usually enhances rapid development of its economy (Ibitomi *et al*., 2014). A durable road reduces any incidence of material and human losses that could emanate from any avoidable accident. However, highway deficiencies in terms of capacity and reliability can have an economic cost such as reduced or missed opportunities and lower quality of life. The Ogbomoso-Ilorin dual carriage way, Nigeria is situated between latitudes 8^0 9’22.7’’ N & $8^0$24’28.96’’ N and longitudes $4^0$13’38.97’’ E & $4^0$27’11.87’’ E (Figure1). The road was constructed between the years 2008 and 2010 and is about 35km long. It primarily serves as a major route for the transportation of people and goods from southwestern region to the northern part of the country and vice versa. Few years after construction, it was observed that the major portions of the road pavement have started failing (Figure 2).

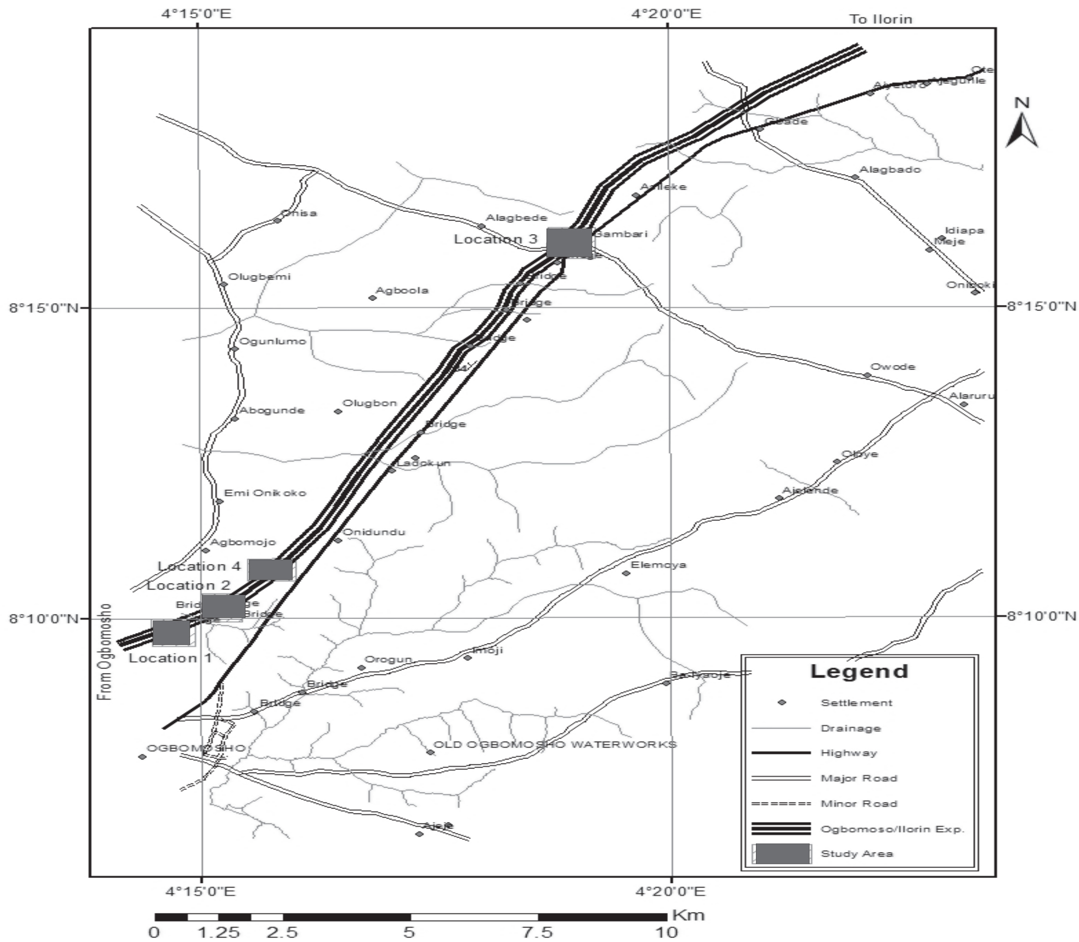

Fig. 1. Map of the area around Ogbomoso-Ilorin dual carriage way showing the specific studied localities.

PLATE1

PLATE 2

Fig. 2. Typical Pavement Failure along Ogbomoso-Ilorin Highway, Nigeria

This phenomenon has become a major challenge in recent decades, as most of the highways located within the southwestern basement complex of Nigeria do not usually stand the test of time (Oladapo *et al*., 2008; Momoh *et al*., 2008; Akintorinwa *et al*., 2010). Therefore, the need to understand and unravel the possible cause (s) of the susceptibility of Ogbomoso-Ilorin highway to failure few years after construction from diverse disciplines is very imperative. Oladeji & Adedeji (2001) observed non-uniform occurrence of deformation features on highway pavement in Ogbomoso using environmental studies.

They concluded that localized failure is due to shallow groundwater level. Adewoye et.al. (2004) also suggest environmental factors such as poor drainage and maintenance as causes of pavement failure in highway pavement around Ogbomoso. Further studies using geophysical techniques particularly on the hydrogeology of Ogbomoso suggest weathered layer typical of clay materials at shallow depth which often overly the water table (Adebola & Adewoye, 2012; Adagunodo *et al*., 2013; Sunmonu *et al*., 2012). The hydrogeologic setting will in no small measure impact on the failure of pavement in the area. Therefore, a synergy between geophysicists, geologists and civil engineers at pre-construction or pre alignment of a road route cannot be overemphasized (Al-Duaij *et al*., 2001; Al –Sulaimi & Al-Ruwaih, 2004; Rucker, 2006; Falowo, 2012; Sangodiji, 2012). Geophysical prospecting methods have the potential to provide appreciable information in a broad range concerning the relevant earth material properties needed in assessing the competence of subsurface soil for highway construction (Ozegin *et al*., 2013; Olorunfemi *et al*., 2010). In this present work, integrated geophysical investigation was used for a post construction study with the aim of bridging the gap between geotechnical, environmental and geological studies, and to bring to fore what can be done to ameliorate the sudden and gradual collapse of the road, particularly at the southwestern portion within Ogbomoso area. The study successfully applied geophysical methods, particularly the integration of VLF-EM, Magnetics and 2-D resistivity image for the first time along the highway to effectively identify the major causes of pavement failure different from the established environmental factors.

2. Study area and geologic setting

The Ogbomoso-Ilorin dual carriage road falls within the precambrian basement complex of Southwest Nigeria (Rahaman, 1976). The area is entirely underlain by migmatite and granite gneiss rock units (Figure 3) of Migmatite-gneiss complex group (Afolabi *et al*., 2013).

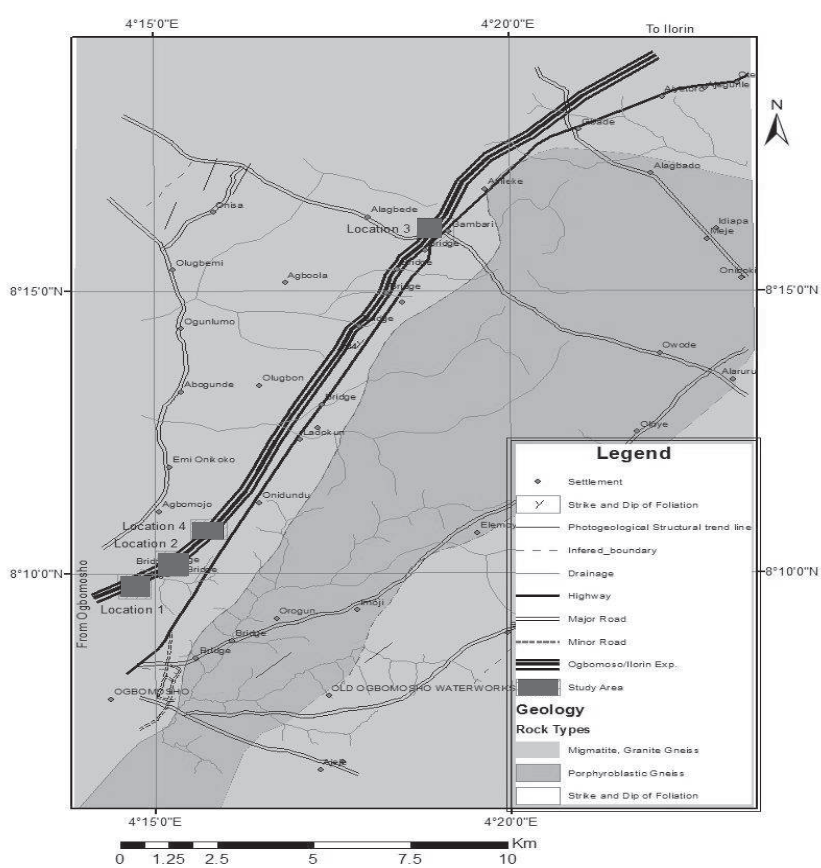

Fig. 3. Geological map of the study area

Texturally, the granite gneiss is medium to coarse grained, and there is no definite foliation pattern (Adabanija *et al.*, 2013). The gneisses with high content of mafic minerals is believed to have weathered into clayey soils, while those that are coarsely grained and more granitic may account for soils with varying textures with less clay in the study area (Adabanija *et al.*, 2013; Afolabi *et al.*, 2013).

Aquifers in the study area are isolated and compartmentalized (Sunmonu *et al.*, 2012). Primary porosity in these rocks are rare and thus groundwater accumulation is only feasible through secondary porosity. Two geologic processes, weathering and fracturing accounts for secondary porosity in a typical basement complex terrain (Fetter, 2001). Geologic factors such as parent rock type, weathering pattern, depth and thickness of weathered materials and permeability accounts for groundwater localization in the study area (Eduvie & Olabode, 2001; Vandenbergie, 1982; Ako & Olorunfemi, 1989) Drainage pattern is dendritic and surface water percolates down through the fractured and weathered zones.

The clay medium in Ogbomoso is generally shallow and it overlies the water table (Adebola & Adewoye, 2012; Adagunodo *et al.*, 2013). This poses a threat to the competence of highway pavement in the area.

3. Data set and methodology

Data were acquired over three failed portions (locations 1, 2, and 3) and one control stable portion (location 4) along the highway (Figures 4 and 5). Two traverses of equal lengths 200 m were established parallel to the road pavement per locality, with one traverse located on either side of the dual carriage (Figure 4).

Each of the traverses were made to cut across the unstable and the classified stable (as at the time of this investigation) segments of the road pavement. At locality 4, one traverse of length 200 m was established along the control stable segment. The employed geophysical methods for the investigation are very-low-frequency (VLF) EM, ground magnetic, and electrical resistivity methods involving vertical electrical sounding (VES) and dipole-dipole profiling. VLF-EM and ground magnetic measurements were taken at a regular station interval of 5 m using ABEM-WADI VLF-EM receiver unit and GEM 8 proton precession magnetometer respectively. The electrical resistivity data were obtained using the Ohmega resistivity meter. The VES technique involves the Schlumberger electrode configuration, while the 2-D resistivity imaging adopts the dipole-dipole configuration.

The VLF-EM method is an inductive exploration technique that is primarily used to map shallow subsurface structural features in which primary electromagnetic (EM) wave induces current flow (Sinha, 1990; Sharma & Baranwal, 2005, Adelusi *et al.*, 2009). The transmitter used for the study is that of Cutler, Maine USA (NAA) with frequency range of 24.827.6-KHz. The raw real and filtered real data obtained VLF-EM data were plotted against station distance and presented as profiles. Conductive zones are typical of areas where the peak positive filtered real coincides with the inflection on the raw real (Reynolds, 1997). Karous-Hjelt program (Karous & Hjelt, 1983) was used to invert the VLF–EM data to 2-D models.

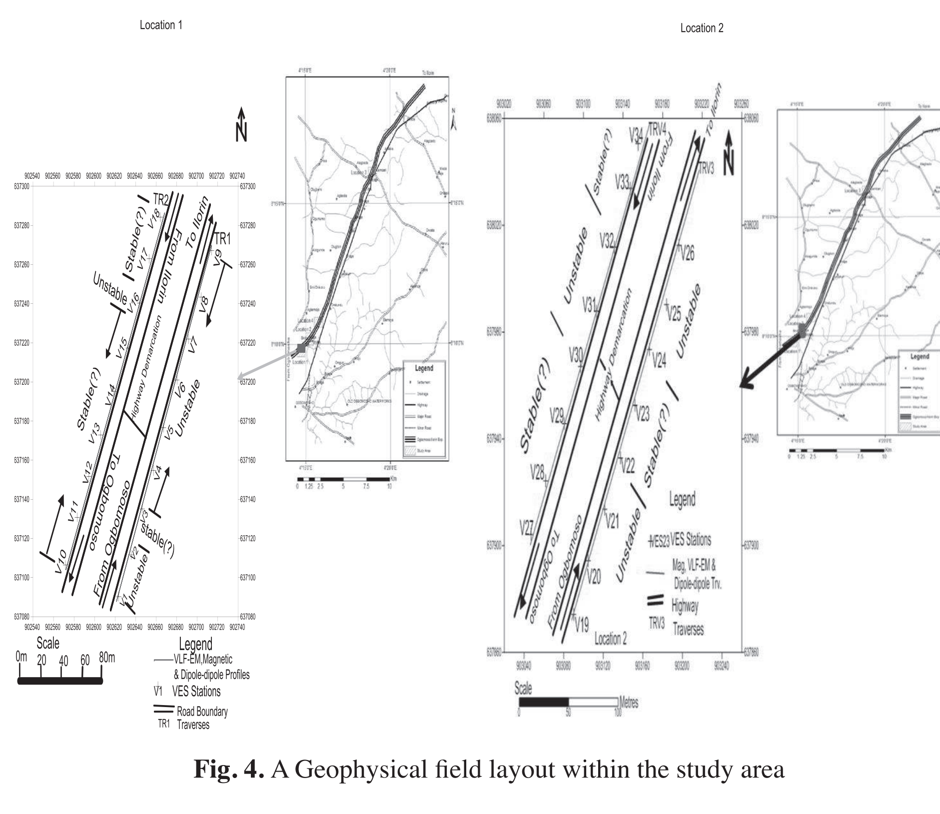

Fig. 4. A Geophysical field layout within the study area

Magnetic method involves the measurement of the earth's magnetic field intensity where the magnetic field and or vertical magnetic gradient is measured (Mariita, 2009; Telford *et al*., 1976. The observed magnetic readings were corrected for drift and offset effects using the base station readings. Magnetic intensity values were plotted against station distance. Varying amplitude of the magnetic intensities is indicative of probable fracture zones along the traverses.

The electrical resistivity method is used in the study of horizontal and vertical discontinuities in the electrical properties of the ground (Keller & Frischknecht, 1966; Keary *et al*., 2002). It utilizes direct current or low frequency alternating current to investigate the electrical properties of the subsurface. A total of fifty-three (53) VES stations (Figure 4) were occupied along the established traverses at intervals of 25 m using the conventional Schlumberger electrode array. The obtained VES data were quantitatively interpreted using partial curve matching and iteration modeling technique with the aid of Win Resist geophysical software (Vander, 1988). The combined horizontal profiling and vertical electrical technique adopting the dipole-diple array was carried out along the established traverses using an inter-electrode spacing of 5 m with an expansion factor, n, varying from 1 to 5. The obtained apparent resistivity values were subjected into inversion using the DipproWin software package and presented as 2-D resistivity structures. Low resistivity zones are typical of geologic structures such as fractures, faults, weathered materials such as clay materials and saturated zones which are inimical to highway pavement.

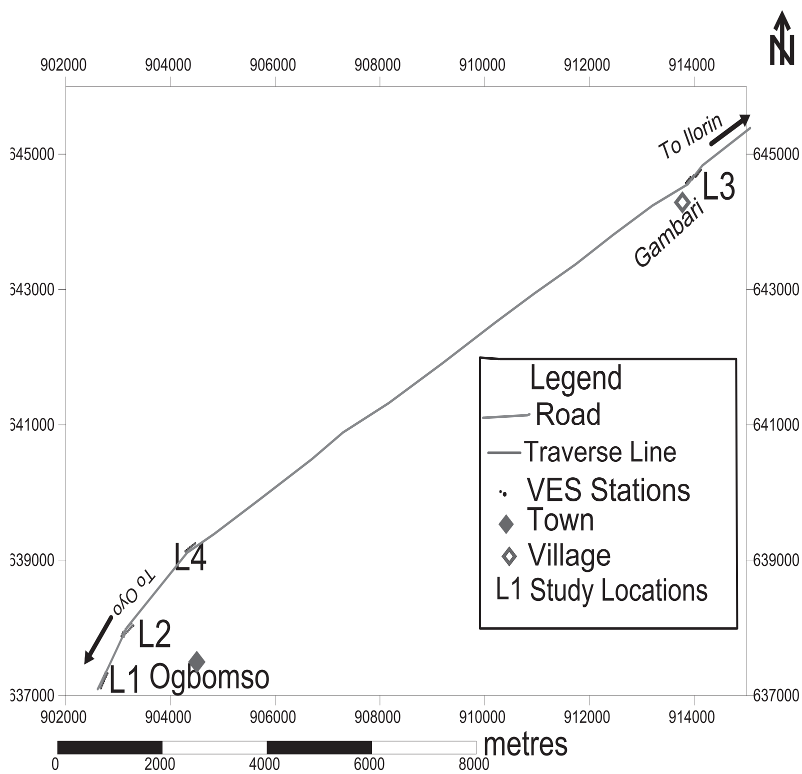

Fig. 5. The study localities alongOgbomoso-Ilorin highway.

4. Results and discussion

4.1 Locality 1:

4.1.1 Traverse 1 (SW-NE directions)

A linear conductive body is observed on the VLF-EM section within the unstable portion at distance between 125 m and 135 m (Figure 6a). This is also identified as a magnetic low on the magnetic profile at stations between 115 m and 145 m (Figure 6b). The subsoil in the upper 0 – 5 m within the unstable and classified stable portions on the geoelectric section is inferred to be predominantly clayey with resistivity values generally less than 150Ωm (Figure 6c). This correlates with the low resistive part in the upper 0 – 5 m on the corresponding 2-D resistivity image with resistivity values that range from 20 Ωm – 60 Ωm (Figure 6d). Both the geoelectric and 2-D resistivity sections display a bedrock interface that is undulating. This coincides with a major linear feature identified on the corresponding 2-D resistivity structure at distances between 120 m and 135 m (Figure 6d). This suspected linear feature has significant depth extent of about 21 m and may indicate geological features such as a fractured or faulted zones.

4.1.2 Traverse 2 (SW-NE directions)

Observed linear features display fairly high conductivity and magnetic low on the corresponding VLF-EM section and magnetic profile respectively (Figures 7a and 7b). These suspected linear features have significant depth extent of about 20 m and may indicate geological features such as fracture/fault zones and cavities or voids.

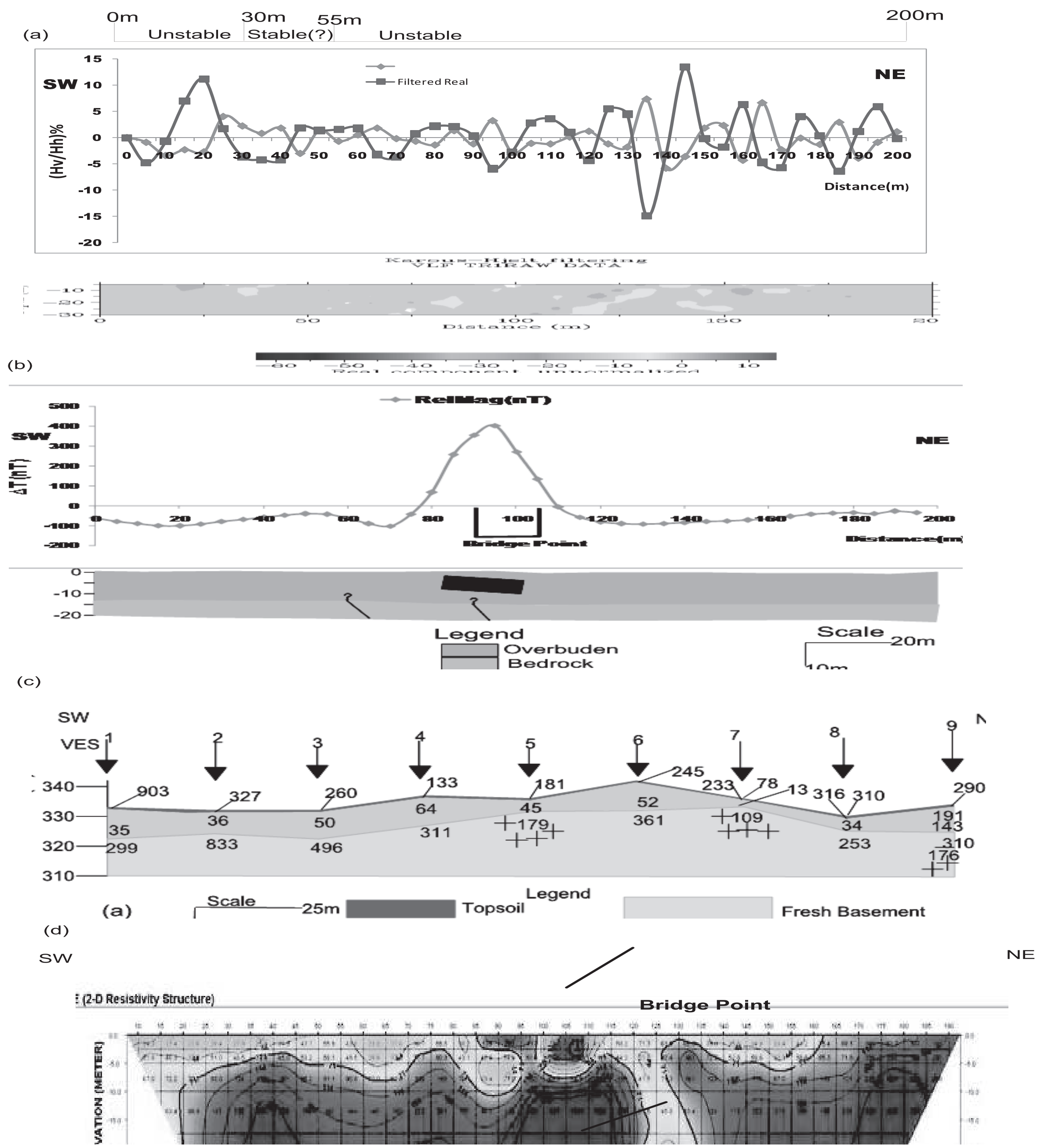

Fig. 6. (a) VLF-EM profile & corresponding section, (b) Magnetic profile & corresponding section, (C) Geoelectric section, and (d) 2-D resistivity structure along traverse 1 at locality 1

The subsoil (both the topsoil and weathered layer) in the upper 0 – 6 m within the classified stable segment and unstable segment with resistivity values that generally less than 200 Ωm is inferred to compose of clay, sandy clay clayey sand and lateritic sand (Figure 7c). The observed bedrock interface is uneven and forms a depression at VES stations between 11 and 17. Also, suspected linear features are observed on the 2D resistivity image at distances between 25 – 40 m, 60 – 95 m and 115 -125 m within the classified stable and unstable segments (Figure 7d).

4.2 Locality 2:

4.2.1 Traverse 3 (SW – NE directions)

Conductive bodies cross cutting between stations 65 m and 80 m and also between stations 90 m and 110 m were observed on the VLF-EM section (Figure 8a), and the magnetic low between station 60 m and 70 m on the corresponding magnetic profile (Figure 8b). Both the topsoil and weathered layer are observed to compose of clayey materials and sandy clay with resistivity values that are generally less than 150 Ωm (Figure 8c). The bedrock forms a depression between VES stations 20 and 23, and dips towards the southwest direction (Figure 8c). A low resistive part in the upper 2.5 – 10 m is inferred to be clayey on the 2D resistivity image at distance between 10 m and 50 m within the unstable portion (Figure 8d).

This correlates with the weatherd layer observed on the geoelectric section at distance between 0 m and 50 m. Also, a major suspected linear feature observed on the 2D resistivity image at distance between 60 m and 70 m within the stable portion (Figure 8d). The linear feature observed on the 2D resistivity structure within the unstable segment at distance between 95 m and 105 m correlates with the observations on the VLF-EM section.

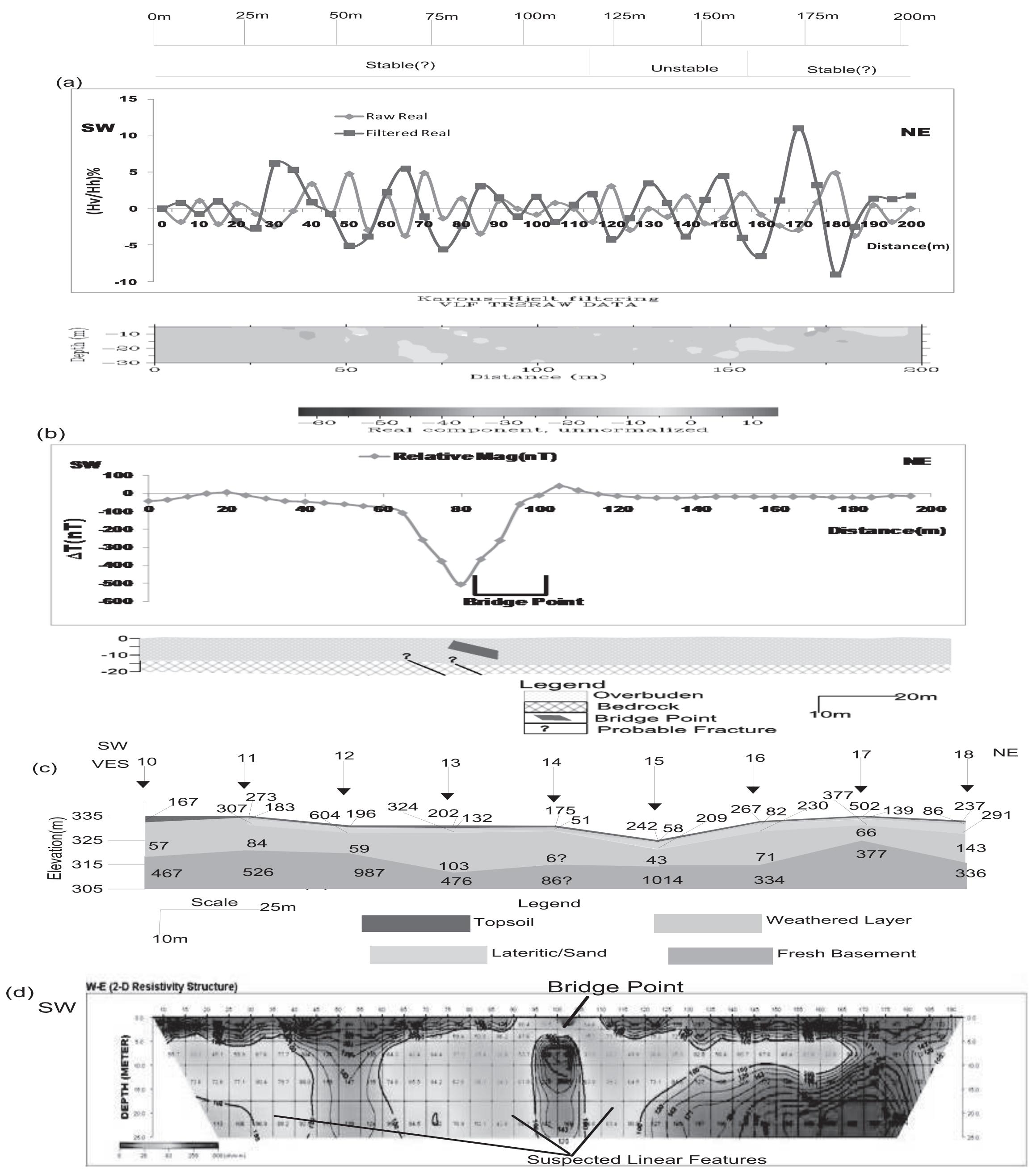

Fig. 7. (a) VLF-EM profile & corresponding section, (b) Magnetic profile & corresponding section, (C) Geoelectric section, and (d) 2-D Resistivity structure along traverse 2 at locality 1

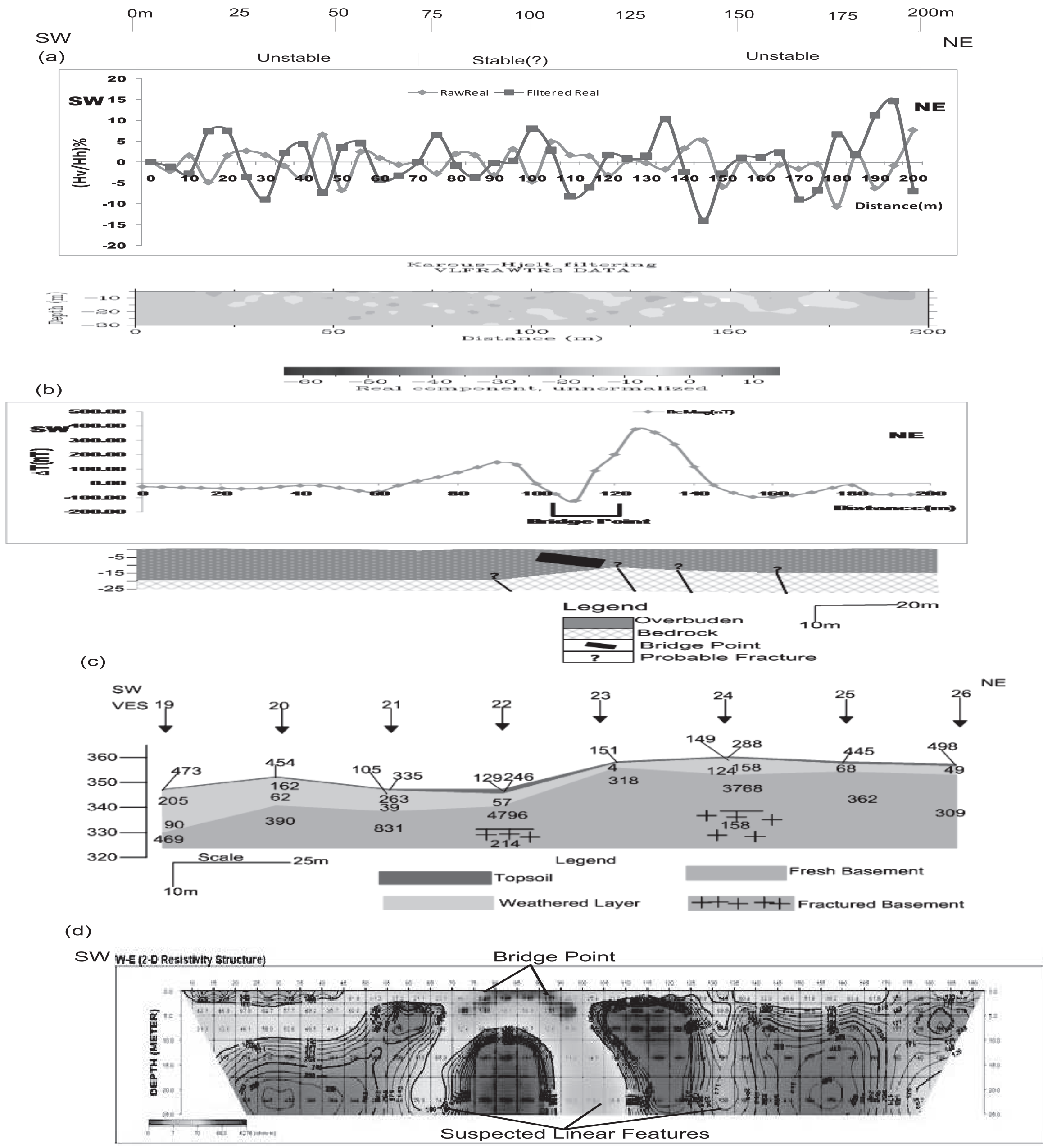

Fig. 8. a) VLF-EM profile & corresponding section, (b) Magnetic profile & corresponding section, (C) Geoelectric section, and (d) 2-D Resistivity structure along traverse 3 at locality 2

4.2.2 Traverse 4 (SW – NE direction)

The linear conductive body identified on the VLF-EM section at distances between 33 and 44 m (Figure 9a) coincides with the depression observed on the geoelectric section at distance between 35 m and 55 m, and low resistive part observed on the 2D resistiviy structure at distance between 40 m and 50 m. Varying magnetic intensity typical of fractures or faults were observed at distance between 60 and 100 m (Figure 9b). The formation in the upper 0 – 6 m on the geoelectric section within the unstable and classified stable segments is characterised by lateritic sand, sandy clay, clay and clayey sand with resistivity values that range from 8 Ωm - 677Ωm (Figure 9c). The overburden thickness ranged from 4.8 – 10.7 m. The bedrock interface is uneven and forms deppressions at distances between 25 – 75 m, 78 – 125 m and between 130 – 175 m. The formation identified as sandy clay and clayey soil in the upper 0 – 4 m on the geoelectric section (Figure 9c) correlates with low resistive part in the upper 0 - 5 m on the corresponding 2-D resistivity image with resistivity values ranging from 12 – 60 Ωm (Figure 9d). A suspected linear feature identified on the 2D resistivity section within the classified stable portion at distance between 120 m and 140 m (Figure 9d) coincides with the highly conductive body observed on the VLF-EM section at distance between 120 m and 165 m . Figures 10(a-d), 11 (a-c) show similar patterns as observed in locality 1 and locality 2.

4.3. Locality 4 (control stable segment):

4.3.1. Traverse 7 (SW – NE directions).

The observed topsoil composed of sandy clay, clayey sand and lateritic sand with resistivity values that vary from 139 Ωm to 1165 Ωm and thickness that varies from 0.4 – 0.6 m (Figure 12a).

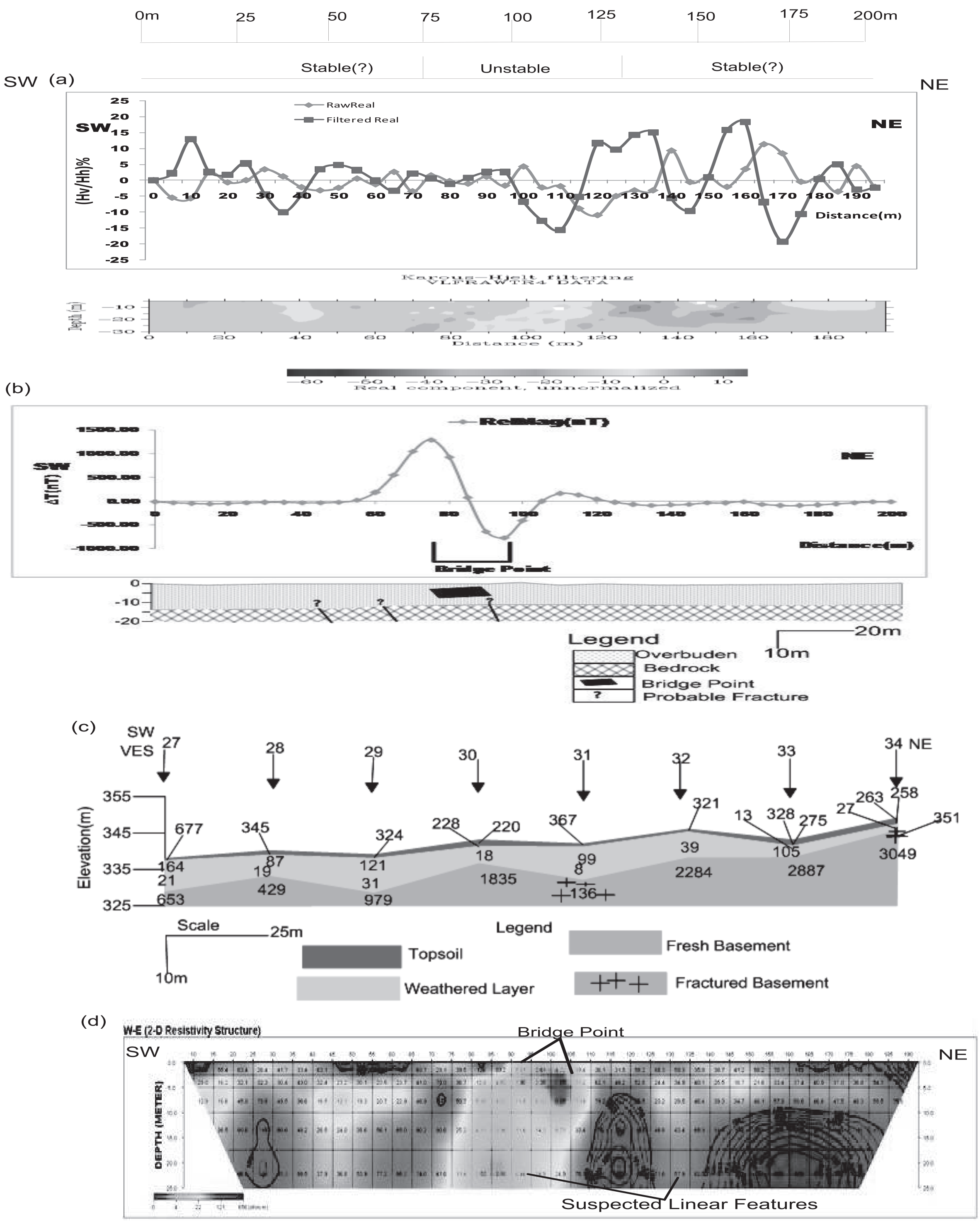

Fig. 9. a) VLF-EM profile & corresponding section, (b) Magnetic profile & corresponding section, (C) Geoelectric section, and (d) 2-D Resistivity structure along traverse 4 at locality 2.

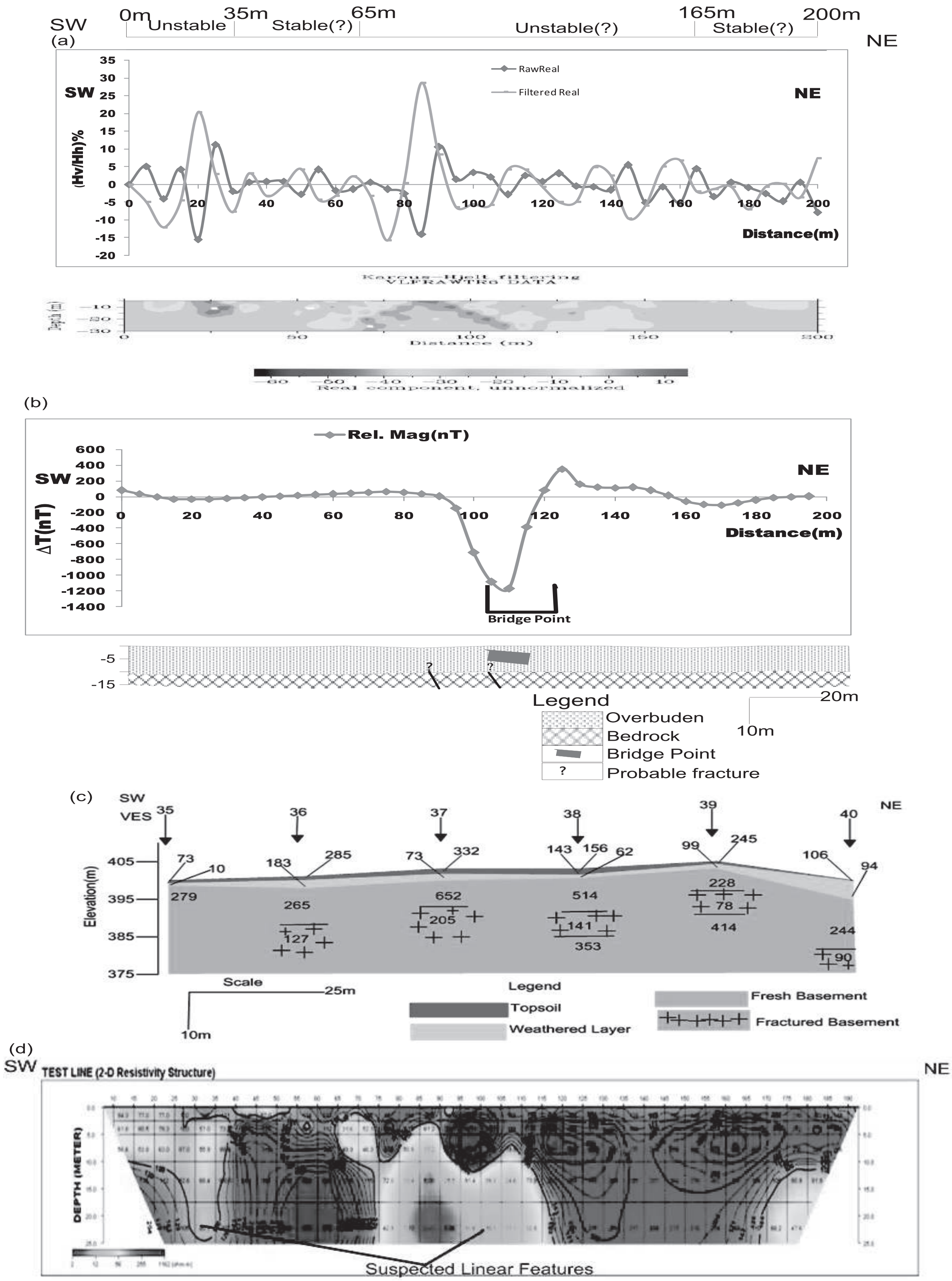

Fig. 10. a) VLF-EM Profile & corresponding section, (b) Magnetic profile & corresponding section, (C) Geoelectric section, and (d) 2-D Resistivity structure along traverse 5 at locality 3

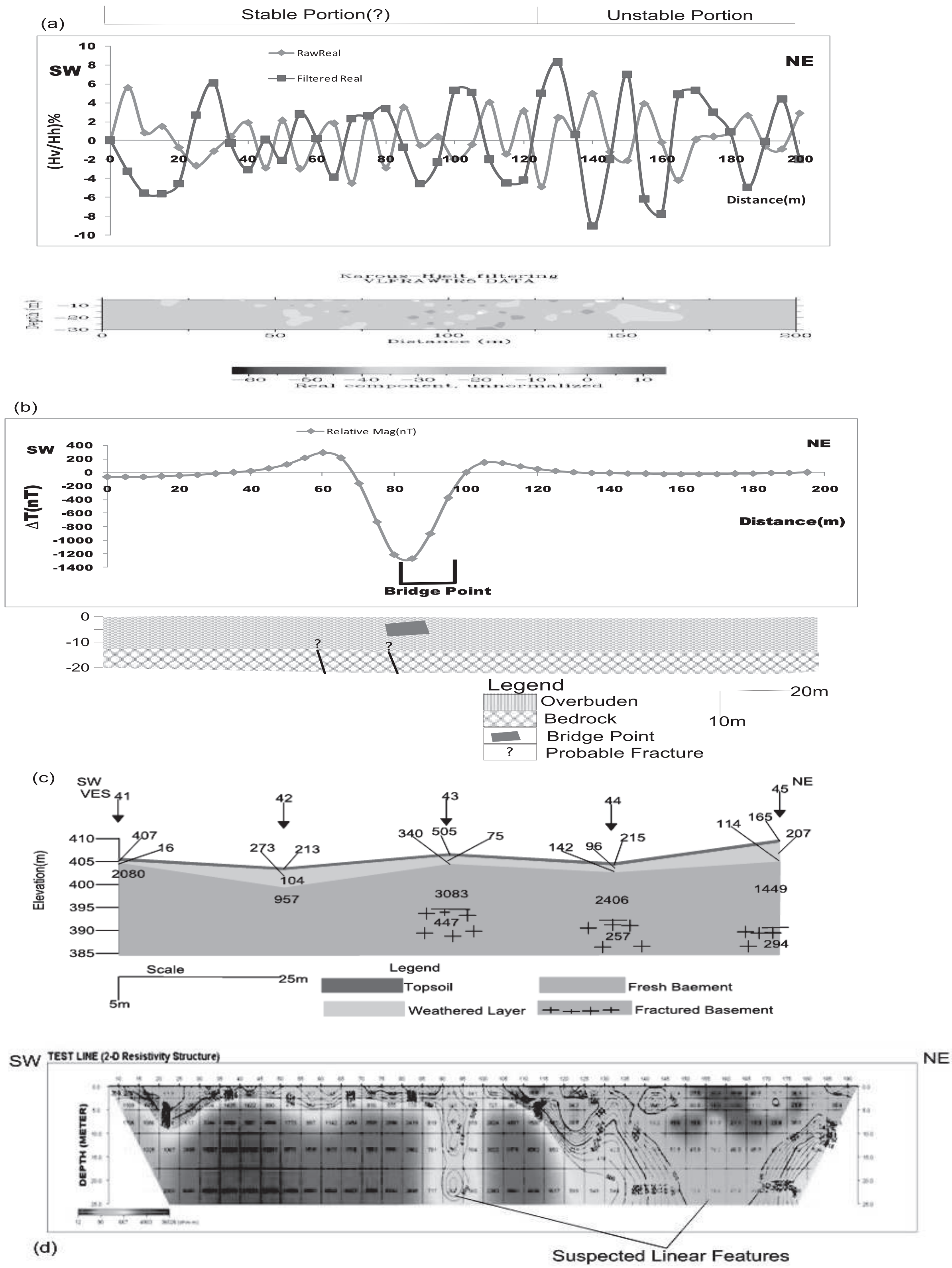

Fig. 11. (a) VLF-EM profile & corresponding section, (b) Magnetic profile & corresponding section, (C) Geoelectric section, and (d) 2-D Resistivity structure along traverse 6 at locality 3

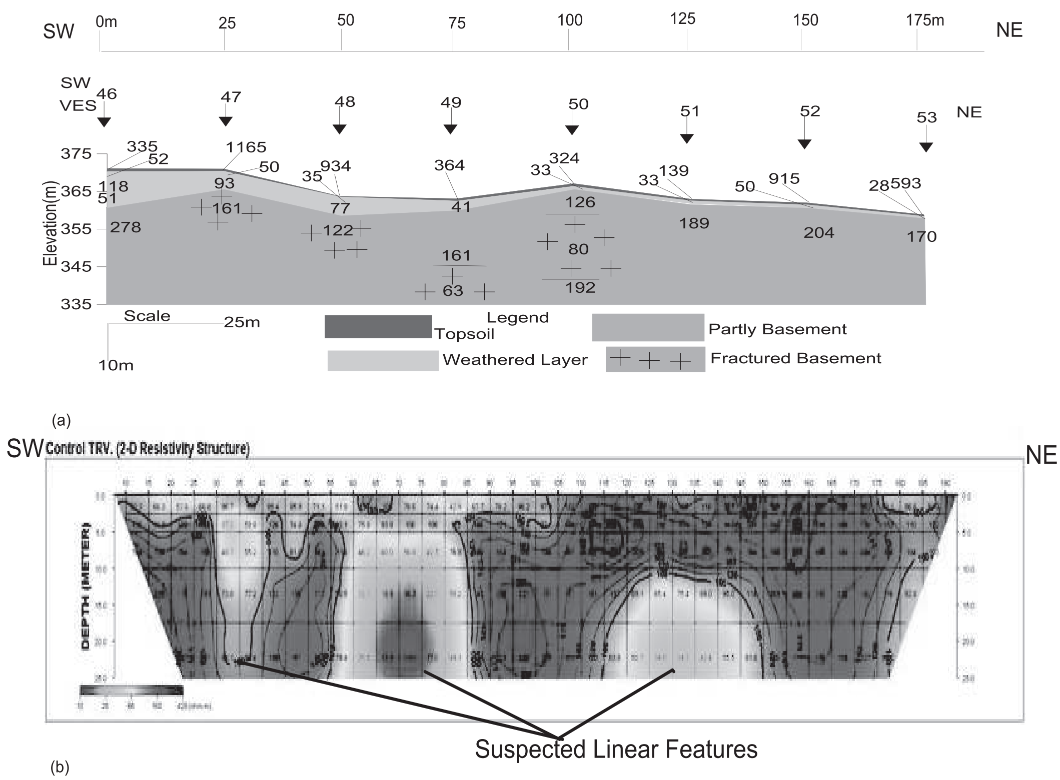

Fig. 12. (a) Geoelectric section and (b) 2-D Resistivity structure along traverse 7 (control traverse) at control locality 4

These observed geological structures have significant width and depth extent and may indicate fractures and fault zones. Though, the road pavement along this traverse is presumed to be stable, however the observation of major fractures/fault zones are very inimical to the integrity of the road pavement foundation at this locality.

5. Findings

The subsoil on which the road pavement is founded in major parts is predominantly clayey in nature with relatively low resistivity values generally less than 150 Ωm. Therefore, the plasticity nature of the clayey soil may cause differential settlement and reduction in the bearing capacity of near surface subsoil under imposed wheel load stress and consequently, the failure of the overlying engineering structure.

The presence of lateral inhomogeneity beneath the road pavement in some parts has also contributed to the pavement failure. An inhomogeneous near surface may result in the differential settlement of the overlying structure under prolonged vehicular traffic and the eventual failure of the engineering structure.

Geological features such as faults, fractures and voids/cavities identified in the major parts of the subsoil on which the road pavement is founded are very inimical to the road foundation integrity. Failure possibly caused by the shallowness of the saturated zone to the road foundation in some parts and elevation changes. Fluctuation in groundwater table may result in elevation changes during the dry and wet seasons. Such an occurrence causes the wetness of the foundation of an engineering structure and consequently, the weakening and instability of the overlying structures.

6. Conclusion

The study reveals that the subsoil on which the pavement is founded is typically clayey. Major geologic structures such as fractures that are inimical to engineering works were also delineated. The typically low resistivity observed near surface in most of the 2-D resistivity image suggest that the water table is at the base of the clay layer and also above the transitions zones.

The pavement in most part of the studied location is bound to fail. This is due to the subgrade of road being on the zone of saturation particularly during the wet seasons, when groundwater table rises. The region delineated as geologically incompetent along this studied highway require engineering reinforcement in order to forestall the further failure and complete collapse of the road pavement in the nearest future particularly at the southwest flank of the road within Ogbomoso area and any other typical basement terrain across the globe. Ditches can be constructed in the saturated zones to increase infiltration capacity. The findings of this study have been able to show the importance of geophysical investigation in complementing geotechnical study at any engineering / construction site cannot be overemphasized. It was able to bring to fore why integrated geophysical investigation is very imperative in bridging the gap between the geoscientist and civil engineers in relation to engineering structure design and construction.

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دراسة جيوفيزيائية متكاملة عن انهيار رصيف على طول طريق النقل المزدوج، جنوب غرب نيجيريا: دراسة حالة

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خلاصة

تم إجراء دراسة جيوفيزيائية متكاملة على بعض أجزاء طريق النقل المزدوج أوغبوموسو – إيلورين Ogbomoso-Ilorin الواقع داخل منطقة المجمعات السفلية the basement complex area في جنوب غرب نيجيريا، بهدف تحديد سبب (أسباب) انهيار الرصيف الذي لوحظ على طول الطريق. وقد تمت دراسة ثلاثة أجزاء منهارة وجزء واحد مستقر من الرصيف داخل الجانب الجنوبي الغربي من الطريق. وقد دمجت هذه الدراسة طرق التنقيب الجيوفيزيائية ذات التردد المنخفض جداً (VLF) والموجات الكهرومغناطيسية (EM)، والمغناطيسية الأرضية والمقاومة الكهربائية (ER) لإجراء دراسة تفصيلية عن التضاريس الأرضية. تم إنشاء حاجزين ذوا تردد منخفض جداً وموجات كهرومغناطيسية ومغناطيسية أرضية للموقع المدروس. وقد تم إجراء ما مجموعه ثلاثة وخمسين (53) سبر جيوكهربائي عمودي (VES) باستخدام ترتيب شلمبرجير. وتم استخدام تصوير المقاومة ثنائي الأبعاد باستخدام ترتيب ثنائي الأقطاب على طول الحواجز. ويشير التفسير النوعي للمقاطع ذات التردد المنخفض جداً والموجات الكهرومغناطيسية والمغناطيسية الأرضية إلى وجود مناطق كسر نموذجية. وأظهرت النتائج التي تم الحصول عليها من السبر الجيوكهربائي العمودي وتصوير المقاومة ثنائي الأبعاد من تحت سطح الأرض السمات الجيولوجية الرئيسية، والتي هي عبارة عن كسور وتصدعات ووصلات وتجاويف وفراغات نموذجية. وفي الغالب تتميز التربة القريبة من سطح الأرض التي يقع عليها رصيف الطريق في الأجزاء المنهارة والمستقرة بمواد منخفضة المقاومة (100 Ωm>) و(Ωm 150<) على التوالي. لذلك، فإن العوامل الجيولوجية المسؤولة عن قابلية الطريق للانهيار هي التربة الطينية تحت سطح رصيف الطريق، وعدم التجانس الجانبي، والبنية الجيولوجية القريبة من السطح والتغيرات في الارتفاعات بسبب التقلبات في المنطقة المشبعة.