Subsurface characterization for foundation valuation of existing engineering structures in basement complex of southwestern Nigeria

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English Summary:

This paper addresses the importance of assessing the structural competence of foundation bedrock in engineering structures such as buildings, bridges, and runways. The stability of these structures depends on the bearing capacity of the underlying soil and bedrock. Geological factors such as weathering, rock deformation, fractures, and faults can affect the foundation's integrity. The paper highlights the use of geoelectrical methods, including very-low-frequency electromagnetic (VLF-EM) and electrical resistivity techniques, to evaluate subsurface materials and detect potential structural defects. The study focuses on the University of Ilorin's campus in Nigeria, a region with a complex geological history. The findings indicate that most of the area has structurally competent bedrock, suitable for the construction of high-rise buildings.

Resumenen Español:

Este artículo explora la importancia de evaluar la competencia estructural del lecho rocoso en proyectos de ingeniería como edificios, puentes y pistas de aterrizaje. La estabilidad de estas estructuras depende de la capacidad de carga del suelo y la roca subyacente. Factores geológicos, como la meteorización, la deformación de la roca, las fracturas y las fallas, pueden comprometer la integridad de la base. El artículo destaca el uso de métodos geoeléctricos, como las técnicas electromagnéticas de muy baja frecuencia (VLF-EM) y la resistividad eléctrica, para evaluar los materiales subterráneos y detectar posibles defectos estructurales. El estudio se llevó a cabo en el campus de la Universidad de Ilorin, Nigeria, una region con una geología compleja. Los resultados indican que el lecho rocoso en la zona es estructuralmente competente, lo que lo hace adecuado para la construcción de edificios de gran altura.

Abstract

The subsurface characterization for foundation evaluation of existing engineering structures aims to investigate the structural competence of selected high-rise buildings on the University of Ilorin campus, located in the basement complex of north-central Nigeria. Very Low Frequency Electromagnetic (VLF–EM) and Vertical Electrical Sounding (VES) techniques were used to explore the subsurface geological sequence.

Twenty-one VLF-EM traverses were established in an E-W orientation, following the prominent NE–SW geological trend. The 32 anomalous zones identified from the filtered EM data were further examined using the Schlumberger VES technique. The EM responses ranged from -40% to 45%, showing alternating positive and negative peaks, which indicate contrasting near surface formations, identified as vadose zones (associated with lateritic clay and/or clayey sand) and water-bearing weathered layers extending to an estimated depth of about 8 meters. The vertical geoelectrical sequence revealed 3 to 5 electrical horizons, comprising topsoil made up of clay lenses, sandy-clay, lateritic hard-pan, and clayey-sand, along with a highly weathered basement and fractured to fresh bedrock. The basement is predominantly weathered and lies at a shallow depth, ranging from 1.0 to 10.6 meters. The overburden is relatively thin, composed of some clay lenses, sandy clay, and a dominant lateritic hard-pan or clayey-sand, which are considered competent subsoils for high-rise buildings. However, thick clay layers in the southern and northern parts of the area could pose a risk to high-rise structures if they extend continuously across other profiles. The predominantly fractured bedrock is also notable for groundwater development, but if seismically active, it could lead to building failures. Overall, the study area has a subsurface sequence and structurally competent bedrock capable of supporting the selected high-rise structures, as evidenced by several traverses and VES points, including Traverses 1 (VES1, VES2, and VES3), 2, 5 (VES7, VES8, and VES9), and 20 (VES30, VES31, and VES32).

Keywords: Electromagnetic response, near–surface formation, structural competency, geoelectrical horizons, high-rise structure

Resumen:

La caracterización del subsuelo para evaluar los cimientos de estructuras de ingeniería existentes tiene como objetivo investigar la competencia estructural de varias torres de gran altura seleccionadas en el campus de la Universidad de Ilorin, ubicada en el Complejo Subterráneo del centro-norte de Nigeria. Para este estudio, se emplearon técnicas de electromagnetismo de muy baja frecuencia (VLF-EM) y sondeos eléctricos verticales (SEV) para analizar la secuencia geológica del subsuelo. Se realizaron veintiún perfiles VLF-EM en dirección este-oeste, alineados con la tendencia geológica predominante NE-SW. Las 32 zonas anómalas identificadas en los datos EM filtrados fueron investigadas a fondo utilizando la técnica SEV de Schlumberger. Los resultados EM muestran respuestas que varían entre -40 % y 45 %, con una serie de picos positivos y negativos alternados. Esto sugiere la presencia de formaciones contrastantes cerca de la superficie, identificadas como zonas vadosas, compuestas por arcilla laterítica y/o arena arcillosa, y capas meteorizadas portadoras de agua que se extienden hasta una profundidad estimada de 8 metros. La secuencia geoeléctrica vertical reveló la existencia de entre 3 y 5 horizontes eléctricos, destacando una capa superior formada por lentes de arcilla, arcilla arenosa, suelo laterítico compacto o arena arcillosa, sobre un basamento altamente meteorizado y roca madre fracturada hasta fresca. El basamento, en su mayoría meteorizado, se encuentra a poca profundidad, variando entre 1.0 y 10.6 metros. La sobrecarga es delgada y está compuesta principalmente por lentes de arcilla y suelo laterítico compacto, considerados como un subsuelo competente para estructuras de gran altura. Sin embargo, las gruesas capas de arcilla en las zonas sur y norte podrían ser problemáticas para estas estructuras si

se extienden en otros perfiles. La presencia de roca madre fracturad a es también relevante para el desarrollo de aguas subterráneas y, si es sísmicamente activa, podría representar un riesgo para los edificios. En general, el área de estudio presenta una secuencia subsuperficial y una roca madre estructuralmente competente, capaz de soportar las estructuras de gran altura seleccionadas. Esto se corrobora en algunos de los perfiles y puntos VES, incluyendo los recorridos 1 (VES1, VES2 y VES3), 2, 5 (VES7, VES8 y VES9), y 20 (VES30, VES31 y VES32).

Palabras clave: Respuestaelectromagnética, formación de superficiecercana, competenciaestructural, horizontes geoeléctricos, estructura de gran altura

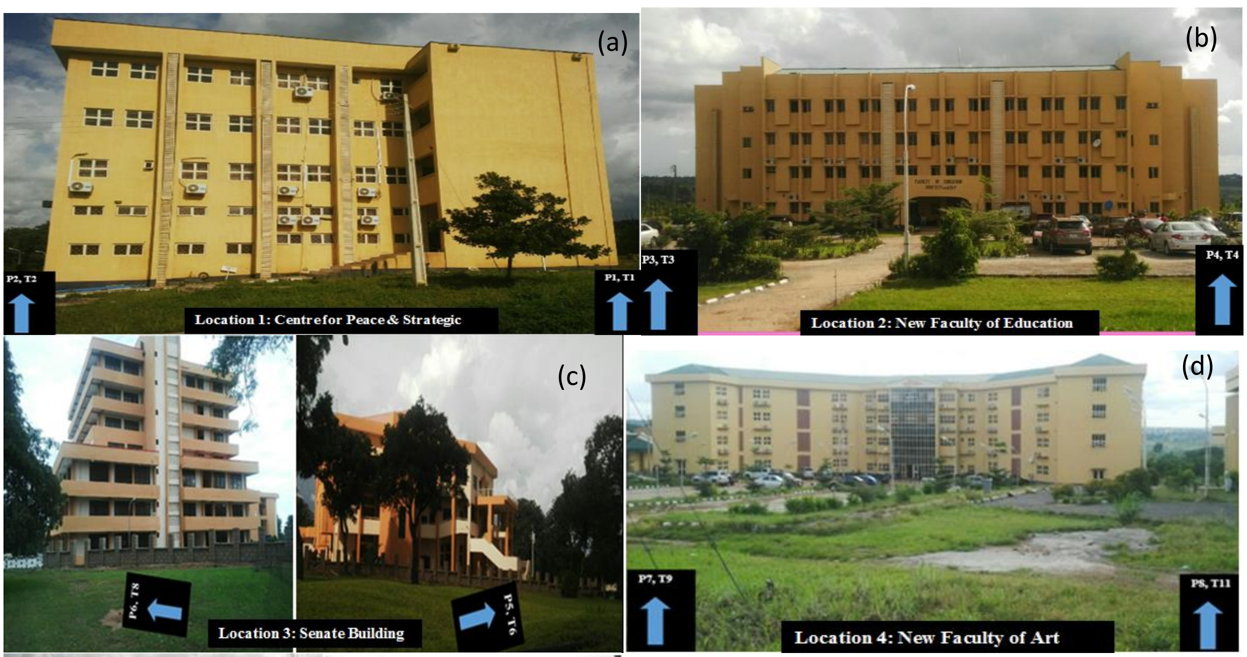
formando el suelo superior subrayado con lentes

1. **Introduction**

Engineering structures such as buildings, bridges, airport runways and roadways are laid directly or indirectly on the ground (Akingboye and Osazuwa 2021; Ademilua et al., 2015; Ademila 2021; Ayodele et al., 2022). As a result, the primary consideration is the bearing capacity of the foundation bed to withhold the load imposed by the overlying structure. Foundation assessment is a significant endeavor in building and engineering structures, since it is responsible for transmitting the weight of the structure to the underlying rock. Deformation or collapse of engineering structures could occur if the soil below does not possess the required geotechnical properties or due to geological factors such as; degree of weathering, rock deformation, fluid saturation, presence of fractures or faults (Olatunde, 2015; Lawrence, 2015; Nwankwoala and Warmate, 2014; Oyedele, 2009; Ademila et al., 2020; Oyedele et al., 2022), presence of sinkholes, cavities and human error (such as inadequate construction materials or inexperienced personnel) and sometimes are occasioned by moisture and temperature influences the engineering properties (bearing capacity, shear resistance, permeability, electrical and thermal conductivity). Structural failure could emanate shortly after construction or on long term basis or never, and it could be accompanied with loss of life or material loss and the cost of repair/reconstruction may be exorbitant (Akinbiyi et al., 2020).

Geoelectrical methods, including very-low-frequency electromagnetic (VLF-EM) and electrical resistivity, are non-invasive geophysical methods used to differentiate subsurface materials based on their electromagnetic properties (Zohdy, 1975; Mousa, 2003; Olasunkanmi et al., 2018; Mohammed et al., 2020; Boyede et al., 2020; Jinguujin and Yokota, 2022; Oyedele et al., 2022). These methods can also reveal deformations like pores, cracks, and joints in rocks, potentially affected by mineral content or fluid saturation, porosity, and water content (Alagbe et al., 2013; Magawata et al., 2020; Ajayi et al., 2022; Olatunji and Fauzan, 2022;). VLF-EMand electrical resistivity traversing techniques are cost-effective and efficient, making them invaluable tools for foundation investigations due to their ability to estimate the electrical properties (resistivity/conductivity) of subsurface rocks, serving as indicators of potential structural defects (McDowell, 1981;Sumonu et al., 2013; Usman, 2019).

The University of Ilorin (Unilorin) has in recent time, received special interventions of the Federal Government of Nigeria for construction of high-rise buildings. The buildings are mostly designed for office spaces and lecture rooms, with long life expectancy. The institution is situated within the Precambrian basement complex of southwest Nigeria, which was characterized by intense deformation, accompanied by faulting and fracturing (Obaje, 2009). However, fractures and faults in foundation bedrock could hinder the integrity of the super structures and mostly leading to building collapse or subsidence (Alagbe, et al, 2013; Boyede et al., 2020). This study is conceptualized at investigating the structural competence of the underlining bedrock of the Six-storey Senate building, Faculty of Education building, Faculty of Art building, Centre for Peace and Strategic building and Faculty of Communication building (Figure 1) using electromagnetic and electrical resistivity methods to avoid the accompanying disaster of building failure, its significant to identify potential hazards prior to begin the construction (Mohammed et al., 2020; Oyedele et al., 2022; Alao, et al., 2023).



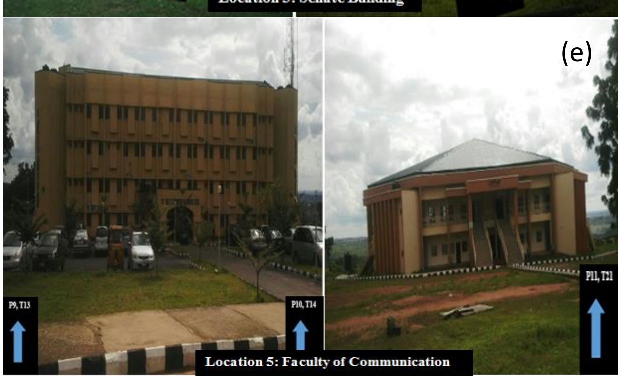


Figure 1: Study locations, showing the high-rise buildings (a) Centre for Peace and Strategic building(b) Faculty of Education building(c) Senate building (d) Faculty of Art buildingand; (e) Faculty of Communication building

2. Geology of the Area

Ilorin is underlain by the Precambrian to Cambrian basement complex rocks represented basically by migmatite-gneiss, and granitic gneiss and metasediments such as quartzites (Figure 2). The university of Ilorin campus, which lies entirely within the basement rocks in the Western part of Central Nigeria, falls within the eastern part of Ilorin town. The study area is a semi-arid region of Nigeria with vegetation mainly of the guinea savannah type with shrubs and undergrowth. Rugged troughs and crests due to erosions characterize the topography of the area; In contrast, the eastern part features granite rock suites that were emplaced in the northeast-southwest direction, exhibiting steeper dips ranging from 70° to 90° towards the east. Geologically, the area appears to have undergone isoclinal folding, forming a south-plunging anticlinal structure with a notably steep eastern limb (Raji and Bale, 2008).These geological details provide valuable context for understanding the subsurface conditions in the study area, which is essential for any construction project to ensure the stability and integrity of buildings and infrastructure.

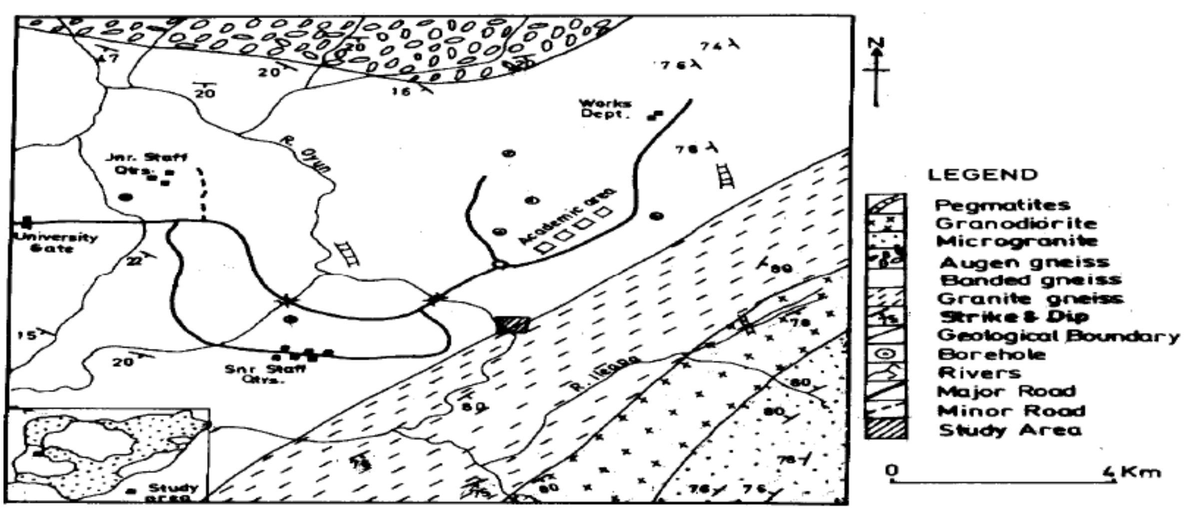


Figure 2 Geologic map of University of Ilorin (After Raji and Bale, 2008).

3. Materials and Methods

3.1. Geophysical Investigation Methods:

To investigate the lithologic settings and geologic structural disposition of the earth material beneath the selected existing buildings within University of Ilorin, very-low-frequency electromagnetic (VLF-EM) and vertical electrical sounding (VES) geo-electrical resistivity techniques were employed. VLF-EMis an inductive exploration technique that is suitable in mapping shallow subsurface features in which the primary EM waves induces current flow (ABEM, 1990), while VES is suitable in investigating the changes of the electrical properties of subsurface features with depth and horizontal layer contacts; which has been comprehensively discussed by Methiez and Huot (Methiez and Huot, 1966).

A total of 21 electromagnetic traverses were established in E-W orientation (Figure 3), across the prominent geologic trend NE-SW, using ABEM WADI VLF-EM equipment. This equipment harnesses radio signals transmitted from worldwide transmitters at frequency range between 15 and 30 kHz to acquire the amplitude of real (in-phase) and quadrature (out-of-phase) components of the electromagnetic wave (for induced current) in the conducting earth material of the area, at an interval of 6 m. The length of each of the first 5 traverses is 192 m, while the remaining traverses vary in size with respective to the available space within the built-up areas. The VLF-EM Data Processing involve Universal Traverse Mercator (UTM) coordinate converter software was used to convert the GPS data, recorded in degree-minutes, to kilometer. This is based on the relationship of degrees equivalent in kilometers.The VLF field data were filtered using Fraser Filtering method. Fraser (1989) suggested a simple numerical technique aimed at eliminating erroneous interpretation of very low frequency (VLF) data caused by large geological noise component generated from the transmitted frequency. According to Fraser (1989), this filtering method improves the resolution of the anomalies and eases their recognition.The interpretation of VLF data involves analyzing the amplitude and phase variations recorded by the receiver. Conductive and resistive features in the subsurface manifest as anomalies in the VLF data, the conductive anomalies typically appear as amplitude highs or lows, while resistive anomalies can affect both amplitude and phase. The interpretation process involves correlating anomalies with known geological features or subsurface structures. Interpretation may be aided by integrating VLF data with other geophysical data or geological information. Anomalies may indicate the presence of faults, fractures, mineral deposits, or groundwater zones. Interpreted VLF data is often presented in the form of maps or profiles, showing the distribution of anomalies across the survey area.

The theoretical vertical resolution of Very Low Frequency (VLF) data within the frequency range of 15 to 30 kHz depends on various factors such as the sampling rate, signal-to-noise ratio, and the characteristics of the measurement system. In general, the vertical resolution can be determined by the Nyquist theorem, which states that the highest frequency that can be accurately represented is half the sampling frequency. Therefore, if you have a sampling frequency fs, the theoretical maximum frequency resolution (vertical resolution) would be $\frac{Fs}{2}$

For VLF data with frequencies ranging between 15 and 30 kHz, a common sampling rate might be around 100 kHz or higher to adequately capture the signal. So, using the Nyquist theorem, the theoretical vertical resolution would be around $\frac{100khz}{2}$ = 50 kHz.

However, this is a simplified theoretical estimation. In practice, the actual vertical resolution can be affected by noise, signal processing techniques, and other factors specific to the measurement setup. The field strength and the phase displacement around the resistive-conductive-water saturated- fractured zone along each profile were presented as raw and filtered data. The data were inverted into a two dimensional (2-D) section using the Fraser filtering method (Fraser, 1990). The Fraser filtering method can improve the resolution of anomalies in VLF data by enhancing the signal-to-noise ratio and highlighting subtle variations associated with geological features. The Fraser filtering method is a technique used in the analysis of Very Low Frequency (VLF) data, which is a type of electromagnetic survey method commonly employed in geophysical exploration. VLF surveys utilize the natural electromagnetic fields generated by lightning strikes and other atmospheric phenomena, which propagate through the Earth's ionosphere and interact with subsurface geological structures. By measuring variations in these electromagnetic fields at specific frequencies, geophysicists can infer information about the composition and structure of the subsurface.

The Fraser filtering method is named after the geophysicist William Fraser, who developed the technique. It is primarily used to enhance the signal-to-noise ratio and identify subtle anomalies in VLF data associated with geological features of interest, such as mineral deposits, faults, or hydrocarbon reservoir. Here's how it can contribute to improved resolution:

3.1.1 Noise Reduction

VLF data often contains background noise from various sources, such as electromagnetic interference and environmental factors. By applying the Fraser filtering method, which selectively attenuates frequencies outside the desired range, the noise can be effectively suppressed. This reduction in noise enhances the clarity of the signal, making it easier to identify and interpret anomalies with higher resolution.

3.1.2 Anomaly Enhancement

The band-pass filter used in the Fraser filtering method targets specific frequencies associated with geological anomalies of interest. By amplifying these frequencies while attenuating others, the method enhances the visibility of anomalies in the VLF data. This enhancement allows geophysicists to discern subtle variations in electromagnetic signals that may correspond to geological structures or mineralization, thereby improving resolution.

3.1.3 Localization of Anomalies

The filtering process can help localize anomalies within the VLF data, providing clearer delineation of their spatial extent and boundaries. This localization contributes to improved resolution by precisely defining the locations of geological features or mineral deposits, allowing for more accurate interpretation and targeting in subsequent exploration activities.

3.2. Vertical Electrical Sounding (VES)

To further investigate the geological features thirty two (32) anomalous (weak) zones of the filtered electromagnetic data were vertically probed using the Schlumberger array geoelectrical technique. The process involved multiplying the resistance 'R' values obtained from the resistivity meter by the equivalent geometric factor 'Gs' (Equation 1). This calculation converted the resistance values into apparent resistivity (ρa) for different lithological units beneath the study area. Maximum electrode spacing of 200 meters (AB) to estimate depth ranges. The sounding curves for each point were manually plotted, with apparent resistivity (ρa) on the ordinate and half current-electrode spacing (AB/2) on bilogarithmic coordinates and a preliminary interpretation of each VES curve. These curves were then correlated with master and auxiliary curves, which provided gradient apparent resistivity and layer parameters. Finally, Winrest computer modeling software (Zohdy, 1973; 1975; 1989) was utilized to automate the layer parameters, allowing us to construct 2D geo-electric sequences at various depths. The interpretation of the VES results was used for producing the geoelctric sections. These geophysical techniques provide valuable insights into the subsurface geology and help in assessing the foundation conditions beneath the selected buildings at the University of Ilorin.

$$Rhoa = k^{*}\Delta U/I \qquad 1$$

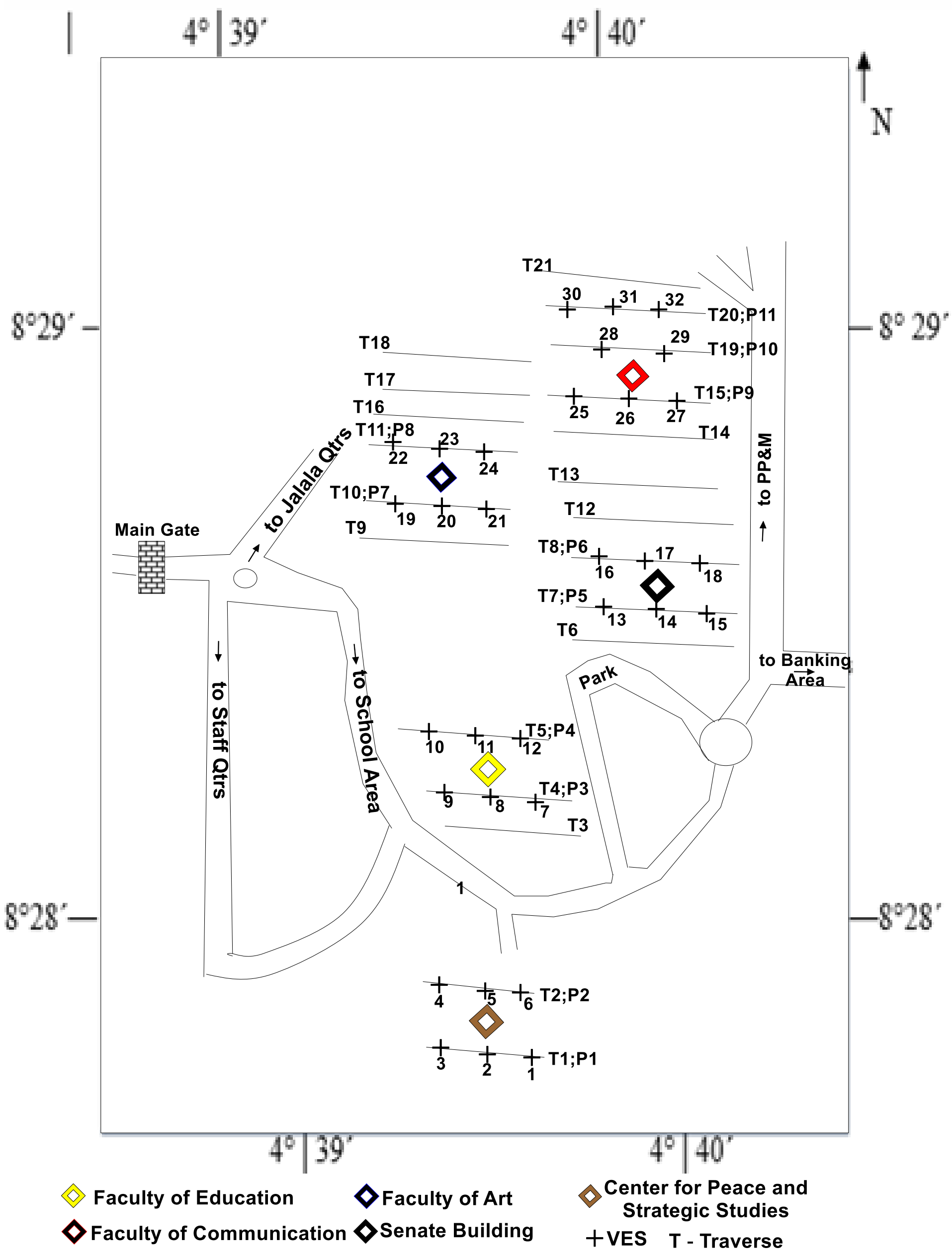


Figure 3 Location base map; showing the study sites, VLF-EM traverses and VES points.

4. Results and Discussion

High positive values in the data indicate the presence of conductive subsurface structures, whereas low or negative values suggest the presence of resistive formations

(Sharma and Baranwal, 2005). The electromagnetic signal strength measured is referred to as the response. The VLF-EM data results are presented as filtered real signal plots and inverted 2-D maps. Similarly, the data from electrical resistivity surveys are presented as sounding curves and geoelectric sections. The VLF results demonstrate both horizontal and vertical variations in subsurface conductivity across traverses (1-21), as shown in (Figure 4.1 to 4.11).

4.1. Vertical electrical sounding VES

The Vertical Electrical Sounding (VES) method acts as a follow-up or complementary process to the Very Low Frequency Electromagnetic (VLF-EM) technique. The depth sounding curves obtained from VES data are categorized into five main geoelectric characteristics resistivity sounding curves: A, H, HA, KH, and HKHfor 32 VES curves and layering parameter range (Table 1-5). These curve types represent different geoelectric layers encountered along the 21 traverses. The dominant curve type is KH, constituting 41% of the total, followed by HKH at 28%, H at 19%, and HA and A types each constituting 6% respectively (Figure 5).

4.2 Geophysical methods Inversion model and geoelectric section

4.2.1 Inversion Model for the 2D Pseudo Section (Traverse T1-T2) and the 2D Geoelectric Section

The inversion model for the 2D pseudo sections (Figure 4.1a) and the 2D geoelectric section (Figure 4.1b) reveals key subsurface features over a 160-meter East-West stretch. The pseudosections show a negative EM conductivity response at 60 meters depth, a conductive zone between 56-62 meters, and negative responses at 40-50 meters and 65-80 meters. The geoelectric section identifies four layers: high-resistivity topsoil, lateritic clay beneath VES 3, sandy clay beneath VES 2, and weathered basement.The high resistivity in the topsoil indicates a solid foundation suitable for construction. The conductive zones in the pseudosections might suggest water-bearing formations, important for groundwater management. However, the variations in conductivity are unlikely to pose significant threats to engineering structures.

The lateritic clay and sandy clay, with their respective resistivity values and thicknesses, also provide insights into the subsurface stability. Specifically, the sandy clay beneath VES 2, while thick, is not considered hazardous for civil engineering structures, thus indicating safe construction conditions. Regarding groundwater implications, the conductive zones identified in the pseudosections could suggest areas with higher moisture content, potentially indicating aquifers or water-bearing formations. The variation in conductivity and resistivity helps in identifying these zones, which could be crucial for groundwater exploration.

4.2.2 Inversion Model for the 2D Pseudo Section (Traverse T3-T4) and the 2D Geoelectric Section

The interpretation of the geophysical data combines the inversion models of VLF-EM pseudosections (Figures 4.2a) with the 2D geoelectric section (Figure 4.2b) to understand subsurface conditions and address the equivalence problem. For traverse T1-T2, the VLF-EM pseudosection reveals significant negative EM conductivity response zones (~15% at 60m depth), a positive response zone (56-62m depth), and additional negative response zones (40-50m and 65-80m depth), indicating potential inflection points. The corresponding geoelectric section identifies four subsurface layers: topsoil, lateritic clay, sandy clay, and weathered basement. High resistivity in the topsoil suggests a competent ground for foundations, while lateritic clay under VES 3 shows high resistivity (644 ohm-m), and sandy clay under VES 2, with low resistivity (49-79 ohm-m), suggests thicker deposits but no hazard to engineering structures. For traverse T3-T4, the VLF-EM pseudosection shows positive and negative anomalies, indicating subsurface conductivity variations, while the geoelectric section reveals layers similar to T1-T2: topsoil, lateritic clay, sandy clay, weathered basement, and fractured bedrock. Significant resistivity variations are observed (e.g., topsoil resistivity at 742 ohm-m under VES 6 and sandy clay at 33 ohm-m under VES 4). The presence of fractured bedrock and weathered basement indicates potential for groundwater storage and flow. The high resistivity in the topsoil across traverses indicates stable foundation material, and sandy clay layers with relatively low resistivity are not considered hazardous for construction if mechanical properties are stable. The fractured bedrock zones suggest potential settlement issues if not accounted for in designs. The presence of weathered basement and fractured bedrock suggests zones that could serve as groundwater reservoirs, with variations in conductivity and resistivity indicating heterogeneous aquifer properties.

4.2.3 Inversion Model for the 2D Pseudo Section (Traverse T5-T6) and the 2D Geoelectric Section

In the VLF-EM inversion model sections (Figure 4.3a), we observe variations in the real component along traverse five and six. The Karous-Hjelt filtering of traverse five shows conductive zones at depths between 20-40 meters and 60-80 meters, while traverse six reveals more prominent conductivity anomalies between 40-60 meters and 80-100 meters. These variations indicate potential subsurface heterogeneities, which could be related to changes in lithology or the presence of fluid-filled fractures. The geoelectric section (Figure 4.3b) provides a detailed stratigraphic profile, revealing four distinct subsurface layers: topsoil, lateritic clay/clayey sand, weathered basement, and fresh bedrock. The resistivity values in the topsoil are relatively high (122 ohm-m), suggesting a competent subsurface suitable for engineering structures. Beneath this layer, lateritic clay/clayey sand with resistivity values ranging from 102 to 133 ohm-m indicates moderate conductivity, possibly due to the presence of clay minerals and moisture.The weathered basement and fresh bedrock exhibit significantly higher resistivity values ranging from (429 to 772 ohm-m), indicating more competent and less conductive materials. The presence of these layers suggests a stable foundation for engineering purposes. The identified conductive zones in the pseudosections correspond to variations in the geoelectric layers, providing a comprehensive understanding of the subsurface structure. This integrated approach helps address the equivalence problem, ensuring more accurate interpretations of subsurface conditions.

4.2.4 Inversion Model for the 2D Pseudo Section (Traverse T7-T8) and the 2D Geoelectric Section

The VLF-EM inversion model sections for traverse T7-T8 (Figures 4.4a) and the 2D geoelectric section (Figure 4.4b) reveal key subsurface features. These two traverses cover a total length of 320 meters in the East-West direction. In traverse 7, two relatively positive conductive zones are identified at depths of 26-60 meters and 100-110 meters. The pseudosections show variations in electromagnetic responses across distance and depth, indicating differences in conductivity.Similarly, in traverse 8, a prominent positive conductive zone is noticed at depths of 85-120 meters, with an (EM) response of about 40% at distances of 130-160 meters. The geoelectric section identifies several subsurface layers: topsoil, lateritic clay/clayey sand, weathered basement, fractured bedrock, and fresh bedrock. High resistivity in the topsoil and lateritic clay layers suggests a robust subsurface suitable for construction. Weathered basement and fractured bedrock layers indicate potential zones for groundwater flow. The negative responses in the pseudosections suggest low conductivity areas, possibly due to non-conductive materials or voids. Positive responses indicate high conductivity zones, likely due to clay-rich or water-saturated layers.

4.2.5 Inversion Model for the 2D Pseudo Section (Traverse T9-T10) and the 2D Geoelectric section

Figures 4.5a display VLF-EM inversion model sections for traverses T9 and T10 with their corresponding 2D conductivity structures, while Figure 4.5b shows the combined 2D geoelectric section. The VLF-EM inversion models (Figures 4.5a) reveal variations in conductivity, highlighting potential subsurface features such as zones of increased conductivity which may indicate fractures or areas with higher moisture content. The depth and width of these anomalies vary across the profiles, suggesting a heterogeneous subsurface. In the 2D geoelectric section (Figure 4.5b), the subsurface layers are characterized by their resistivity values. The topsoil is relatively conductive, followed by layers of lateritic clay/clayey sand and clay, with resistivity values indicating a gradual increase in depth. The weathered basement and fractured bedrock show significant resistivity contrasts, providing insight into the subsurface geological structures.The presence of lateritic clay beneath the subsurface with resistivity values ranging from 431 to 1354 ohm-m may prevent the infiltration of surface water to the weathered basement, as depicted in the geoelectric section (Figure 4.5b).

The integration of VLF-EM inversion models with 2D geoelectric sections enhances the reliability of subsurface interpretation. The combined approach allows for the accurate identification of features such as fracture zones and variations in lithology, which are crucial for groundwater exploration and engineering projects.

4.2.6 Inversion Model for the 2D Pseudo Section (Traverse T11-T12) and the 2D Geoelectric Section

Figures 4.6a and 4.6b present VLF-EM inversion model sections and 2D geoelectric sections for traverses T9-T10 and T11-T12, respectively. In traverse T9, significant conductive anomalies are observed at shallow depths (0-10 meters) with negative real component values around 20-30 meters and 70-80 meters, corresponding to high conductivity zones. Traverse T10 shows a prominent conductive feature around 30-40 meters. The geoelectric section (Figure 4.6b) indicates topsoil with resistivity values of 125-216 Ωm, lateritic clay/clayey sand layers with 178-487 Ωm, weathered basement at 70 Ωm, and fresh bedrock with 487-503 Ωm. Traverse T11 exhibits alternating conductive and resistive zones with negative real component anomalies around 20-30 meters and 70-80 meters, while traverse T12 shows significant conductive features at 20-40 meters and 100-120 meters. The geoelectric section for T11-T12 (Figure 4.6b) reveals topsoil at 220 Ωm, clay at 191 Ωm, lateritic clay/clayey sand at 21-60 Ωm, weathered basement at 27-267 Ωm, and fractured bedrock at 714 Ωm. The negative real component values in VLF-EM sections align with low resistivity zones in geoelectric sections, confirming the presence of conductive materials such as clay and weathered basement, while positive values correlate with resistive materials like lateritic clay, clayey sand, and fresh bedrock. These comparisons validate the use of VLF-EM inversion and 2D geoelectric sections for detailed subsurface geological interpretation, providing consistent results for identifying conductive and resistive layers.

4.2.7 Inversion Model for the 2D Pseudo Section (Traverse T13-T14) and the 2D Geoelectric Section

Figures 4.7a and 4.7b show the VLF-EM inversion model sections for traverse T13-T14 and the corresponding 2D conductivity structures, respectively. The real component responses in Figures 4.7a indicate variations in subsurface conductivity, with notable high and low anomalies. The Karous-Hjelt filtering results in Figure 4.7b highlight regions of differing conductivity at various depths, with red indicating higher conductivity and blue indicating lower conductivity. These findings align with the 2D geoelectric section, which reveals a topsoil layer with resistivity values of around 36 ohm-m, followed by a clay layer with resistivities ranging from 26 to 50 ohm-m, and weathered basement layers with resistivity values up to 644 ohm-m. The integration of VLF-EM and geoelectric data provides a comprehensive understanding of the subsurface structure, confirming the presence of conductive and resistive zones.

4.2.8 Inversion Model for the 2D Pseudo Section (Traverse T15-T16) and the 2D Geoelectric Section

The interpretation of Figure 4.8a and 4.8b reveals significant geoelectric sections and 2D conductivity structures for traverses T15 and T16. The VLF-EM inversion model sections illustrate variations in resistivity values along the traverses. For example, in traverse T15 (Figure 4.8a), there is a notable resistivity low around 40 meters distance, indicating a possible conductive zone. The corresponding 2D pseudosection (Figure 4.8b) highlights this zone with warmer colors, suggesting a conductive feature at a shallow depth. Similarly, traverse T16 shows multiple resistivity anomalies, with significant lows around 50 and 100 meters. The pseudosection supports these findings, showing areas of high conductivity at these locations. The geoelectric section beneath these pseudosections reveals a complex subsurface structure with distinct layers, including lateritic clay, clayey sand, weathered basement, and fresh bedrock. Notably, resistivity values in the weathered basement range between 10 and 60 Ωm, correlating with the conductive zones in the pseudosections. This comparison highlights the consistency between the resistivity values from the geoelectric section and the 2D pseudosection, providing a comprehensive understanding of the subsurface conditions in the study area.

4.2.9 Inversion Model for the 2D Pseudo Section (Traverse T17-T18) and the 2D Geoelectric Section

Figures 4.9a exhibit the plot, pseudo section, and the inverted 2D conductivity structure beneath the subsurface of traverse 17 and traverse 18, spanning a total length of 400 meters in the East-West direction. In traverse 17, some prominent positive conductive responses are observed at distances of 30 meters, 80 meters, and 140 meters, while minor responses are identified at certain points (Figure 4.9a). Traverse 18 displays a conductive response at depths of 20 meters, 180 meters, and 120-145 meters. Additionally, the presence of non-material is noticed sporadically, with major occurrences at distances of 40 meters, 60 meters, 120 meters, and 160 meters in traverse 18. The geoelectric section along the two traverses reveals four geoelectric layers: topsoil, lateritic clay, weathered basement, and fracture bedrock. These layers exhibit relatively high resistivity values, indicating that the subsurface beneath these structures is competent to hold engineering structures (Figure 4.9b).

4.2.10 Inversion Model for the 2D Pseudo Section (Traverse T19-T20) and the 2D geoelectric section

Figure 4.10a displays the plot, pseudo section, and the inverted 2D conductivity structure beneath the subsurface of traverse 29 and traverse 18. The traverse covers a total length of 200 meters in the East-West direction. Positive (EM) conductive responses are observed in this model, particularly at a depth of 20 meters, at the surface of the profile. However, some negative responses may indicate void or empty spaces beneath the surface of the profile. The geoelectric section of the profile reveals four geoelectric layers with high resistivity values, especially within the topsoil and lateritic layer (Figure 4.10b). The presence of a weathered basement beneath the profile with low resistivity indicates an unstable foundation due to contrasting moisture levels with upper layers. This can lead to differential settling, causing structural damage like cracks in walls and foundations.

4.2.11 Inversion Model for the 2D Pseudo Section (Traverse T21) and the 2D geoelectric section

Traverse 20 and 21, depicted in Figures 4.11a, respectively, span a total length of 360 meters and run along the East-West direction. In Traverse 20 (Figure 4.11a). However, the presence of a relatively low/negative (EM) response is identified at the surface of the traverse, indicating that the profile is competent without posing any threat to engineering structures beneath the subsurface. Also the presence of fresh bedrock within the profile with extremely high resistivity provides stable and strong foundations for engineering structures, with limited water seepage and high load-bearing capacity (Figure 4.11b). However, excavation through such bedrock may pose challenges during construction. However, Traverse 21 reveals highly conductive responses at distances ranging from about 20 meters to 35 meters, with a significant response observed at a distance of 100 meters, which may indicate a buried pipe, cavity or sinkhole.

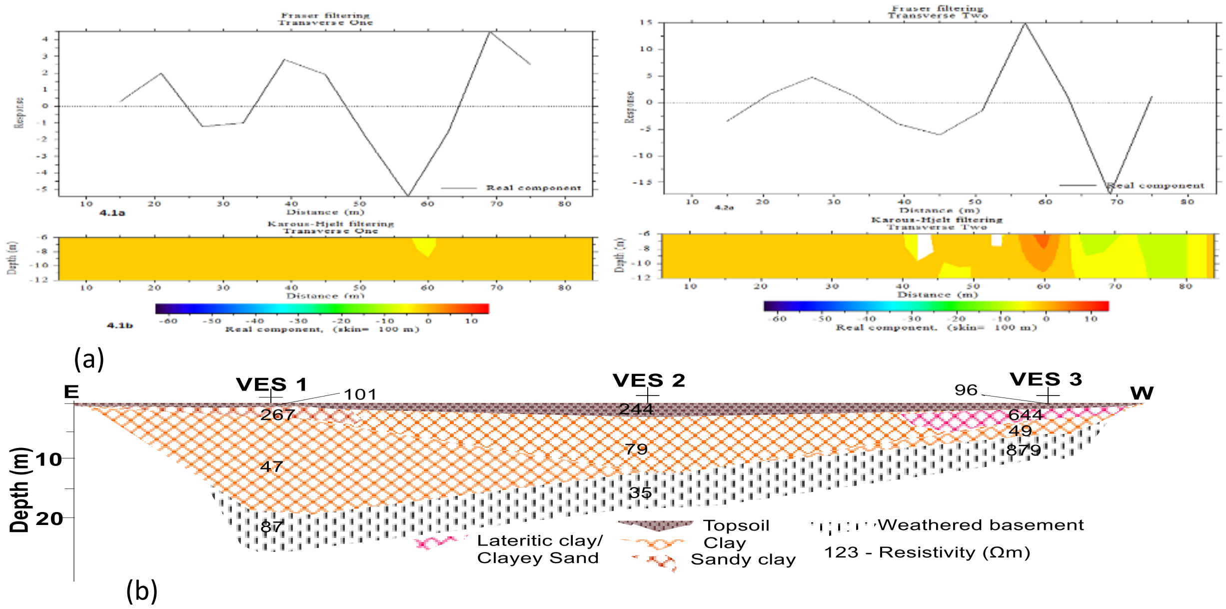


Figure 4.1 a) VLF-EM inversion model sections for traverse T1-T2 with 2D conductivity structure (b) Geoelectric section

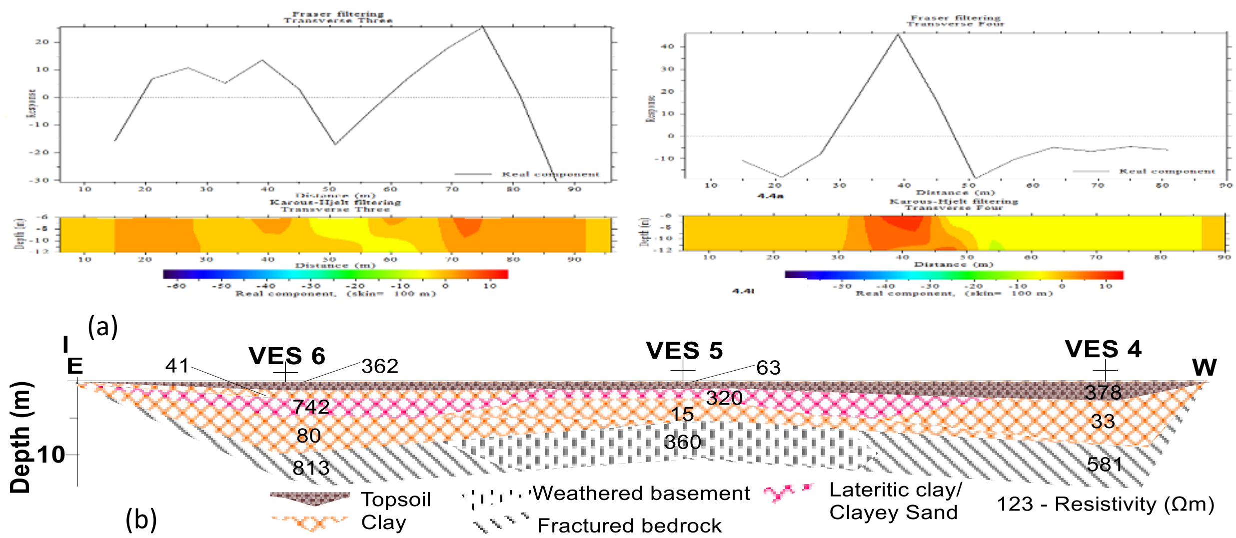


Figure 4.2 a) VLF-EM inversion model sections for traverse T3-T4 with 2D conductivity structure (b) Geoelectric section

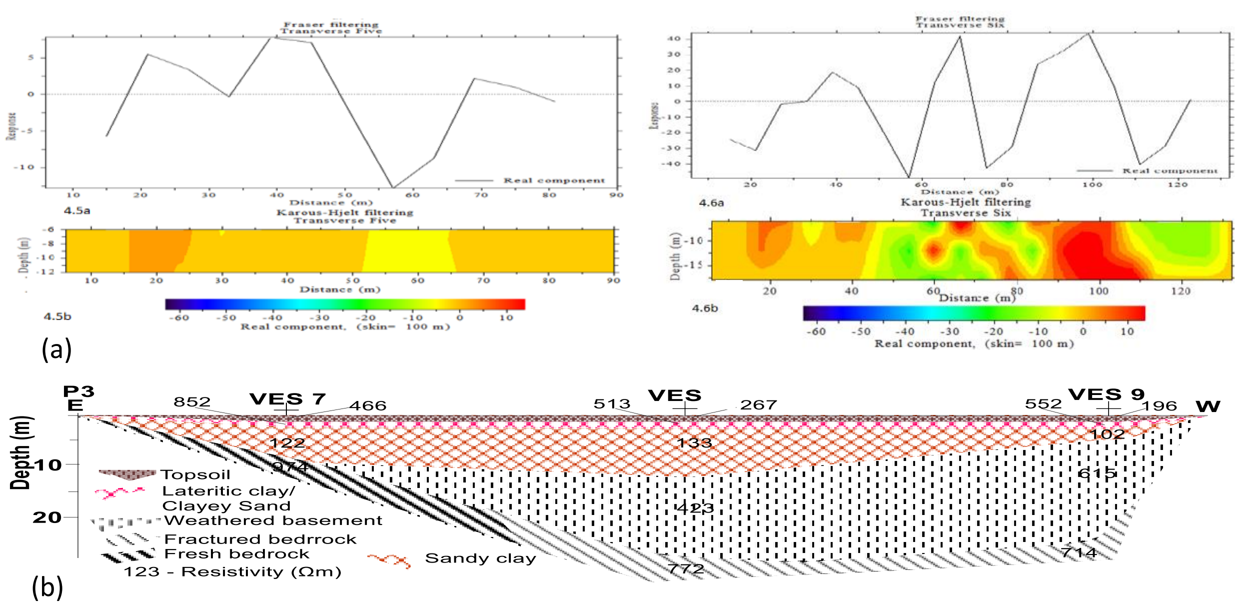


Figure 4.3 a) VLF-EM inversion model sections for traverse T5-T6 with 2D conductivity structure (b) Geoelectric section

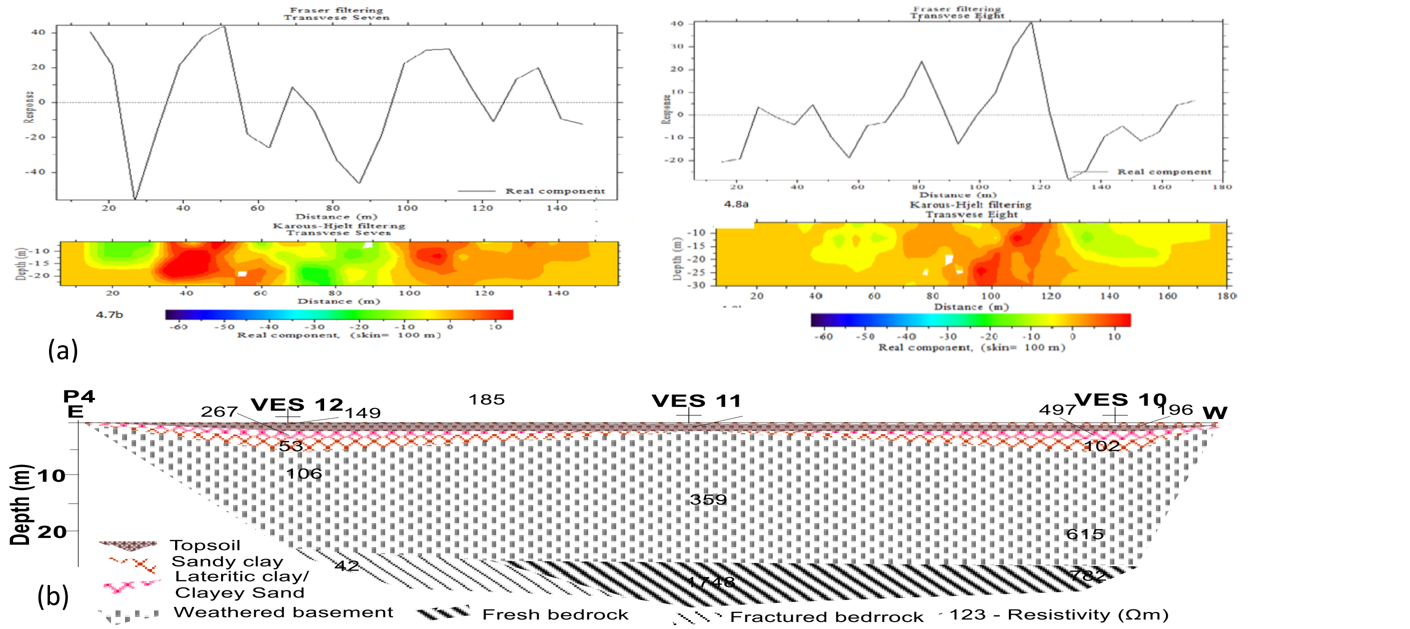


Figure 4.4 a) VLF-EM inversion model sections for traverse T7-T8 with 2D conductivity structure (b) Geoelectric section

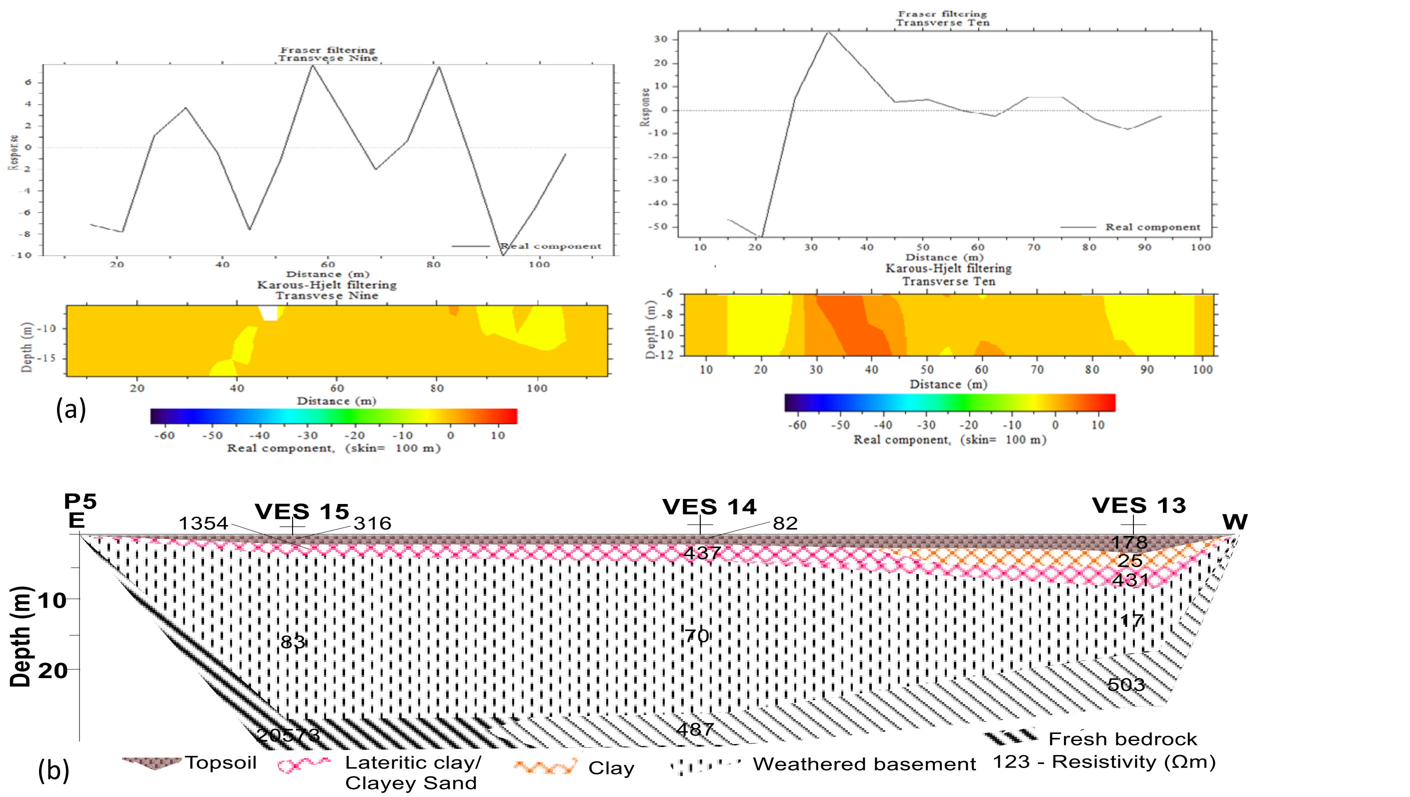


Figure 4.5 a) VLF-EM inversion model sections for traverse T9-T10 with 2D conductivity structure (b) Geoelectric section

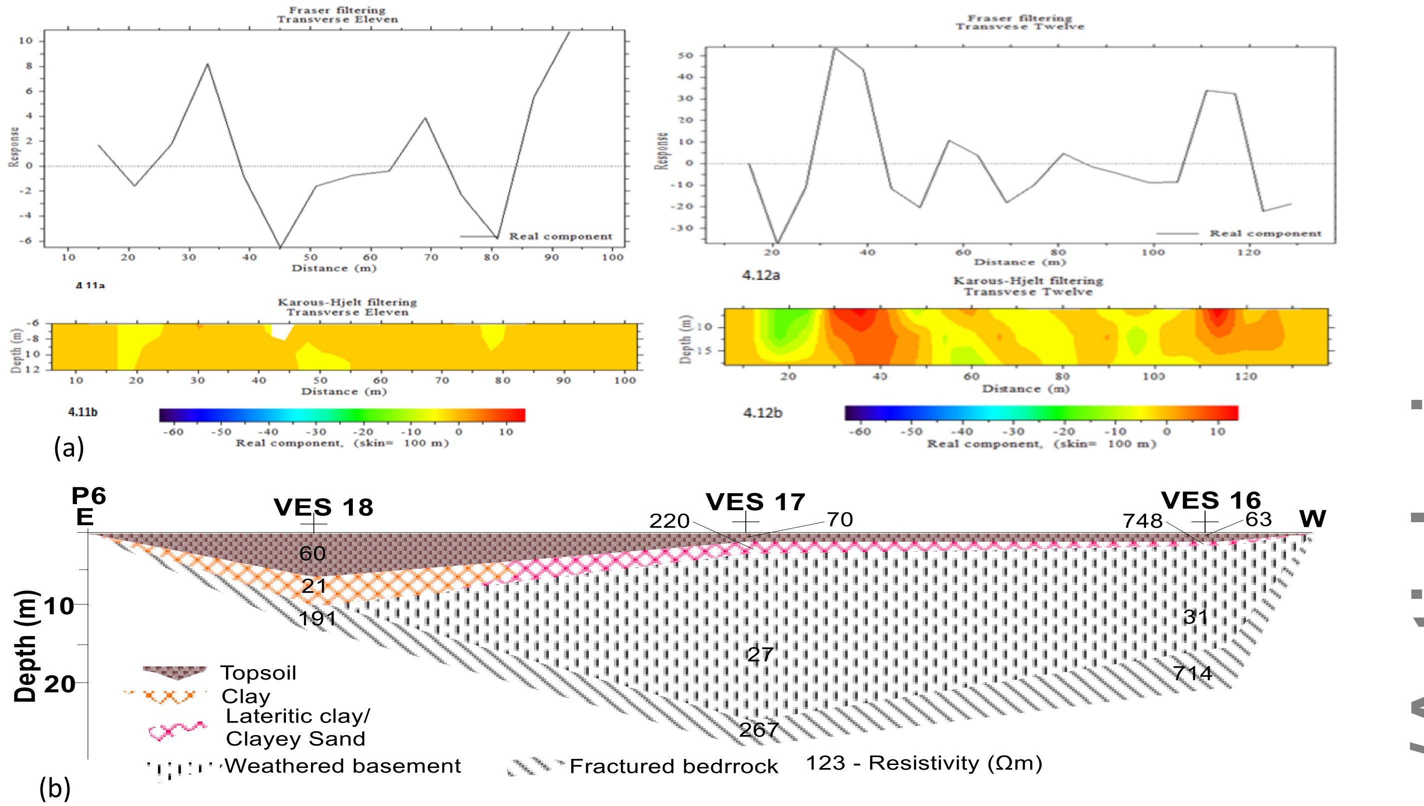


Figure 4.6a) VLF-EM inversion model sections for traverse T11-T12 with 2D conductivity structure (b) Geoelectric section

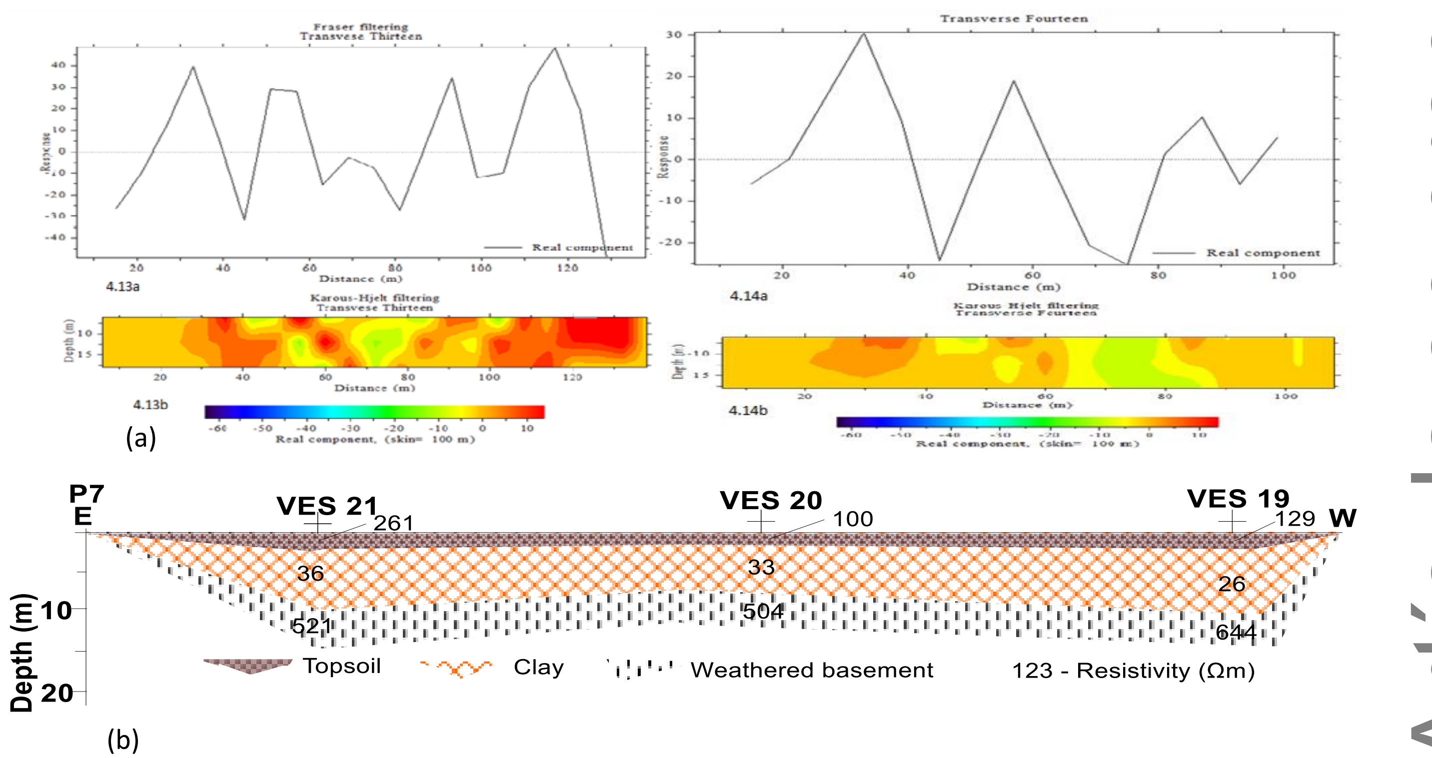


Figure 4.7 a) VLF-EM inversion model sections for traverse T13-T14 with 2D conductivity structure (b) Geoelectric section

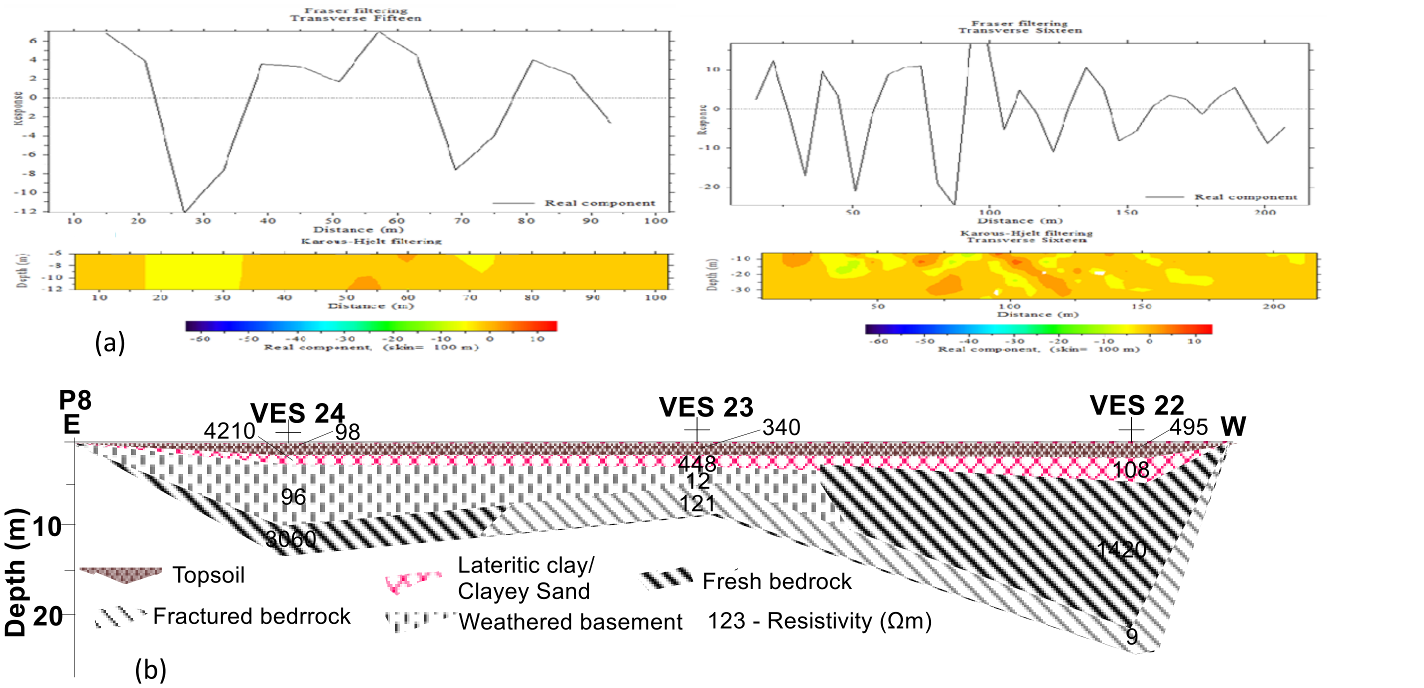


Figure 4.8 a) VLF-EM inversion model sections for traverseT15-T16 with 2D conductivity structure (b) Geoelectric section

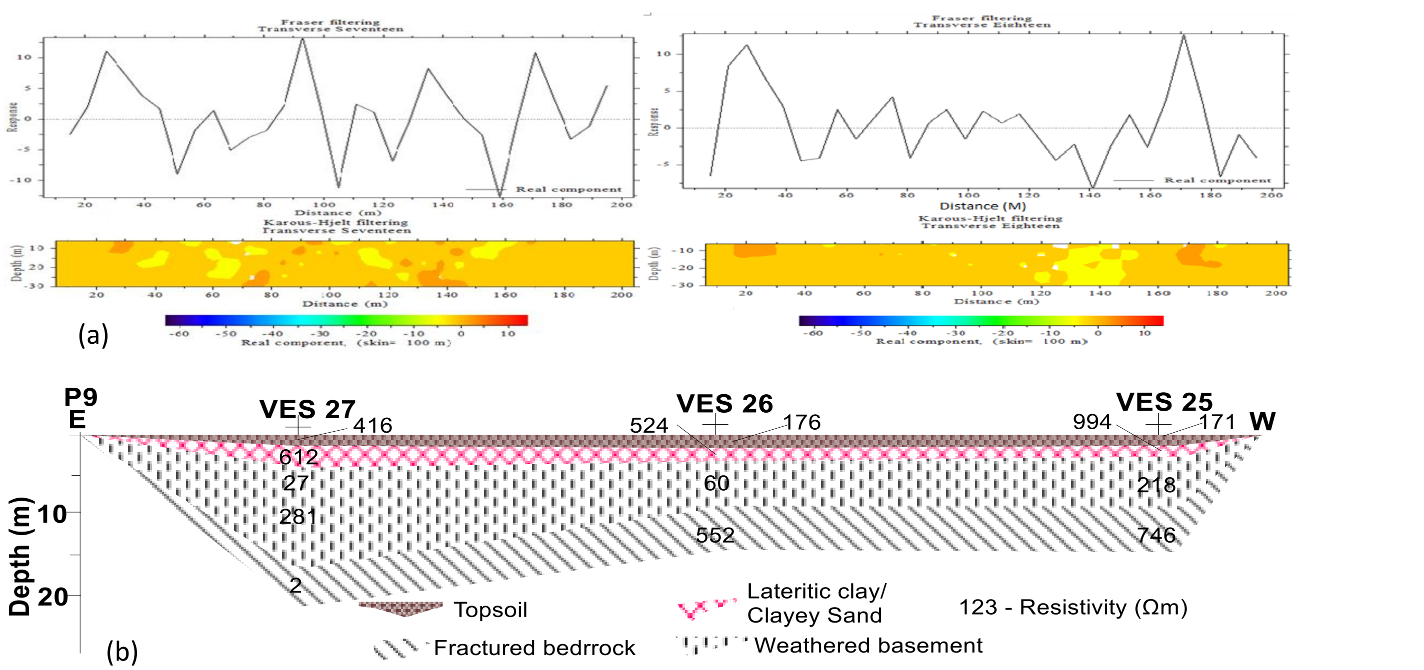


Figure 4.9 a) VLF-EM inversion model sections for traverseT17-T18 with 2D conductivity structure (b) Geoelectric section

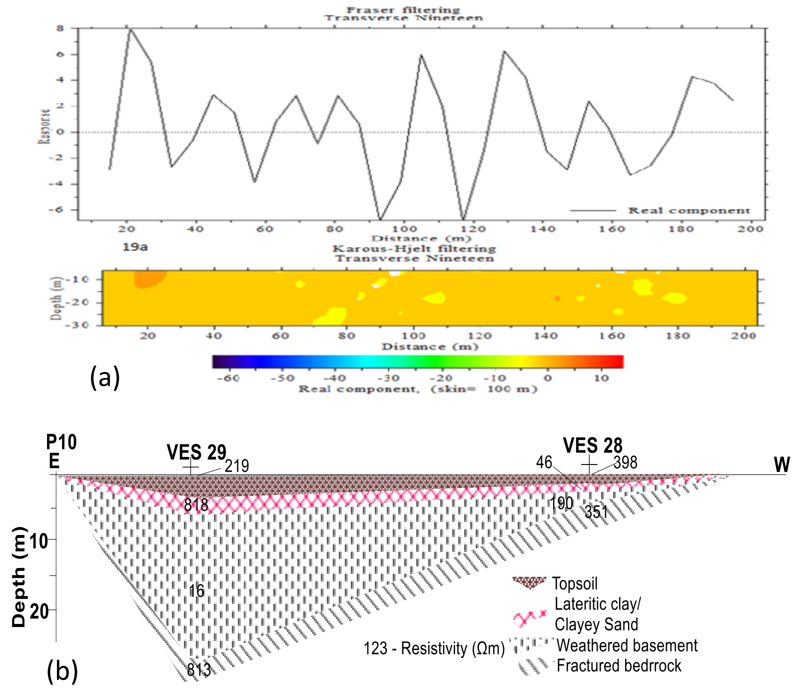


Figure 4.10 a) VLF-EM inversion model sections for traverse T19 with 2D conductivity structure (b) Geoelectric section

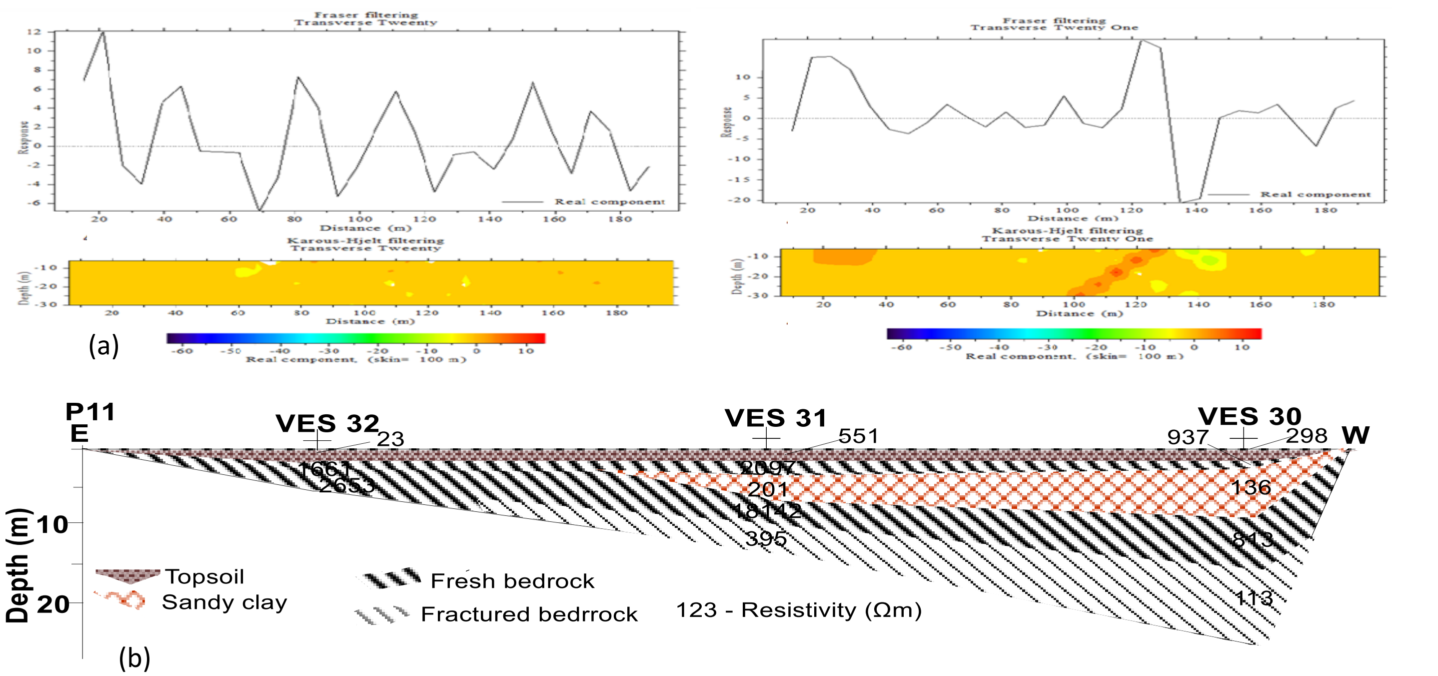


Figure 4.11 a) VLF-EM inversion model sections for traverse T20-T21 with 2D conductivity structure (b) Geoelectric section

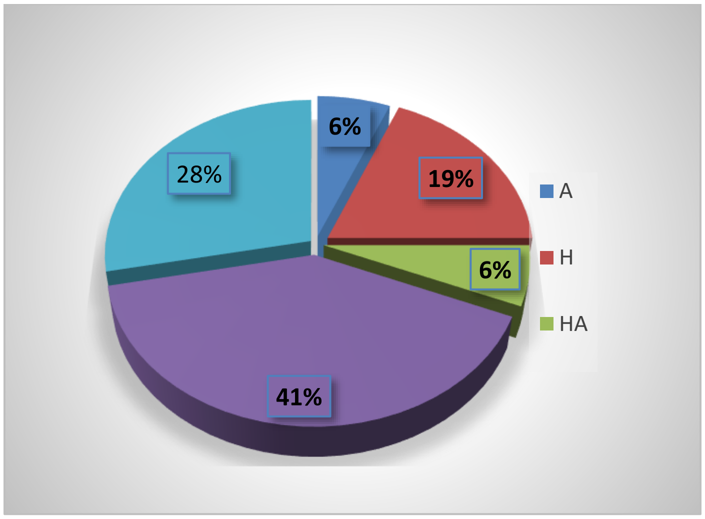


Figure 5Curve-type distributions

Table 1 Layering parameter range and geo-electric characteristic of H-type apparent resistivity curves obtained for VES(s) 2;4;18;19;20;21

Layer	Resistivity Range (Ωm)	Thickness (m)	Probable Sediments	Competence significance
1	60.2 – 378	1.03 – 5.06	Topsoil	-----
2	20.9 – 79.2	4.14 – 12.7	Clay	Incompetent
3	191 – 644	–	Sandy clay/clayey sand Weathered basement	Incompetent - Moderately competent

Table 2 Layering parameter range and geo-electric characteristic of A-type apparent resistivity curves obtained for VES(s) 11; 32

Layer	Resistivity Range (Ωm)	Thickness (m)	Probable Sediments	Competence significance
1	23 – 106	0.5	Topsoil	-----
2	359 – 1661	1.07 – 67.7	Lateritic hard-pan/basement	Competent
3	1748 – 2653	–	Fresh bedrock	Highly competent

Table 3 Layering parameter range and geo-electric characteristic of KH-type apparent resistivity curves obtained for VES(s) 1;3;5;7;14;15;16;17;23;24;25

Layer	Resistivity Range (Ωm)	Thickness Range (m)	Probable Sediments	Competence significance
1	62.7 – 466	0.5 – 1.52	Topsoil	----
2	220 – 4210	0.39 – 3.16	Lateritic hard-pan/basement	Competent
3	12 – 122	1.32 – 27.2	Weathered basement	Incompetent
4	86.8 - 3060	-	Fractured/fresh bedrock	Incompetent

Table 4 Layering parameter range and geo-electric characteristic of HA-type apparent resistivity curves obtained for VES(s) 22; 28

Layer	Resistivity Range (Ωm)	Thickness Range (m)	Probable Sediments	Competence significance

1	398 – 495	1.33 – 3.04	Topsoil	-----
2	46.1 – 108	1.2 – 3.56	Clay	Incompetent
3	190 – 1420	31.4 – 50.4	Weathered/fresh basement	Moderately competent
4	8.29 - 351	-	Fractured bedrock	Incompetent

Table 5 Layering parameter range and geo-electric characteristic of HKH-type apparent resistivity curves obtained for VES(s) 8; 9; 10; 12; 27; 30; 31

Layer	Resistivity Range (Ωm)	Thickness Range (m)	Probable Sediments	Competence significance
1	149 – 551	0.5 – 1.02	Topsoil	----
2a	25.3 – 267	0.77 – 1.6	Clayey sand/sandy clay	Incompetent
2b	497 – 2097	0.62 – 1.49	Basement rock	competent
3a	27.3 - 742	1.81 - 11.5	Weathered/fracture basement	Incompetent
4a	17.1 – 18142	4.49 – 60.7	Fractured/fresh bedrock	Incompetent - competent
5	1.18- 813	-	Fractured bedrock	Incompetent

5. Conclusion

The integrated geophysical mapping for subsurface competent at University of Ilorin campus in southwestern Nigeria basement complex has been carried out. The quantitative and qualitative interpretations of the VLF and VES data have provided adequate information regarding the subsurface conductivity and geoelctrical parameters. The very-low-frequency electromagnetic responses indicate the near-surface contrasting formation which comprises of vadose zones (associated with lateritic clay and/or clayey sand) and the water-bearing weathered layers to an estimated depth of about 8 m. The vertical resistivity distribution corroborated the results of VLF-EM and VES revealed three to five geoelectical sequences which include topsoil, lateritic layer (not present in all), weathered layer, and fractured or fresh bedrock. Predominantly weathered basement rock is observed within a shallow depth range of 1.0-10.6 meters, with the overburden primarily comprising thin layers such as clay lenses, sandy-clay, and prevalent lateritic hard-pan or clayey-sand formations. These subsoil characteristics classify the area as suitable for supporting high-rise engineering structures. However, notable thick clay horizons detected beneath specific profiles, particularly profiles 1 and 7 in the southern and northern regions raise concerns regarding the potential implications for high-rise construction integrity. Continuous presence of such thick clay layers across profiles or seismic activity in the area could pose risks of structural failure. Overall, the study concludes that the subsurface sequence within the investigated area is predominantly conducive to the construction of high-rise engineering structures, given the structurally competent bedrock identified. However, careful consideration of localized variations, particularly the presence of thick clay horizons, is essential to mitigate potential risks and ensure the long-term stability of the built environment.

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