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Determining Subsurface Bedrock Depth Using Vertical Electrical Sounding: Principles, Applications, And Case Studies

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ABSTRACT

Accurate determination of bedrock depth is a critical parameter across numerous geoscience disciplines, including civil engineering, hydrogeology, and environmental studies. Traditional intrusive methods, such as drilling and digging, are often costly, time-consuming, and provide limited spatial coverage. This article provides a comprehensive assessment of Vertical Electrical Sounding (VES) as a non-invasive, cost-effective geophysical technique for evaluating subsurface bedrock depth. It elucidates the fundamental principles of VES, detailing its operational methodology, common electrode configurations (e.g., Schlumberger, Wenner), and the process of data acquisition and interpretation. The article highlights diverse applications of VES in geotechnical investigations, groundwater exploration, and environmental assessments, with a particular focus on its utility in bedrock mapping. Case studies from Nigeria illustrate the practical application of VES and the correlation of its results with borehole data. Furthermore, the discussion addresses the advantages and limitations of VES, comparing it with other geophysical methods and exploring future prospects, including the integration of artificial intelligence and machine learning for enhanced interpretation. This synthesis aims to underscore the indispensable role of VES in providing crucial subsurface information for sustainable development and infrastructure planning.

KEYWORDS: Subsurface investigation, bedrock depth, vertical electrical sounding (VES), geophysical methods, resistivity survey, hydrogeology, geotechnical exploration, earth resistivity, site characterization, case studies in VES.

INTRODUCTION

Background: The Critical Importance of Bedrock Depth in Geoscience and Engineering

Bedrock, defined as the solid, unweathered rock underlying soil and other loose surface materials, plays a fundamental role in shaping Earth's environment and influencing human activities. Its depth and characteristics are crucial parameters across a wide array of disciplines, including civil engineering, hydrogeology, and environmental studies. In civil engineering, understanding bedrock depth is paramount for the design and construction of stable foundations for buildings, roads, and other critical infrastructure. Areas with stable bedrock can support heavy structures, while regions with weak or fractured bedrock necessitate specialized foundation designs, posing significant engineering challenges and impacting initial construction costs. Shallow bedrock can be advantageous for solid foundation shoring, minimizing soil removal, whereas deeper bedrock, especially with lateral variations in soil characteristics, can lead to footing and slab failures if not properly accommodated.

In hydrogeology, bedrock controls the movement and quality of groundwater. The permeability of bedrock dictates the recharge and flow of groundwater, directly affecting the availability of water resources. Fractured bedrock can act as conduits for groundwater flow, while impermeable bedrock can form barriers. Characterizing deeper bedrock hydrogeology in mountainous watersheds is vital for predicting drought impacts on stream ecosystem health and water resource sustainability, as deeper groundwater flow systems can store more water and sustain streamflow during dry periods. Environmentally, knowledge of bedrock depth is essential for mitigating historic spills by quantifying excavation volumes of contaminated material and understanding the fate and transport of contaminants that tend to travel along bedrock surfaces.

Problem Statement: Limitations of Traditional Methods and the Need for Non-Invasive Alternatives

Traditionally, bedrock investigations have primarily relied on intrusive methods such as digging and drilling. While these methods provide direct subsurface information, they are inherently costly, labor-intensive, and time-consuming.

Moreover, boreholes only provide data for the exact location where they are obtained, making extrapolation to broader areas risky due to subsurface variability. This limitation often results in insufficient data coverage, leading to uncertainties in bedrock mapping and potentially costly modifications during construction if unexpected conditions are encountered. The demand for more comprehensive data coverage, driven by the increased use of 3D design tools in infrastructure and resource mapping projects, further highlights the inadequacy of discrete, point-by-point geotechnical investigations. Therefore, there is a pressing need for non-invasive, cost-efficient geophysical techniques that can provide broader spatial understanding of subsurface conditions, including bedrock depth, to supplement or optimize traditional drilling programs.

Research Objectives: Exploring Vertical Electrical Sounding for Bedrock Assessment

This article aims to comprehensively assess the utility of Vertical Electrical Sounding (VES) as a geophysical method for determining subsurface bedrock depth. To achieve this, the study will pursue the following objectives:

- To elucidate the fundamental principles and operational methodology of Vertical Electrical Sounding, including its electrode configurations and field procedures.
- To detail the process of data acquisition, processing, and interpretation in VES surveys for bedrock depth assessment.
- To present various applications of VES in geotechnical investigations, hydrogeology, and environmental studies, with a specific focus on its role in bedrock mapping.
- To analyze the advantages and limitations of VES in comparison to other geophysical methods for bedrock depth determination.
- To explore future prospects for VES, particularly the integration of advanced computational techniques like artificial intelligence and machine learning for enhanced interpretation.

Significance of the Study: Enhancing Subsurface Characterization for Sustainable Development

This study holds significant importance by highlighting a proven, non-invasive geophysical method that can substantially improve the accuracy and cost-efficiency of subsurface investigations. By providing a detailed understanding of VES, this research aims to:

- **Reduce Project Costs and Risks:** By offering a preliminary interpretation of ground conditions and identifying variability, VES can help optimize the placement of costly borings, thereby reducing overall geotechnical investigation costs and minimizing risks associated with unforeseen subsurface conditions.
- **Improve Infrastructure Design:** Accurate bedrock depth information is crucial for designing stable foundations, especially in earthquake-prone areas, and for planning pipeline routes, ensuring long-term structural integrity and safety.
- **Enhance Water Resource Management:** Understanding bedrock hydrogeology is vital for assessing groundwater potential, flow behavior, and storage capacity, which is critical for sustainable water resource management, particularly in drought-prone or mountainous regions.
- **Support Environmental Mitigation:** Precise mapping of bedrock surfaces aids in quantifying excavation volumes for contaminated material and understanding contaminant transport pathways, facilitating more effective environmental remediation efforts.

Ultimately, this research contributes to a more informed and sustainable approach to land use, resource management, and infrastructure development by promoting the effective application of geophysical techniques like VES.

METHODOLOGY

A. Principles of Vertical Electrical Sounding (VES)

Vertical Electrical Sounding (VES) is a direct current (DC) electrical resistivity method used to investigate the vertical variation of electrical resistivity in the subsurface. The fundamental principle behind electrical resistivity methods is that an electrical potential difference (voltage) forms around current-carrying electrodes implanted in a conductive medium. The distribution of this voltage depends on the electrical resistivities of the subsurface materials and their spatial variations.

A single resistivity measurement involves injecting electrical current into the subsurface through two current electrodes (typically labeled A and B) and measuring the potential difference across two potential electrodes (M and N). This measurement yields the "apparent resistivity" of the materials influencing the current flow. Apparent resistivity is a bulk average resistivity of all ground materials beneath the electrodes, rather than a discrete point or layer. By progressively increasing the spacing between the current electrodes (A and B) while keeping the center of the array fixed, the current penetrates deeper into the ground, allowing for the measurement of resistivity variations with depth. This process builds up a 1D resistivity profile with depth.

Different geological materials exhibit distinct electrical resistivity values. For instance, clay and shale tend to conduct electricity well (low resistivity), while limestone and igneous rocks have relatively high resistance (high resistivity). The presence of water or mineral ores typically lowers resistivity, while stronger, harder deposits often have higher resistivity compared to weaker rock. This contrast in electrical properties allows for the differentiation of various subsurface geological formations.

B. Electrode Configurations

Various electrode configurations, or "electrode devices," are used in VES surveys, with the most common being the Schlumberger and Wenner arrays.

- **Schlumberger Array:** This is the most common VES array for mapping subsurface lithology. In the Schlumberger configuration, the four electrodes (A, B, M, N) are aligned. The current electrodes (A and B) are successively moved away from the center, while the potential electrodes (M and N) are kept relatively close to the center and are only moved when the measured voltage becomes too small. The distance between M and N is typically very small compared to the distance between A and B. This method is generally more rapid than the Wenner method for deeper investigations. The apparent resistivity (ρa) for the Schlumberger configuration is calculated using a geometrical factor (K) that depends on the electrode separations.
- **Wenner Array:** The Wenner method also uses four electrodes arranged in a line, but with equal spacing between all adjacent electrodes. The Wenner method is commonly used to determine the resistivity of shallow, near-surface soils.

The choice of array depends on site parameters and survey applications. The depth of investigation is generally proportional to the distance between the current electrodes, typically ranging from 0.1 to 0.3 times the AB length for Schlumberger, and around 0.2 times the total cable length for Wenner.

C. Field Procedure and Equipment

The field procedure for a VES survey involves setting up the electrodes and taking measurements systematically. The resistivity meter is typically placed in the central part of the sounding. Metallic electrodes are plugged into the ground as deeply as possible to decrease ground resistance. For Schlumberger soundings, the survey starts with small AB/2 values, and the current electrodes are progressively moved outwards. For some AB/2 values, two readings with different MN/2 values may be taken to check for lateral resistivity variations.

Common geophysical equipment used for VES surveys includes:

- **Resistivity Meters/Terrameters:** Devices like the ABEM SAS 300/1000/4000 or SYSCAL resistivity meters are used to inject current and measure voltage. These instruments are designed to be portable and measure multiple parameters like resistivity, induced polarization (IP), and spontaneous potential (SP).
- **Electrodes and Wires:** Stainless steel electrodes are used for current input and voltage measurements, connected by electric wires.
- **GPS/GLONASS Receivers:** For accurate geo-positioning of survey points.

The data collected in the field includes the voltage drop (mV) between potential electrodes and the current intensity (mA). These values are recorded during the expansion of the electrode array.

D. Data Processing and Interpretation

Raw data from VES surveys (voltage and current measurements) are used to calculate apparent resistivity values. These apparent resistivity values, on their own, are not sufficient for direct interpretation as they represent a bulk average. Therefore, a crucial processing step called **inversion** is required.

Inversion software is used to find a subsurface resistivity distribution model that would produce the same apparent resistivity values as those recorded in the field. Popular software for 1D automatic and manual interpretation of VES curves includes **IPI2win** and **WinResist**. These programs allow users to:

- Input field data (apparent resistivity vs. electrode spacing, typically AB/2).
- Perform automatic or manual interpretation to generate a layered subsurface model.
- Adjust model parameters (resistivity and thickness of each layer) and observe how they fit the field curve.
- Output results showing the resistivity, thickness, and depth of each geoelectric layer.

The interpreted geoelectric sections provide inferences on the hydrogeological, stratigraphic, engineering, and geological characteristics of the soil and underlying rock. For bedrock depth assessment, the interpretation focuses on identifying layers with very high resistivity, which typically correspond to fresh, unweathered bedrock.

RESULTS (Applications and Case Studies)

A. Applications of Vertical Electrical Sounding

VES surveys are widely utilized in geotechnical investigations and have numerous applications across the construction industry, environmental studies, and hydrogeology due to their rapid acquisition and ability to provide a quick and accurate picture of subsurface electrical properties.

- **Geotechnical Investigations:** VES aids in identifying soil lithology, as changes in electrical properties often relate to changes in physical properties. It is used for determining bedrock depth, identifying the resistivity of the subsoil for grounding systems, and defining geological structures distinguishable by their resistivity.

- **Groundwater Exploration:** The electrical resistivity of soils can indicate the presence of groundwater. VES is frequently used to aid groundwater investigations, locate geological structures that can function as aquifers (e.g., coarse-grained detrital, karstified limestones), and assess groundwater potential, flow behavior, and storage capacity. It can distinguish between clay (low resistivity) and sand (high resistivity), or saltwater (low resistivity) from freshwater (high resistivity).
- **Environmental Assessments:** VES data is used in mapping landfill sites, as the electrical conductivity of soils can indicate waste content. It can also map heavy metals soil contamination, delineate disposal areas, and track the lateral extent of conductive contaminant plumes.
- **Bedrock Depth Determination:** VES is a direct method for determining bedrock depth by identifying the resistivity contrast between overburden and the underlying solid rock.

B. Case Studies: Bedrock Depth Assessment in Nigeria

Several studies in Nigeria have successfully utilized VES for groundwater exploration and, by extension, bedrock depth assessment, particularly in areas characterized by sedimentary basins and basement complex rocks.

- **Gombe, Northeastern Nigeria (Liji Area):** A study aimed at evaluating bedrock depth in the Liji area of Gombe, Northeastern Nigeria, employed ten VES points using the Schlumberger array with a maximum electrode separation of AB/2 = 100m. The data were processed using the WinResist program. The results revealed that the area is predominantly underlain by three layers: topsoil, weathered sandstone, and basement rock. Seven VES points showed three layers, while three points had four layers, with the third layer representing fresh sandstone and the fourth being the basement. Bedrock (basement rocks) was identified at depths ranging from 5.7m to 24.0m, with infinite thickness, indicating the depths to be reached to encounter the bedrock.
- **Kaltungo and Environs, Northeastern Nigeria:** Geo-electrical data analysis, likely involving VES, was used to demarcate groundwater pocket zones in Kaltungo and environs.[1] This type of study inherently involves characterizing subsurface layers, including the depth to less permeable bedrock or fractured zones that may act as aquifers.[1]
- **Gwoza Town and Environs, Northeastern Nigeria:** A hydro-geoelectrical investigation in Gwoza Town and environs also utilized VES, which would have involved determining the vertical distribution of resistivity and thus the depth to various geological formations, including bedrock, to understand groundwater potential.[2]
- **Boh Shongom Local Government Area, Gombe State, Nigeria:** Geophysical investigation for groundwater potentials in this area specifically used VES, demonstrating its application in identifying subsurface layers and their characteristics relevant to water-bearing zones, which often involves delineating the underlying bedrock.[3]
- **Gadam Town, Gombe State, Northeastern Nigeria:** Groundwater investigation in Gadam town also utilized VES, contributing to the understanding of subsurface conditions for water resources.[4]
- **Tudun Wada, Kano State, Nigeria:** A geophysical evaluation for groundwater exploration in Tudun Wada, Kano State, utilized VES with a Schlumberger array system. The study area comprised sedimentary, igneous, and metamorphic rocks with alluvial deposits. The interpreted geological profile included topsoil, weathered layer, fractured basement, and fresh basement (bedrock). The fresh bedrock was found to have a resistivity of 1011Ωm to 3006Ωm, extending infinitely downwards, with the depth of the bedrock from the earth's surface ranging from 2m to 45m.
- **Otuoke, Bayelsa State, Nigeria:** A study in Otuoke, Bayelsa State, Nigeria, applied the VES method, and the obtained geoelectrical stratigraphy correlated well with borehole lithology in the area for groundwater exploration. The study used five VES points, and the interpreted data confirmed stratigraphy including sandy clay, dry sand, clay, and saturated fine/coarse sand as aquifers, with the results indicating good aquifer zones for portable groundwater development.

These case studies demonstrate the practical utility of VES in diverse geological settings across Nigeria for effectively assessing bedrock depth and characterizing subsurface conditions relevant to various engineering and hydrogeological applications.

C. Correlation with Borehole Data

While geophysical methods like VES provide extensive spatial coverage and preliminary interpretations, direct ground truthing through boreholes or drilling is often required to "calibrate" the geophysical results and confirm interpretations. The correlation of VES results with borehole data is a common practice to validate the accuracy of the geophysical model.

Studies have shown that geoelectrical stratigraphy obtained from VES often correlates well with borehole lithology. For instance, in the Otuoke, Bayelsa State, Nigeria case study, the interpreted VES data matched drilled borehole logs, confirming the subsurface stratigraphy and identifying good aquifer zones. Similarly, in the Daloa commune, a study using

VES and electrical profiling found that borehole productivity was related to conductive anomalies identified by geoelectric data, with new boreholes validating these results. This integration of surface geophysical data with borehole information provides a more comprehensive and accurate understanding of subsurface conditions, including bedrock depth and its variations.

DISCUSSION

A. Advantages of Vertical Electrical Sounding

Vertical Electrical Sounding offers several significant advantages that make it a valuable tool for subsurface investigations, particularly for bedrock depth assessment:

- **Non-Invasive and Cost-Effective:** Unlike drilling or digging, VES is a non-destructive method that does not require excavation, making it environmentally friendly and generally less expensive. It provides a cost-efficient way to gain a better understanding of ground conditions.
- **Rapid Acquisition and Broad Coverage:** VES data can be acquired relatively quickly, providing a rapid picture of the soil's electrical properties. It offers greater area of interpretation compared to point-by-point borings, covering hundreds of feet at less expense. This allows for more detailed data coverage than traditional methods.
- **Vertical Resolution:** VES is specifically designed to determine the vertical variation of electrical resistance, providing detailed information on the vertical succession of various conducting zones and their individual thickness and apparent resistivity. This makes it well-suited for 1D depth investigations.
- **Versatility:** VES can be applied in various environments (land, water, boreholes) and for diverse applications, including geotechnical, hydrogeological, and environmental studies. It is particularly useful for defining and characterizing deep phreatic levels in hydrogeological studies.
- **Complementary to Drilling:** By providing a preliminary interpretation of subsurface conditions and identifying variability, VES can help optimize the placement of costly borings, ensuring that future drilling locations yield the most critical data.

B. Limitations of Vertical Electrical Sounding

Despite its advantages, VES also has certain limitations that need to be considered:

- **1D Interpretation:** VES is primarily a 1D method, meaning it provides information about vertical variations directly below a single ground point. It is not well-suited for identifying confined features like fracture zones or intrusions, or for detailed lateral variations, where 2D or 3D methods are preferable.
- **Galvanic Contact Requirement:** VES requires galvanic contact with the ground via electrodes, which can be challenging and time-consuming in environments with bare rock or asphalt.
- **Environmental Interference:** While not explicitly stated for VES, similar electrical methods can be affected by industrial and electrical interference.
- **Interpretability and Non-Uniqueness:** The interpretation of geophysical data, including VES, can be challenging due to factors like non-unique relationships between resistivity values and geological materials, anisotropy (resistivity varying with direction), and inhomogeneity. The apparent resistivity is a bulk average, and its inversion to true resistivity layers requires careful interpretation.
- **Limited Depth in Certain Conditions:** While generally effective for depth, the depth of investigation is limited by the electrode spacing and power of the equipment.

C. Comparison with Other Geophysical Methods

VES is one of several geophysical methods used for bedrock depth assessment, each with its own strengths and weaknesses.

- **Seismic Methods (Refraction Seismics, MASW, DHS):** Seismic methods, particularly refraction seismics, are common for bedrock depth determination. They provide quantitative information about the spatial variability of depth-to-bedrock and the strength of bedrock through acoustic velocity. Multichannel Analysis of Surface Waves (MASW) and Downhole Seismic (DHS) also use shear wave and compressional wave velocities to estimate bedrock depth, showing good agreement with borehole data. Seismic methods can provide quantitative appraisal of geological strength and stability. However, active seismic methods require a source, which needs consideration for energy and legislative/environmental constraints.
- **Ground Penetrating Radar (GPR):** GPR is a powerful imaging tool for shallow bedrock (0-8 feet) and can provide excellent detail on stratigraphy. It is suitable in non-conductive conditions (e.g., without clayey soils) down to approximately 30-50 meters. However, GPR is limited by soil conditions and data processing time.
- **Terrain Conductivity Mapping (TCM):** Ideal for rapidly mapping subsurface conductivities to differentiate conditions, especially when bedrock is expected to vary between 5-20 feet below grade. TCM is fast, efficient, and results in highly detailed maps and profiles.
- **Microtremor Measurement:** This method can be used to estimate the thickness of soft soil based on resonant frequency, and is important for determining bedrock

depth, especially where the soil completely passes into rock or S-wave velocity reaches 600-760 ms-1.

Often, integrating multiple geophysical methods (e.g., GPR with resistivity or seismic) is beneficial to minimize uncertainties and validate conceptual models, especially in complex subsurface conditions. This multidisciplinary approach provides a more comprehensive understanding of the subsurface.

D. Future Prospects: AI and Multi-Data Integration

The future of bedrock depth assessment using geophysical methods, including VES, lies in the increasing integration of advanced computational techniques and multi-source data.

- **AI and Machine Learning (ML):** AI and ML techniques are being explored to enhance shear wave velocity (Vs) prediction, offering a cost-effective and sustainable alternative to conventional approaches. ML algorithms and statistical models can predict bedrock levels and estimate uncertainties, with methods like Bagging regressor with decision tree showing promise for accurate bedrock surface prediction and narrower prediction intervals. Spatially enabled ML approaches, using borehole lithologs, digital elevation models, satellite imagery, and spatial feature engineering, significantly improve predictive performance for depth to bedrock mapping.
- **Multi-Data Source Integration:** Future research will focus on integrating various geophysical methods (e.g., VES, seismic, GPR) with borehole data and remote sensing datasets. This integration, often facilitated by AI/ML, can overcome limitations of individual methods and provide more accurate and comprehensive subsurface models.
- **Real-time Monitoring:** Advancements could lead to more real-time monitoring of subsurface changes, which is crucial for dynamic environments or long-term infrastructure projects.

These advancements promise to make bedrock depth assessment even more precise, efficient, and reliable, further enhancing its utility in critical engineering, hydrogeological, and environmental applications.

CONCLUSION

The accurate assessment of subsurface bedrock depth is a foundational requirement for a multitude of critical applications in civil engineering, hydrogeology, and environmental management. Vertical Electrical Sounding (VES) stands out as a robust, non-invasive, and cost-effective geophysical method that effectively addresses many of the limitations associated with traditional intrusive investigation techniques.

This article has detailed the core principles of VES, explaining how it leverages the electrical resistivity contrast of subsurface materials to delineate layered structures and determine bedrock depth. The operational methodology, including the use of Schlumberger and Wenner electrode arrays, coupled with systematic field procedures and sophisticated data inversion software like IPI2win and WinResist, enables the generation of reliable 1D resistivity profiles. Practical case studies, particularly from Nigeria, have demonstrated VES's proven capability in mapping bedrock and identifying groundwater potential, often correlating well with direct borehole observations.

While VES offers significant advantages in terms of cost-efficiency, rapid data acquisition, and broad spatial coverage, it is important to acknowledge its limitations, such as its primary 1D nature and potential susceptibility to environmental interference. However, these limitations can often be mitigated through the strategic integration of VES with other complementary geophysical methods like seismic surveys and GPR, providing a more holistic subsurface understanding. The future of bedrock depth assessment is poised for further transformation with the increasing adoption of artificial intelligence and machine learning, which promise to enhance data interpretation, improve predictive accuracy, and facilitate the seamless integration of diverse geophysical datasets.

In conclusion, VES remains an indispensable tool in the geoscientist's arsenal, providing crucial subsurface information that underpins sustainable infrastructure development, responsible water resource management, and effective environmental protection. Its continued evolution, particularly through technological integration, will further solidify its role in shaping a more informed and resilient built environment.

REFERENCES

1. Roesset, J.M., Stokoe, K.H., & Seng, C.R. Determination of depth to bedrock from falling weight deflectometer test data. Transportation Research Record. (1995) 68-78. https://doi.org/10.3141/1655-17.
2. Leblois, É., & Referee, J.D. Interactive comment on “Modelling Bedrock Topography” by Nils-Otto Kitterød and Étienne Leblois Nils-Otto Kitterød and Étienne Leblois. Earth Surf. Dynam. Discuss. (2020). https://doi.org/10.5194/esurf-2019-57-AC2, 2020.
3. Mohammed Ali. Garba. Ibrahim Abubakar. Geo-Electrical Data Analysis to Demarcate Groundwater Pocket Zones in Kaltungo And Environes, Northeastern Nigeria. IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG) e-ISSN: 2321–0990, p-ISSN: 2321–0982.Volume 2, Issue 3 (2014), PP 43-50 www.iosrjournals.org. Doi: https://doi.org/10.9790/0990-0234350.
4. Moon, S., Subramaniam, P., Zhang, Y., Vinoth, G., & Ku, T. Bedrock depth evaluation using microtremor

measurement: empirical guidelines at weathered granite formation in Singapore. Journal of Applied Geophysics, (2019). 171, 103866. https://doi.org/10.1016/j.jappgeo.2019.103866.

5. Mohammed Ali. Garba., Saidu Ali. Dawa. and Mustapha Ali. Garba. Hydro-Geoelectrical Investigation of Gwoza Town And Environs, Northeastern Nigeria. IOSR Journal of Applied Geology and Geophysics. (IOSR-JAGG) e-ISSN: 2321–0990, p-ISSN: 2321–0982. 9 (3) Ser. II, (2021). PP 48-55. www.iosrjournals.org. DOI: https://doi.org/10.9790/0990-0903024855.
6. Ezekiel Kamureyina, Mohammed Ali Garba, Musa Hayatudeen and Benjamin Odey Omang. Geophysical Investigation of Groundwater Potentials Using Vertical Electrical Sounding: Case Study of Boh Shongom Local Government Area Gombe State, Nigeria. RESPUB Journal of Natural & Applied Sciences SSN: 2770-3649 2 (3). (2022). Available Online: www.irespub.com. Doi: https://doi.org/10.62179/irespub-jnas.v2i3.1.
7. Ntambakwa, E., Šalković, I., & Tomac, I. (2023). Geophysical Reconstruction of Bedrock Depth at the Large Sinkhole in the 2020 Petrinja Earthquake. 2nd Croatian Conference on Earthquake Engineering – 2CroCEE. DOI: https://doi.org/10.5592/CO/2CroCEE.2023.85.
8. Mohammed Ali. Garba. Groundwater Investigation of Gadam town, Gombe State, Northeastern Nigeria. IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG) e-ISSN: 2321–0990, p-ISSN: 2321–0982 11 (1) (2023), PP 10-22 www.iosrjournals.org. Doi: https://doi.org/10.9790/0990-1101011022