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Using resistivity surveying methods for geotechnical study of subsurface properties for foundation design

Adetoyinbo Adedeji Adegoke[a], Bello Adekunle Kazeem[b,*], Ogunseye Titus Taofik[a], Egbeyale Babatunde Godwin[c], Surajudeen Hadi Ademola[a], Adeleke Ayinla Ayooluwa[a]

[a] *Department of Physics, University of Ibadan, Nigeria*
[b] *Department of Physical Sciences, Bells University of Technology, Ota, Nigeria*
[c] *Department of Physics and Material Science, Kwara State University, Malete, Kwara State, Nigeria*

Abstract

The evaluation of subsurface properties plays a pivotal role in understanding geological formations and assessing their suitability for various engineering and environmental applications. In this work, the subsurface properties of open ground were investigated. Two constant separation traversing (CST) profiles were measured using the Wenner array electrode configuration, with electrode positions ranging from 0 to 150 m depending on the profile, and ten vertical electrical soundings (VESs) were conducted using the Schlumberger array electrode configuration, with half-current electrode separation (AB/2) ranging from 1 to 55 m. The topsoil resistivity ranged from 186.9 to 1222.0 Ω m, with an average of 422.5 Ω m, and its thickness ranged from 0.5 to 1.0 m. The weathered layer showed resistivity values between 13.6 and 70.0 Ω m, with a mean of 29.6 Ω m, thicknesses between 1.4 and 9.9 m, and depths between 1.9 and 10.9 m. These variations in resistivity and layer thickness indicate the presence of weathered and fractured zones that must be taken into account during foundation design.

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1. Introduction

Many authors have applied electrical resistivity techniques in civil engineering research. These techniques have been used to identify zones of high porosity and low bearing capacity and to map lithological differences using vertical electrical sounding (VES). Such results verify the importance of resistivity surveys in preventing structural failures. Ref. [1] applied electrical resistivity, magnetic, and geotechnical methods for the subsurface investigation of a proposed site within the senior staff quarters at the University of Ilorin campus. Ref. [2] used resistivity surveying to assess groundwater potential at the Central Mosque, University of Ibadan, and the results showed that the study area has relatively high groundwater potential. Ref. [3] employed the electrical resistivity method to determine groundwater potential at Idu Industrial Estate in Abuja.

Recent research has shown that subsurface mapping, groundwater exploration, and geotechnical assessments are now included in the range of geophysical techniques that use VES and constant separation traversing (CST). Ref. [4] evaluated subsurface features

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[*] Corresponding author Tel. No.: +234-805-814-1055.

Email address: `akbellokazeem@gmail.com` (Bello Adekunle Kazeem)

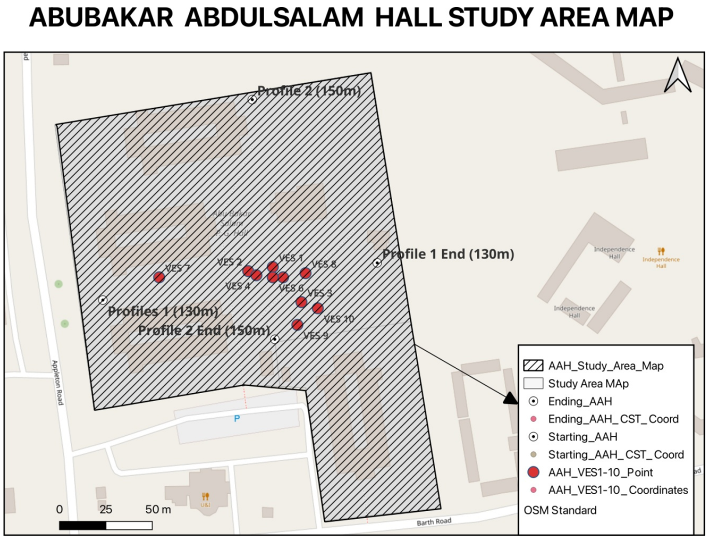


Figure 1. Combined maps for the study areas generated by QGIS.

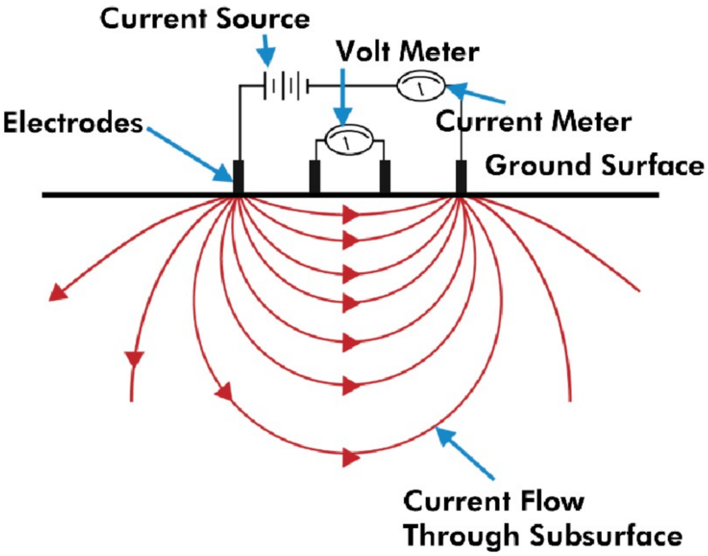


Figure 2. Diagram illustrating electrical current flow through the subsurface [12].

and groundwater potential in Idi-Ayunre, Ibadan, using a geographic information system (GIS) and VES; their study revealed areas with low groundwater potential by identifying significant geological features such as aquifer units and fracture zones. Ref. [5] used soil samples and laboratory tests to conduct a geochemical analysis of soil properties in Mokola, Ibadan. Their results showed heavy-metal contamination, highlighting its consequences for groundwater quality and the importance of incorporating geochemical assessment in subsurface investigations. Ref. [6] assessed the geotechnical properties of subsurface soil samples for shallow foundation design in Port Harcourt, Nigeria. Resistivity surveys may also be used as a reconnaissance method to detect anomalies that can be investigated further by complementary geophysical methods and/or drill holes [7]. Ref. [8] investigated the effect of horizontal voids on a soil-nailed wall; the results showed that increasing the void diameter exacerbated horizontal deformation and vertical ground settlement. Ref. [9] investigated the major causes of cracks in some buildings in the School of Engineering, Kogi State Polytechnic, Itakpe Campus, using resistivity methods; their results identified incompetent subsoil materials as possible causes of settlement failure. Ref. [10] established a soil profile and determined the engineering geological properties of subsoils at a proposed construction site in Port Harcourt using geotechnical investigation. Ref. [11] investigated building distress through foundation-performance assessment using field observation and electrical resistivity tomography. To provide practical insight into foundation stability, this work assesses subsurface layers for structural foundation design using electrical resistivity techniques, namely VES with the Schlumberger configuration and CST with the Wenner configuration.

Figure 3. Resistivity meter used for the survey.

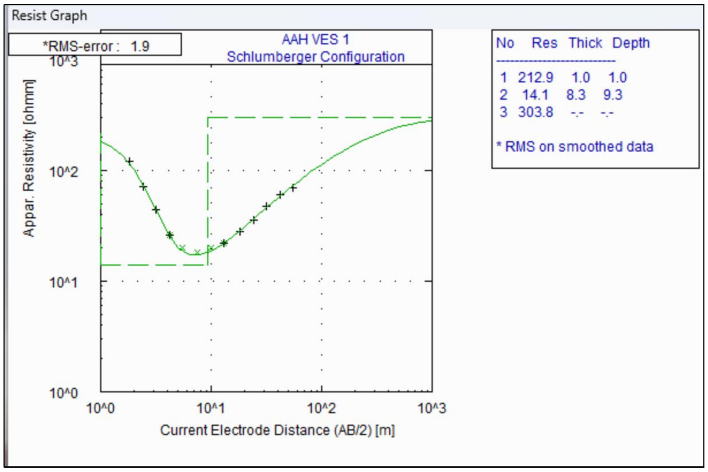
Figure 4. Survey layout for the study area.

2. Study site

The survey covered an area centered around coordinates 7.4°N and 3.8°E. The investigation site is located at Appleton Road in Abubakar Abdulsalam Hall (AAH), University of Ibadan. With a variety of basement rocks and the potential for differing soil compositions because of its proximity to various geological structures, this location exemplifies the region's geological diversity. The site was selected to evaluate the effect of these variables on foundation stability and to characterize variations in soil composition. Two CST profiles and ten VES stations were established at the site. Figure 1 shows the study area.

3. Background information on electrical resistivity techniques

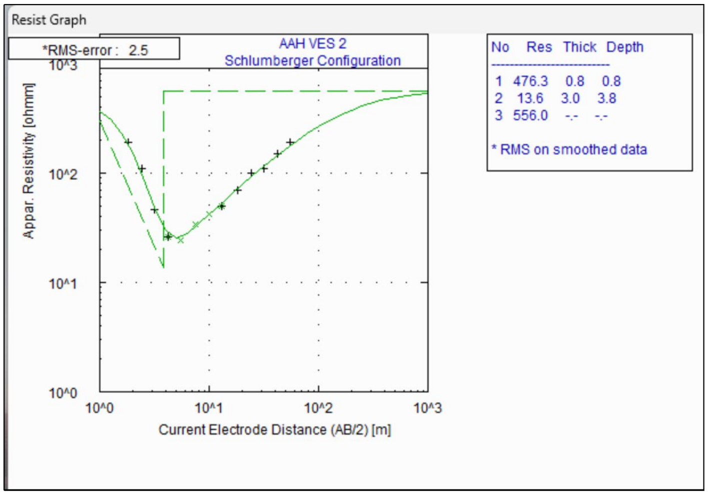
Compact, dry rocks exhibit high resistivity values, whereas conductive materials such as clays and water-saturated zones exhibit low resistivity. This variation makes it possible to characterize the underlying strata. In subsurface investigations, resistivity (ρ) is



No	Res	Thick	Depth
1	212.9	1.0	1.0
2	14.1	8.3	9.3
3	303.8	-.-	-.-

* RMS on smoothed data

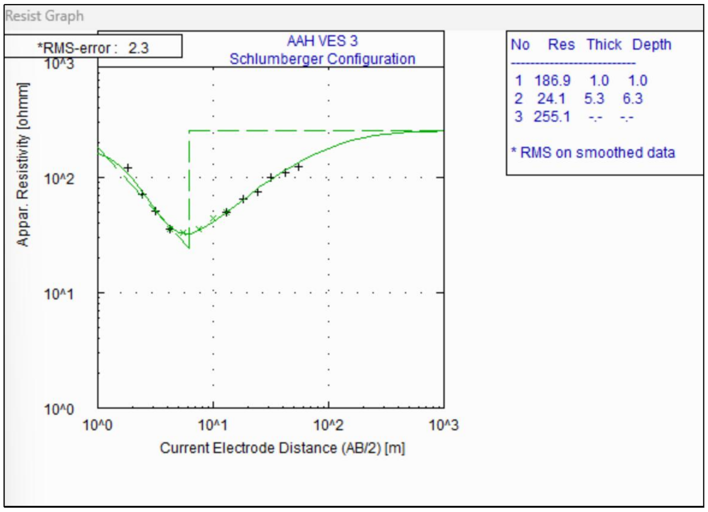
Figure 5. Graphical representation of VES 1.



No	Res	Thick	Depth
1	476.3	0.8	0.8
2	13.6	3.0	3.8
3	556.0	-.-	-.-

* RMS on smoothed data

Figure 6. Graphical representation of VES 2.



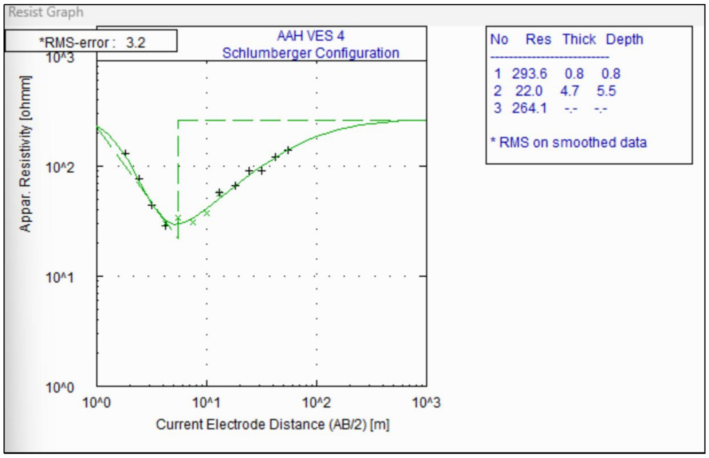
No	Res	Thick	Depth
1	186.9	1.0	1.0
2	24.1	5.3	6.3
3	255.1	-.-	-.-

* RMS on smoothed data

Figure 7. Graphical representation of VES 3.

calculated by considering the geometric dimensions of the material:

$$\rho = R\frac{A}{L}, \tag{1}$$

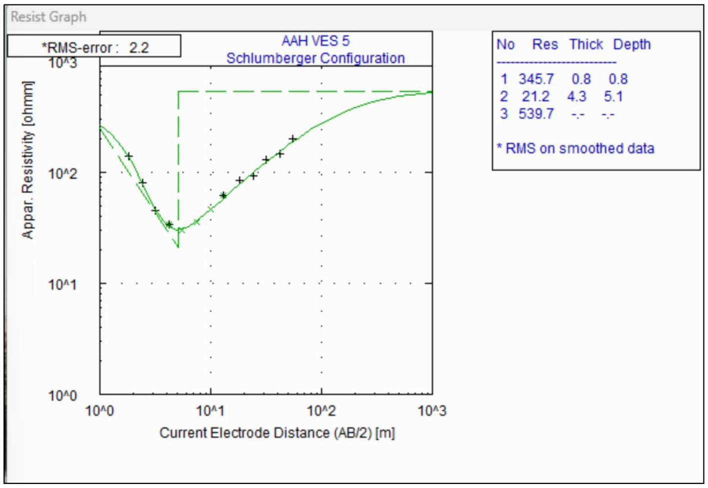


```
*RMS-error :  3.2
AAH VES 4
Schlumberger Configuration

No   Res   Thick  Depth
---------------------------
 1  293.6   0.8    0.8
 2   22.0   4.7    5.5
 3  264.1   -.-    -.-

* RMS on smoothed data
```

Figure 8. Graphical representation of VES 4.

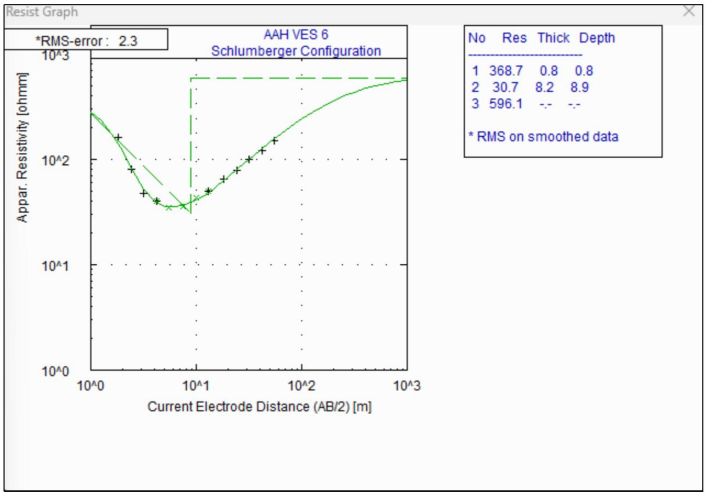


```
*RMS-error :  2.2
AAH VES 5
Schlumberger Configuration

No   Res   Thick  Depth
---------------------------
 1  345.7   0.8    0.8
 2   21.2   4.3    5.1
 3  539.7   -.-    -.-

* RMS on smoothed data
```

Figure 9. Graphical representation of VES 5.



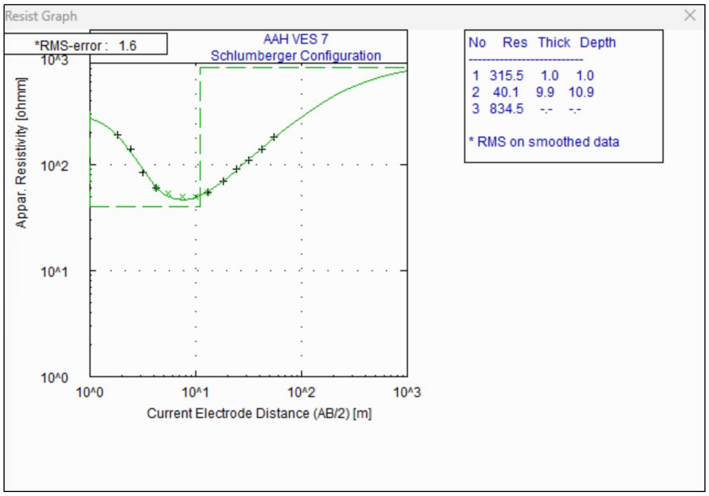
```
*RMS-error :  2.3
AAH VES 6
Schlumberger Configuration

No   Res   Thick  Depth
---------------------------
 1  368.7   0.8    0.8
 2   30.7   8.2    8.9
 3  596.1   -.-    -.-

* RMS on smoothed data
```

Figure 10. Graphical representation of VES 6.

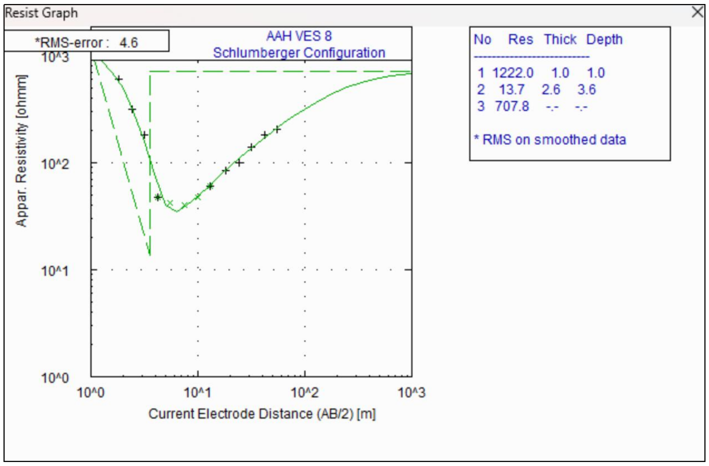
where R is the measured resistance (Ω), A is the material cross-sectional area (m^2), and L is the material length (m).



No	Res	Thick	Depth
1	315.5	1.0	1.0
2	40.1	9.9	10.9
3	834.5	-.-	-.-

* RMS on smoothed data

Figure 11. Graphical representation of VES 7.



No	Res	Thick	Depth
1	1222.0	1.0	1.0
2	13.7	2.6	3.6
3	707.8	-.-	-.-

* RMS on smoothed data

Figure 12. Graphical representation of VES 8.

3.1. *Electric current flow in subsurface materials*

Potential electrodes are used to measure the electric field produced by the current. The current density is given by

$$J = \sigma E, \tag{2}$$

where σ is the electrical conductivity ($1/\rho$, S/m), J is the current density (A/m^2), and E is the electric-field intensity (V/m). Figure 2 shows the flow of electrical current across the subsoil [12].

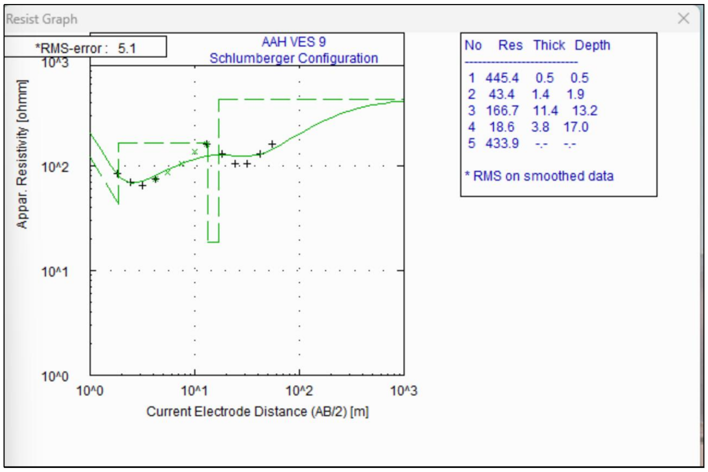
3.2. *Electrical field and potential*

The resistivity of the intervening materials affects the potential difference (ΔV) measured between two points. Current-flow lines and equipotential lines help interpret resistivity data by giving a visual depiction of the distribution of the electrical field beneath the surface [13]. According to Coulomb's law, the electric field of a charge is a force F applied to another unit charge [14]. The force F is given by

$$F = k_e \frac{q_1 q_2}{r^2}, \tag{3}$$

where F is the force between charges in newtons, k_e is Coulomb's constant, approximately 8.987×10^9 N m^2 C^{-}2, q_1 and q_2 are charges in coulombs, and r is the distance between the charges in metres. The electric field E at a point in space is defined as the force per unit charge:

$$E = k_e \frac{q}{r^2}. \tag{4}$$



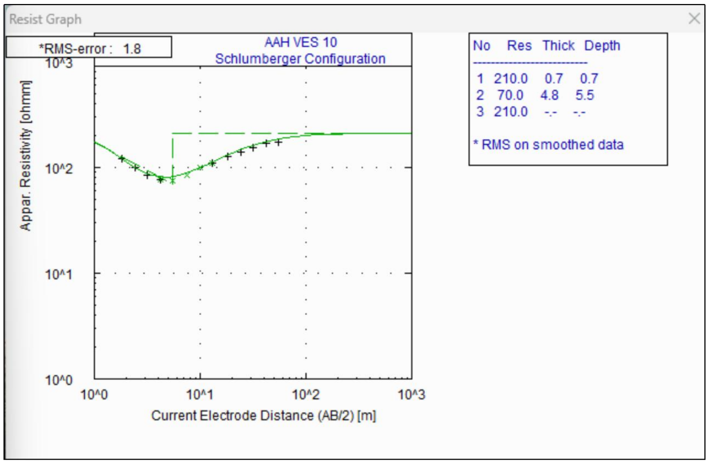
*RMS-error : 5.1

AAH VES 9
Schlumberger Configuration

```
No   Res   Thick  Depth
---------------------------
 1  445.4   0.5    0.5
 2   43.4   1.4    1.9
 3  166.7  11.4   13.2
 4   18.6   3.8   17.0
 5  433.9   -.-    -.-

* RMS on smoothed data
```

Figure 13. Graphical representation of VES 9.



*RMS-error : 1.8

AAH VES 10
Schlumberger Configuration

```
No   Res   Thick  Depth
---------------------------
 1  210.0   0.7    0.7
 2   70.0   4.8    5.5
 3  210.0   -.-    -.-

* RMS on smoothed data
```

Figure 14. Graphical representation of VES 10.

4. Materials and methods

Constant separation traversing with the Wenner array electrode configuration and vertical electrical sounding with the Schlumberger array electrode configuration were used for the geophysical survey. There were two CST profiles and ten VES profiles in all. The coordinates of the points in the selected area were obtained and compiled. To identify subsurface resistivity changes, current was injected into the ground and the resulting potential difference was measured. These differences helped identify faults or fractures, evaluate lithological characteristics, and define geological layers. The appropriate selection and application of specialized tools and materials are essential to the success of a geophysical survey. Figure 3 shows the resistivity meter used for the investigation, and Figure 4 shows the survey layout for the AAH study site.

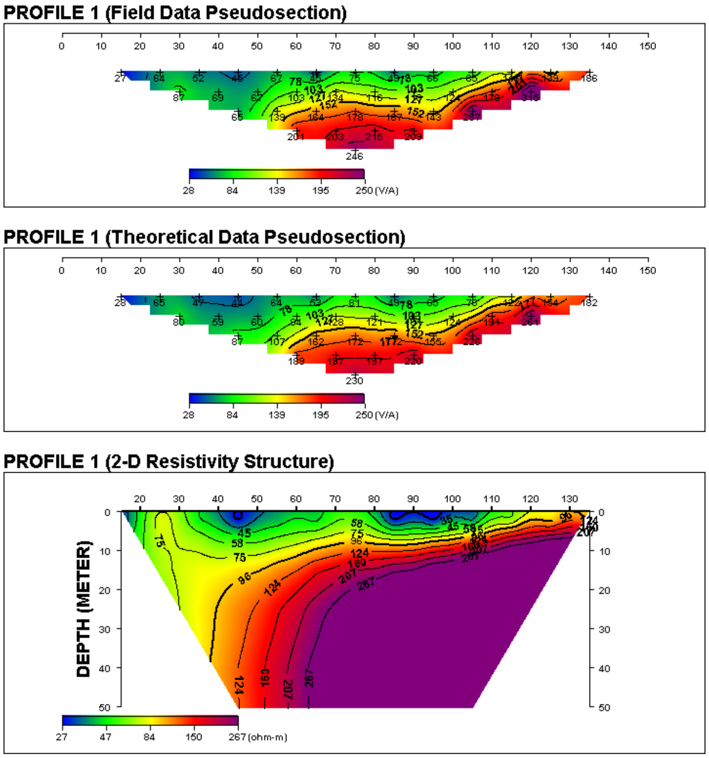
4.1. *Field layout and data acquisition*

For the VES survey, measurements were acquired at ten fixed locations. Electrode spacing was gradually increased to record changes in apparent resistivity with depth. For the CST survey, electrodes were moved along fixed separations during two lateral traverses to identify changes in horizontal resistivity.

5. Results and discussion

5.1. *Curve matching and subsurface interpretation*

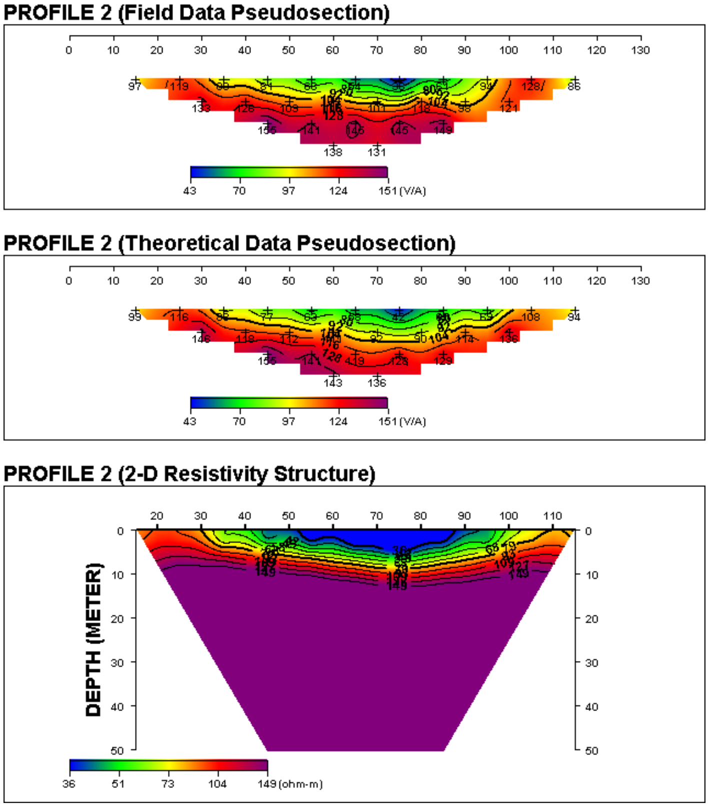
Resistivity curves were matched manually and by computer modeling to estimate layer resistivities and thicknesses. The H-type curve, which is typical of a weathered basement profile, was prominent and showed a conductive layer bounded by two resistive layers. The important conclusions are as follows: the topsoil resistivity ranged from 186.9 to 1222.0 Ω m; the resistivity of the weathered layer ranged from 13.6 to 70 Ω m; and the resistivity of fresh bedrock was between 210.0 to 834.7 Ω m. These values


PROFILE 1 (Field Data Pseudosection)

PROFILE 1 (Theoretical Data Pseudosection)

PROFILE 1 (2-D Resistivity Structure)

Figure 15. Two-dimensional view of CST profile 1.


PROFILE 2 (Field Data Pseudosection)

PROFILE 2 (Theoretical Data Pseudosection)

PROFILE 2 (2-D Resistivity Structure)

Figure 16. Two-dimensional view of CST profile 2.

indicate alternating basement rock, clay, and sand/laterite zones, including low-resistivity zones. The VES data interpretations for stations 1–10 are presented in Figures 5–14.

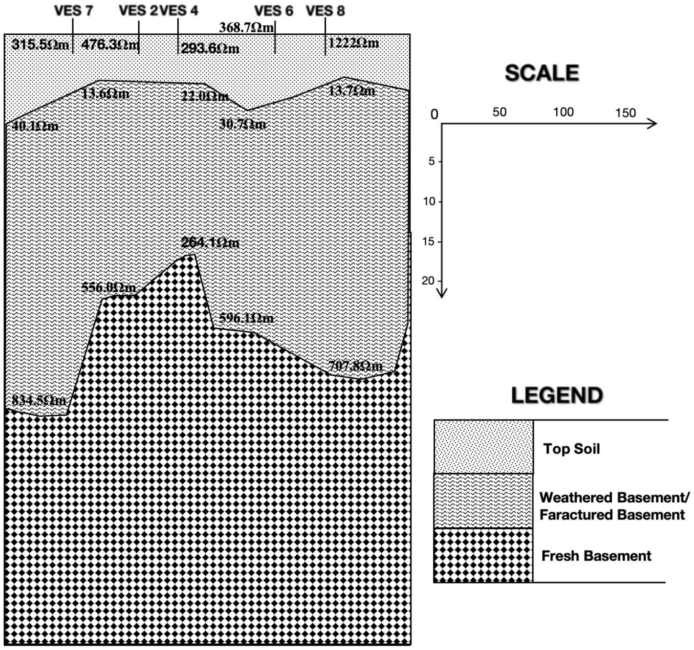


Figure 17. Geoelectric section along profile 1 using Surfer.

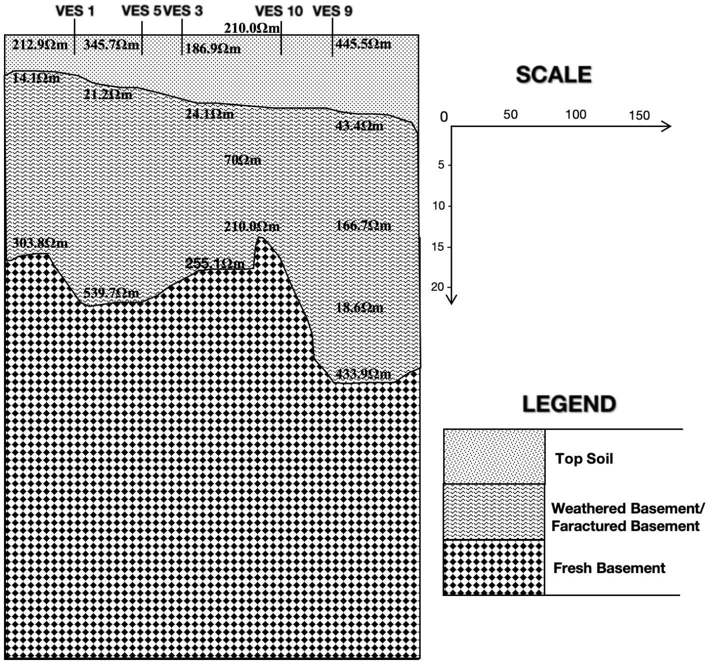


Figure 18. Geoelectric section along profile 2 using Surfer.

5.2. Profile interpretation

Two-dimensional CST resistivity profiles (Figures 15 and 16) show clear variations in subsurface composition. High-resistivity zones (> 1000 Ω m) indicate compact, coarse-grained materials or fresh rock that may be suitable for shallow foundations. Low-resistivity zones (< 50 Ω m) indicate clayey or saturated soils that require either deeper foundations or soil stabilization.

The geoelectric sections of profiles 1 and 2 are shown in Figures 17 and 18, respectively.

6. Conclusion

The study identified three main subsurface layers: topsoil, weathered basement, and fresh bedrock. For shallow foundations, the weathered and clayey zones at intermediate depths could present difficulties. Based on the KHK-type curve shown in Figure 13, it is advised that layers between 0 and 0.5 m may sustain shallow foundations if compacted. The stability of layers between 0.5 and 1.9 m needs to be assessed, and deeper layers might provide adequate bearing capacity for deep foundations. Overall, resistivity techniques provided useful structural information for efficient foundation design, emphasizing the need to combine direct geotechnical testing with geophysical data for optimal site assessment.

Data availability

Data will be made available upon reasonable request from the corresponding author.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

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