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Subsurface Soil Characterisation Using Vertical Electrical Sounding for Supporting Infrastructure Development at Syiah Kuala University

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Abstract

This study characterises the subsurface soil properties in the western sector of Syiah Kuala University, specifically the Kopelma Darussalam area, using Vertical Electrical Sounding (VES) with a Schlumberger configuration. Nine measurement points were deployed to obtain resistivity profiles supporting infrastructure development planning. The results indicate that the surface layer (0–15 m) exhibits high resistivity (12.0–270.2 Ωm), suggesting dry sandy material with high permeability and sufficient bearing capacity. Below 15–30 m, resistivity decreases (1.9–26.5 Ωm), indicating a water-saturated layer potentially functioning as an aquifer, which has implications for soil stability. The deepest layers (>30 m) show low resistivity (<5 Ωm), reflecting low-permeability materials less suitable for heavy construction, though some high-resistivity anomalies suggest dense sandstone formations suitable for foundations. These findings provide preliminary geotechnical zoning insights, aiding developers in selecting appropriate foundation locations, improving construction safety, and ensuring long-term infrastructure stability at University Syiah Kuala.



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Introduction

Infrastructure development is crucial for driving progress, especially for higher education institutions like Syiah Kuala University (USK). The ongoing campus expansion includes constructing faculty buildings, research centers, laboratories, and student facilities. This requires a thorough understanding of soil conditions to ensure long-term safety, structural stability, and cost efficiency [1,2,3]. Although geotechnical investigations are often used for

this purpose, their spatial coverage is often limited due to their cost and invasive nature. Therefore, the Vertical Electrical Sounding (VES) method provides a practical, extensive, and non-destructive approach for subsurface mapping [4]. The VES method can identify variations in soil resistivity, which is closely related to lithology, water content, and strong or weak layers [5,6,8]. In seismically active areas like Banda Aceh, this information is crucial for determining the appropriate foundation system, avoiding hazardous zones, and anticipating risks such as ground subsidence and earthquake amplification [7]. Despite its potential, the application of VES in supporting infrastructure planning at educational institutions, particularly in Aceh, remains limited. This research is driven by the need to address this gap by providing location-specific subsurface characterization in the USK campus area, which can serve as a reference for future construction planning. The objective is to support more accurate and efficient geotechnical zoning, foundation design, and early risk mitigation strategies within educational infrastructure development.

The VES method is essential in geophysical research for assessing soil properties by measuring electrical resistivity. This measurement helps determine essential soil properties such as moisture, porosity, and composition to understand subsurface conditions and their impact on infrastructure development [20, 43]. Utilizing the Schlumberger electrode configuration, this technique enables vertical investigation to depths of several meters, rendering it suitable for preliminary assessments of development sites [9,10]. In addition, research by [11] successfully differentiated clay, sand, and bedrock layers by employing the Schlumberger configuration, thereby illustrating the relationship between material type and resistivity values. Additional findings indicate a strong correlation ($R^2 = 0.88$) between soil moisture and resistivity, while lower moisture content correlates with higher resistivity values in the area [12]. This method provides a vertical profile of lithologic distribution and aids in identifying geotechnical weak zones that may affect structural stability [13]. Previous studies have used the VES method for civil engineering and site planning. However, its specific application in campus environments in tropical regions remains comparatively limited [14, 15].

Inversion methods are essential for analyzing VES data, transforming apparent resistivity into subsurface models. The commonly used 1-D inversion approach is efficient and provides quantitative details on layer thickness and resistivity, but assumes horizontal layering. This assumption can lead to misinterpretations in areas with lateral heterogeneity or complex structures [44]. On the other hand, 2-D inversion techniques, often based on the joint interpretation of multiple VES soundings, offer more accurate cross-sectional images and reduce uncertainty. However, they require more data collection and computational effort [45]. This study uses 1-D inversion with the Schlumberger configuration to balance accuracy and efficiency for initial site-specific geotechnical characterization at Syiah Kuala University.

The resistivity method is widely used for subsurface mapping [38, 40, 41, 42], but there is a gap in integrating geophysical data with geotechnical studies for infrastructure development at educational institutions. This research fills that gap by analyzing the physical properties in the western sector of Kopelma Darussalam at Syiah Kuala University, Banda Aceh, using the Vertical Electrical Sounding (VES) technique. Since the area is designated for new infrastructure and is prone to land use changes, preliminary subsurface information is crucial for identifying soft layers like water-saturated clays or loose sands that could affect structural stability.

Unlike previous studies that mainly focused on aquifer detection or regional resistivity profiling [38, 40, 41, 42], this study explicitly utilizes the VES method to support site-specific geotechnical zoning for campus infrastructure, addressing foundation planning, drainage, and safety considerations [39]. It also emphasizes the limited application of VES in educational campuses within Aceh, providing customized resistivity interpretations customized for construction projects in an area with complex alluvial deposits and seismic risks. The novelty of this research lies in employing VES for geotechnical zoning within the Syiah Kuala University campus, where resistivity interpretations are combined with geotechnical considerations to offer practical guidance for foundation design and early risk mitigation in a seismically active alluvial environment.

Regional Geology

The Kopelma Darussalam area is part of the coastal lowland zone formed by sedimentation from large river activities, especially the Krueng Aceh. It is located in the northern part of Sumatra Island and falls within the Banda Aceh and Aceh Besar Alluvial Plain regions. According to the geologic map of the Banda Aceh sheet [25], the surface lithology here is mainly composed of young Quaternary deposits (Qh) made up of clay, silt, sand, and gravel, which result from river, swamp, and flood deposits, as depicted in Figure 1. These Quaternary deposits are typically unconsolidated, making them soft and susceptible to changes from tectonic activity or surface loading. Their thickness varies from a few to tens of meters, depending on their position and flow history. Because they originate from different sources and depositional conditions, the subsoils in this area are heterogeneous, differing in texture, density, and water content.

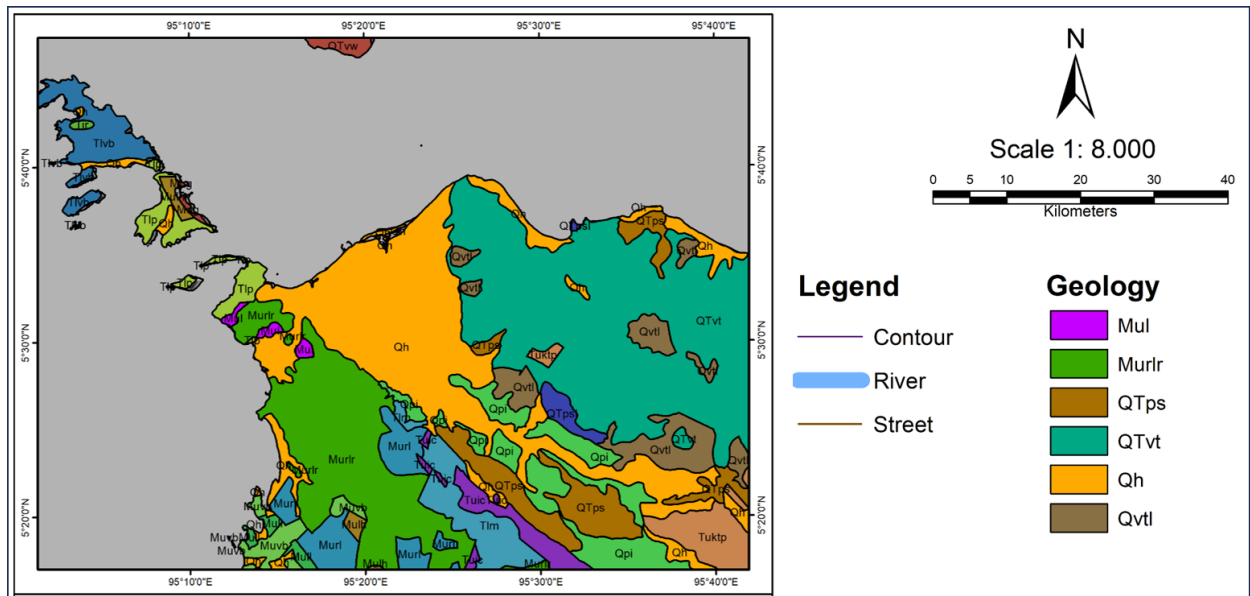


Figure 1. Geological map of the research area

Regarding geological structure, the Banda Aceh area is near active tectonic systems, including the Sumatra Fault in the west and minor fault systems that influence river patterns and landforms. Although not directly on the main fault line, tectonic effects are still significant, especially regarding vulnerability to liquefaction, land subsidence, and the risk of shallow

earthquakes. This should be a concern in infrastructure development. In a geotechnical and hydrogeological context, the Qh unit is important because it often contains shallow aquifers and groundwater-bearing layers, particularly in high-porosity sand and gravel [26]. Therefore, the USK campus area in regional geology is built on heterogeneous, water-saturated, and lithologically complex young alluvial deposits, significantly impacting soil stability, groundwater potential, and civil engineering and building infrastructure planning.

Theory and Calculation

The VES method is one of the geophysical approaches to identify vertical variations in subsurface resistivity using measurements of electric currents and potential differences at the ground surface. This technique is widely used in engineering geology and hydrogeology exploration due to its ability to detect thickness and lithology distribution non-destructively [16, 17, 18]. One of the most commonly used electrode configurations in the VES method is the Schlumberger configuration, which consists of four linearly arranged electrodes, two current electrodes on the outside (A and B) and two potential electrodes in the middle (M and N). In this configuration, measurements are taken by gradually increasing the distance between the current electrodes ($AB/2$) to reach greater depths. At the same time, the distance between the potential electrodes (MN) is maintained constant or only slightly increased when the signal becomes too weak [19, 20, 21]. The diagram of this electrode rule can be seen in Figure 2.

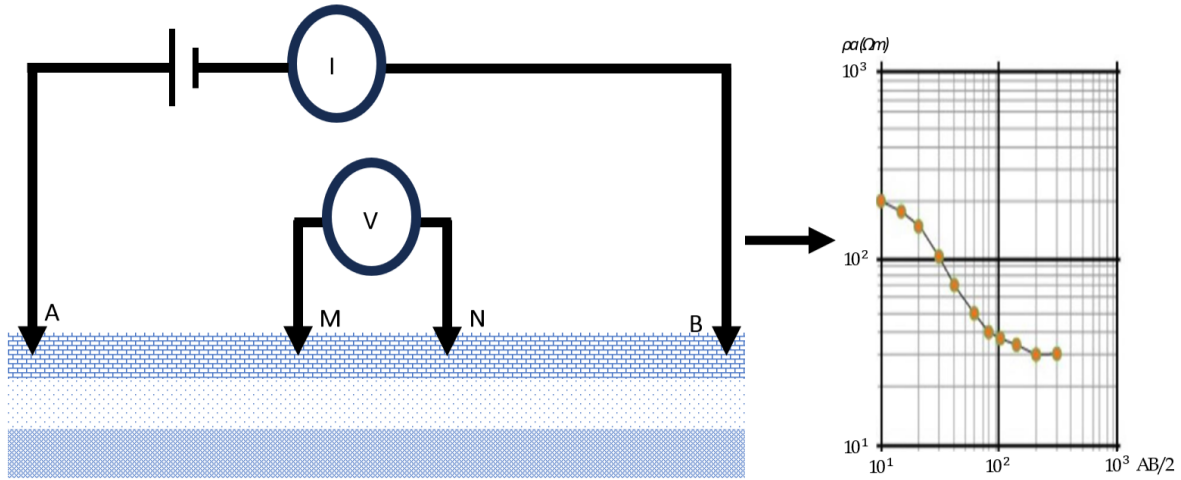


Figure 2. (a) General scheme of a soil-resistivity measurement using the Schlumberger configuration with a four-electrode device (ABMN), (b) bi-logarithmic diagram for the representation of VES measurements [20]

The apparent resistivity can be calculated using the measured potential difference and applied current, as shown in Equation (1). The apparent resistivity (ρ_a) is calculated as:

$$\rho_a = K \frac{V}{I} \quad (1)$$

V is the measured potential difference, I is the applied current, and K is the geometric factor that depends on the distance and arrangement of the electrodes [4, 20].

The resistivity data obtained is then plotted as a logarithmic function of the $AB/2$ distance. This results in a VES curve that can be analyzed to identify subsurface layer types such as A-type, H-type, K-type, and Q-type [21]. The advantage of the Schlumberger configuration lies in field efficiency, as only the current electrodes need to be moved, so this method is considered more practical and economical than other configurations, such as Wenner [20, 21]. In civil engineering, especially for site mapping and building foundation design, the VES method with the Schlumberger configuration is advantageous in providing preliminary information on soil layer thickness and physical properties. Applying this method in tropical environments and campus areas, such as at Syiah Kuala University, provides a scientific basis in assessing the technical feasibility of a site for infrastructure development [15, 22].

Experimental Method

This research was conducted in the West Sector area of USK Campus, Kopelma Darussalam, Banda Aceh, an area with a campus facility development plan. This study aimed to characterize the subsurface conditions as part of the early stages of infrastructure development planning. The VES method with Schlumberger configuration achieved this goal, effectively identifying vertical resistivity variations and subsurface lithological structures [23]. The Schlumberger array was selected because it effectively delivers detailed vertical profiles with minimal field disturbance, making it ideal for evaluating geotechnical weak zones.

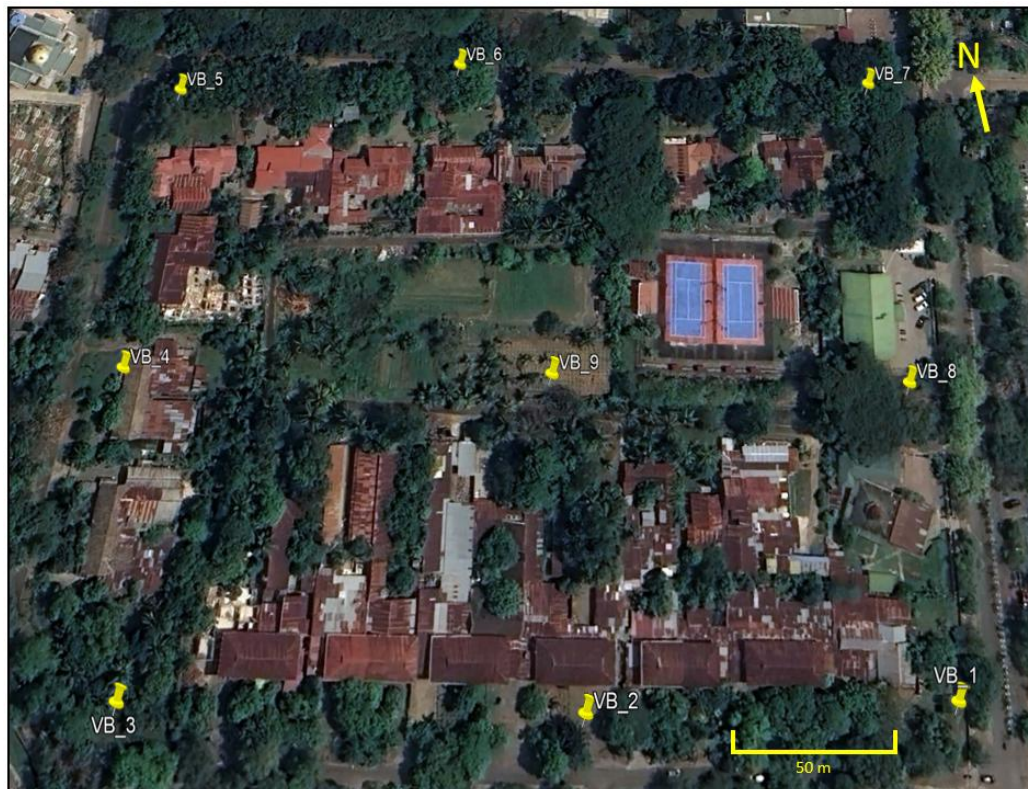


Figure 3. Map of the research area

Figure 3 shows that measurements were carried out at nine sounding points (VB_1 to VB_9) evenly spread across the study site. The locations were chosen based on accessibility and how well they represent local geological variations, considering the planned footprint of new buildings and facilities. At each point, resistivity data were obtained by injecting an electric current through a pair of current electrodes (A and B) and measuring the potential difference between electrodes M and N. An illustration of the field measurements can be seen in Figure 4. The distance between the current electrodes (AB/2) is gradually increased. In contrast, the distance between potential electrodes (MN) is kept small until the signal weakens, according to the standard Schlumberger configuration procedure [19]. Multiple readings were conducted at each point to guarantee data reliability.

The recorded data in the form of voltage and current were then converted into an apparent resistivity value (ρ_a) using the formula:

$$K = \pi \frac{(L^2 - l^2)}{2l} \quad (2)$$

$$\rho_a = K \frac{V}{I} \quad (3)$$

Where k is a geometric factor that depends on the electrode spacing configuration [20, 21], this measurement helps determine essential soil properties such as moisture, porosity, and composition, which are directly related to geotechnical conditions and the potential bearing capacity of the soil [15, 24].

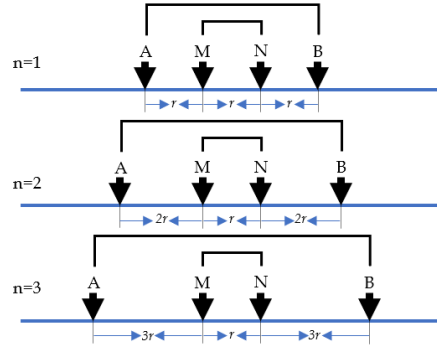


Figure 4. Illustration of field measurements [20]

The acquired data were then plotted into a log-log curve between apparent resistivity and AB/2 distance to generate a VES interpretation curve. Initial interpretation was carried out using the curve matching method, which provides a preliminary estimation of the number of layers, thickness, and resistivity values. The data were then analyzed quantitatively using IPI2Win software, which applies a layered 1-D inversion approach [20]. Iterative adjustments were conducted until a satisfactory fit between measured and modelled curves was achieved, minimizing inversion errors and ensuring reliable determination of subsurface layering.

This approach allowed the determination of the number of layers, their thickness, and resistivity values, which are directly linked to geotechnical conditions and the soil's physical properties. Higher resistivity values generally indicate coarser, drier, and denser materials with greater potential for bearing loads. In contrast, lower resistivity values may suggest

water-saturated or fine-grained soils with reduced stability and load-bearing capacity [15, 24]. This information provides practical guidance for selecting suitable foundation locations and planning safe infrastructure development.

Result and Discussion

Nine data points were collected during the acquisition using the VES Method with Schlumberger configuration, VB_1 to VB_9. Table 1 displays the resistivity values derived from the inversion process. The interpretation of the VES data is based on the resistivity value [20] and is adapted to the geological conditions of the data collection site. The results from each point show different depths, thicknesses, and rock resistivity values in each layer. The shallow layer at 0-5 m and 0-15 m shows resistivity values from 12.0 to 270.2 Ωm . Higher resistivity indicates granular materials like dry, loose sand or gravel with well-defined grains [27]. This is evident at point VB_7, which has the highest surface resistivity of 270.2 Ωm , suggesting a layer of weathered, dry sand near the surface. This interpretation aligns with previous findings by [28], who linked resistivity values of 251-385 $\Omega\text{ m}$ to dry sand in Wadi El Natrun.

Conversely, a surface layer of well-graded dry sand is highly relevant for geotechnical properties like high permeability and sufficient bearing capacity for light to medium structures. Granular materials typically have low cohesion but high internal friction, making them stable when dry but vulnerable to erosion and reduced bearing capacity when saturated or affected by subsurface lateral flow [29]. Although geophysically this layer shows good potential as a base for construction, direct geotechnical tests such as SPT or CPT are necessary to verify its shear and consolidation strengths. Additionally, high resistivity in shallow layers can indicate good natural drainage, which is crucial for foundation stability. Adequate drainage reduces pore water pressure buildup, especially in tropical regions with high rainfall like Banda Aceh [30].

At 5-30 m depths, typically considered the middle zone, resistivity values drop significantly at most measurement points, ranging from 1.9 to 26.5 Ωm . This range usually suggests the presence of water-saturated layers like saturated sand, sandy clay, or silt, which show high electrical conductivity due to pore water and conductive clay minerals [31]. Specifically, at point VB_3, resistivity sharply declines from 40.1 Ωm at 6-13 m depth to 2.6 Ωm at 13-24 m depth, indicating a lithological change from relatively dry material to a more water-saturated zone, likely representing a potential aquifer layer [28].

Water-saturated materials in the intermediate zone have significant technical implications, especially regarding soil stability and load-bearing capacity. Soils with high moisture, like sandy clays or saturated silts, usually exhibit low shear strength and can experience considerable plastic deformation under structural loads, particularly in undrained conditions. High saturation levels can also increase pore water pressure, which directly reduces effective stress and compromises the stability of slopes or shallow foundations. References [32, 33] note that pore water pressure in saturated clay soils causes a slow yet continuous consolidation process, which can lead to long-term settlement.

The deepest zone (>30 m) shows low resistivity readings at most measurements, mostly below 5 Ω m. This suggests the presence of deep clay layers, saturated silts, or altered rocks rich in conductive minerals like clays that can retain large amounts of pore water. Such materials are identified as soils with low permeability, high potential for volume change, and weak shear strength, making them unsuitable for direct support in heavy construction. Key concerns include long-term plastic deformation and consolidation settlement when these layers are near critical foundation depths. Studies such as [34] on marine clay in Jiangsu indicate that resistivity values between 5-10 Ω m point to very low permeability, high expansion potential, and low bearing capacity, confirming that this layer is not ideal for supporting heavy structures.

Table 1. Interpretation at each research point location

Point	Zone	Depth (m)	Resistivity (Ω m)	Lithology Interpretation
VB_1	1	0-5	167.9-100.1	Dry sand/gravel
	2	5-20	10.6-15.4	Wet clay/silt
	3	20-40	6.1-10.4	Water-saturated clay
	4	>40	1.1-2.3	Highly saturated clay
VB_2	1	0-6	26.4-13.1	Fine sand mixed with clay
	2	6-25	3.4-9.2	Saturated clay
	3	25-40	1.8-2.5	Soft silt
	4	>40	3.0-5.0	Stiff clay
VB_3	1	0-6	69.7-44.2	Sand/gravel
	2	6-13	26.2-40.1	Sand mixed with clay
	3	13-24	2.6-7.3	Saturated clay
	4	>24	2.3-4.9	Stiff clay
VB_4	1	0-6	128-71.7	Dry sand/gravel
	2	6-18	15.6-26.5	Mixed sand/clay
	3	18-30	3.0-4.1	Saturated clay
	4	>30	5.7-8.0	Stiff clay
VB_5	1	0-9	34.8-12.0	Fine sand/clay
	2	9-18	2.5-4.4	Saturated soft clay
	3	18-20.7	15.8-16.2	Wet sand
	4	>20.7	20.2-20.3	Silty sand
VB_6	1	0-16	17.5-13.8	Sand mixed with silt
	2	16-30	5.1-9.9	Saturated clay
	3	30-45	2.5-3.0	Soft clay
	4	>45	4.6	Stiff clay
VB_7	1	0-5	270.2-58.3	Dry gravel
	2	5-13	33.5-41.7	Sand gravel
	3	13-32	1.9-3.2	Saturated clay
	4	>32	2.0-2.5	Stiff clay
VB_8	1	0-5	33.1-13.8	Silty sand
	2	5-13	3.4-6.2	Soft clay
	3	13-22	1.9-4.9	Saturated clay
	4	>22	0.7-1.9	Highly saturated silt/clay
VB_9	1	0-15	169.8-27.3	Coarse sand/gravel
	2	15-25	7.9-17.3	Wet sand
	3	25-30	4.9-11.8	Silt/clay
	4	>30	10.0-31.1	Silty sand

Anomalies are noted at VB_5 and VB_9, where resistivity at depths over 30 m increases sharply to 20.3 Ωm and 31.1 Ωm . These readings indicate the possible presence of water-saturated dense sandstone or conglomerate, lithologies characterized by high porosity coupled with significant compaction. Such formations are suitable as bearing layers in geotechnical engineering, like deep foundations such as pile or pit foundations, especially if they are within 40 m depth [35]. The dense rock or consolidated sand in this zone also benefits long-term structural stability, owing to its higher modulus of elasticity and bearing capacity than saturated clays. This is particularly important in the design of tall structures or heavy infrastructure, such as buildings, where stability and deformation are critical factors [36]. Resistivity profiles indicate three main vertical zones based on geotechnical characteristics: the surface layer, which may be suitable as structural fill material; the middle layer, which is water-saturated and must be carefully evaluated regarding load-bearing capacity and the risk of ground subsidence; and the deeper layer, which may indicate the presence of solid rock or impermeable material [3,37]. This interpretation provides important input at the early stages of infrastructure planning, particularly in determining the appropriate foundation type, estimating safe load depths, and identifying zones requiring soil improvement or reinforcement. Therefore, these findings directly support decision-making in foundation design, risk mitigation, and construction safety strategies for ongoing and future campus development.

Conclusion

This research used the Schlumberger configuration of the Vertical Electrical Sounding (VES) method to characterize the physical properties of soil in the western sector of Syiah Kuala University. The findings identified three main zones based on vertical resistivity profiles. The surface layer (0–15 m) shows high resistivity, indicating that granular materials such as dry sand have high permeability and good bearing capacity and are suitable for light to medium structures. The intermediate zone (15–30 m) displays low to moderate resistivity, suggesting the presence of water-saturated materials such as saturated sands and sandy clays, which may act as aquifer layers but can also reduce soil stability and bearing capacity in saturated conditions. The deepest zone (>30 m), with very low resistivity, indicates the presence of saturated clay or silt layers, which are less suitable as direct foundation support for heavy construction. However, localized anomalies suggest potential sandstone formations that could provide stronger foundation support. The inversion of VES data using IP2Win was performed iteratively to ensure stability, with each iteration decreasing the discrepancy between observed and calculated apparent resistivity values. This iterative process confirmed the reliability of the interpreted subsurface layers, increasing confidence in identifying geotechnical weak zones and their load-bearing capacity. These findings provide practical insights for infrastructure planning at Syiah Kuala University by guiding decisions on foundation design and soil stability assessment. Moreover, this study highlights the importance of further direct geotechnical testing to verify the suitability of the identified soil layers for construction purposes.

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