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Application of Vertical Sounding (VES) In Mapping Subsurface Profiles of Erosion Sites: A Case Study from IMO State, Nigeria

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ABSTRACT

Gully erosion is a critical environmental problem in southeastern Nigeria, particularly in Imo State, where intense rainfall, fragile geology, and human activities have accelerated land degradation. The EzeokeNsu area in Ehime Mbano is among the worst affected, with erosion displacing communities, destroying infrastructure, and reducing agricultural productivity. Despite its severity, subsurface data necessary for effective erosion control remain limited. This study investigated the subsurface profiles and geotechnical properties influencing gully erosion in EzeokeNsu using Vertical Electrical Sounding (VES) and laboratory-based geotechnical testing.VES was conducted at ten stations along the erosion site using the Schlumberger configuration and OHMEGA-500 resistivity equipment. Data were processed with AGI 1D software to delineate subsurface layers. Soil samples collected at 15 cm and 30 cm depths were analyzed for moisture content, grain size distribution, and shear strength. Results revealed three main subsurface units: sandstone, siltstone, and silty sand. Sandstone displayed high resistivity, reflecting a stable and consolidated material. In contrast, siltstone and silty sand exhibited low resistivity, indicating permeable, weak soils prone to infiltration and erosion. The average water table depth was 9 m, with highly saturated zones corresponding to unstable soils.Geotechnical results showed high soil moisture (10.2–10.6%) and low shear strength (21.4–23.2 kN/m²), confirming vulnerability to erosion during rainfall. Grain size analysis indicated predominance of sand (55–70%) with significant silt and clay fractions, reducing cohesion and stability.The findings demonstrate that loose sandy soils, weak subsurface layers, and shallow water tables drive gully development and expansion in the study area. Combining geophysical and geotechnical approaches provided valuable insights into erosion mechanisms. The study recommends targeted control measures, including reforestation, soil stabilization, and improved drainage, to mitigate gully erosion impacts in EzeokeNsu and similar environments.

Keywords: Vertical Electrical Sounding (VES)**;** Subsurface profiling**;** Gully erosion**;** Geotechnical properties**;** Soil resistivity**;** Imo State, Nigeria**;** Erosion control

I. INTRODUCTION

Soil erosion is a critical environmental issue worldwide, causing significant degradation of land resources and adversely affecting agricultural productivity, infrastructure, and human settlements. In southeastern Nigeria, gully erosion has become one of the most prominent forms of land degradation, with widespread effects on the environment and the livelihoods of local communities. This region, particularly Imo State, faces severe gully erosion due to its fragile

geology, intensive rainfall, and human-induced activities, such as poor land use and inadequate infrastructure development (Ofomata, 2000; Poesen et al., 2003). Erosion sites in the area, like those in EzeokeNsu, continue to expand, threatening homes, farmlands, and roads, while the traditional methods of erosion control have often proved insufficient.

Erosion is a natural process driven by agents such as water, wind, and human activity. In southeastern Nigeria, however, gully erosion is primarily driven by intense rainfall, improper land management practices, and the region's geology. The Ameki Formation in southeastern Nigeria, which consists of soft, unconsolidated sandstones and sandy clays, is particularly susceptible to erosion, as the soil lacks the cohesive properties necessary to withstand heavy water runoff (Nwajide, 2003; Igwe, 2005). The impact of this erosion is compounded by human activities, such as road construction, farming, and deforestation, which disturb the natural soil structure and lead to the creation of deep, wide gullies (Abegunde et al., 2003; Olori, 2006).

Vertical Electric Sounding (VES) is a geophysical method that can provide valuable insights into the subsurface conditions of erosion sites. This technique measures the resistivity of the soil and bedrock, offering a non-invasive way to characterize soil properties, determine the depth to the bedrock, and identify the underlying lithology. These data are crucial for understanding the erosion process, as the physical properties of the soil such as resistivity, permeability, and shear strengthplay a significant role in soil erosion susceptibility (Spector et al., 2006; Telford et al., 1990). VES can help identify areas with weak soil layers that are prone to detachment and erosion.

In addition to geophysical surveys, geotechnical testing provides critical data on the physical properties of soil that influence erosion dynamics. Key properties such as moisture content, grain size distribution, and shear strength have a direct impact on a soil's ability to resist erosion. Soils with high moisture content and low cohesion are more susceptible to being washed away by rainwater, particularly in regions with heavy rainfall like southeastern Nigeria (Igwe, 2005; Poesen et al., 2003). Studies have shown that the erosion-prone soils in the region often consist of loose sand and silt, which, when subjected to heavy rainfall, are easily eroded, leading to the formation of gullies (Idah et al., 2008; Onyegbule, 2005).

The increasing prevalence and severity of gully erosion in EzeokeNsu in Ehime Mbano underscores the urgency of addressing this environmental challenge. While several studies have highlighted the causes and impacts of erosion, there is a need for more detailed, spatially resolved information on the subsurface conditions that contribute to the development of gullies. Vertical Electric Sounding (VES) offers a unique opportunity to investigate the subsurface characteristics of erosion sites, including the depth of the water table, the resistivity of various soil layers, and the nature of the underlying bedrock. This study, therefore, aims to utilize VES and geotechnical analysis to provide a more comprehensive understanding of the physical conditions that exacerbate gully erosion in EzeokeNsu, with the goal of informing more effective mitigation strategies.

This research aims to assess the subsurface characteristics of erosion sites in EzeokeNsu through the application of Vertical Electric Sounding (VES) and geotechnical testing.

Gully erosion remains one of the most severe environmental challenges in southeastern Nigeria. The increasing rate of soil degradation and loss of agricultural land due to erosion calls for a more scientific approach to understand the underlying causes of the problem. Traditional methods of mapping erosion sites are often limited in scope and do not provide detailed information on the subsurface conditions that influence the erosion process. VES offers a non-invasive, cost-effective solution for mapping subsurface profiles and identifying the geological features that contribute to the formation of gullies. Furthermore, geotechnical testing provides critical data on soil properties, which are essential for designing sustainable erosion control measures. This study fills the gap by using both VES and geotechnical analysis to provide a comprehensive assessment of the erosion site in EzeokeNsu.

II. LITERATURE REVIEW

2.1 Soil Erosion and Its Impact

Soil erosion is a natural process where the topsoil, which is vital for plant growth and agricultural productivity, is detached and transported by external forces such as wind, water, and human activities. The most common form of erosion in tropical regions, especially in areas with steep slopes, heavy rainfall, and weak soil structure, is gully erosion. In southeastern Nigeria, gully erosion has become one of the leading causes of land degradation, displacing communities, destroying farmlands, and impacting the environment (Ofomata, 1985; Idah et al., 2008).

Gully erosion occurs when runoff water accumulates in a narrow, defined channel and erodes the surrounding soil. Over time, these

gullies deepen and widen, often causing permanent damage to the landscape (Poesen et al., 2003). In southeastern Nigeria, areas like Anambra, Imo, and Abia states are most affected by gully erosion due to their sandy and friable soil compositions, which are easily eroded by water (Arua, 1986; Nwajide, 2003).

The consequences of gully erosion extend beyond the immediate loss of soil. It leads to reduced agricultural productivity due to the destruction of farmland, loss of vegetation, and disruption of hydrological cycles. Additionally, the formation of gullies often causes severe damage to infrastructure, such as roads, bridges, and buildings, which are further undermined by the erosion process (Igwe, 2005).

2.2 Geophysical Methods in Erosion Studies

Geophysical methods have become increasingly essential for understanding the subsurface characteristics of erosion-prone areas. Traditional soil erosion studies primarily focus on surface features, but these methods fail to provide insights into the factors contributing to soil detachment and transportation below the surface. The use of geophysical techniques, such as Vertical Electric Sounding (VES), has proven to be a valuable tool in mapping the subsurface profiles of erosion sites (Telford et al., 1990).

Vertical Electric Sounding (VES) is a geophysical method that measures the resistivity of subsurface materials by applying an electric current and measuring the potential difference. The resistivity values indicate the type of subsurface materials (e.g., sand, clay, sandstone, siltstone), their porosity, and the depth of water tables or bedrock. VES allows for a detailed analysis of the geoelectrical properties of the soil, which are critical for understanding the vulnerability of the area to erosion.

Studies by Spector et al. (2006) and Telford et al. (1990) have highlighted the ability of VES to map vertical variations in soil resistivity, which can help identify weak layers prone to erosion. For instance, in areas with weak, unconsolidated soils, VES can identify depth variations, helping engineers design targeted erosion control measures. VES is particularly useful in tropical regions where soil heterogeneity is high, and the subsurface layers vary significantly.

2.3 Geotechnical Testing in Erosion Studies

Alongside geophysical methods, geotechnical testing plays a crucial role in understanding the physical properties of soils and their relationship to erosion susceptibility. The geotechnical properties of soil, such as moisture content, grain size distribution, compaction, and shear strength, all influence a soil's ability to resist erosion. Soils that contain high levels of fine particles (clay and silt) have lower permeability, which increases their susceptibility to water erosion during heavy rainfall (Igwe, 2005).

In areas prone to erosion, particularly gully erosion, the soil's shear strength is one of the most important parameters. Shear strength refers to the ability of soil to resist sliding or failure along a failure plane. Loose soils with low shear strength are highly vulnerable to erosion, especially in regions with steep slopes and intense rainfall (Poesen et al., 2003; Lal, 1998). According to Morgan (1986), understanding the shear strength of soil helps in predicting the stability of slopes and the likelihood of gully formation.

Furthermore, moisture content significantly impacts the erodibility of soil. Soils with higher moisture content tend to be more erodible, especially when subjected to runoff during rainstorms. As rainwater infiltrates the soil, it weakens the bonds between soil particles, making it easier for the soil to be detached and transported by water. Grain size distribution also affects soil erodibility. Soils with a higher proportion of fines (clay and silt) tend to have lower permeability, reducing water infiltration and increasing surface runoff, which accelerates erosion (Igwe, 2005).

2.4 Vertical Electric Sounding (VES) in Gully Erosion Studies

In recent years, VES has gained significant attention as a tool for mapping erosion-prone areas in southeastern Nigeria and other regions with similar environmental conditions. The Schlumberger configuration of VES, which uses a symmetric arrangement of four electrodes, is particularly effective in providing detailed information on subsurface properties. According to Spector et al. (2006), VES is superior in distinguishing vertical variations in resistivity and identifying the presence of water-saturated zones, which are critical in understanding gully formation.

In a study conducted by Abegunde et al. (2003) in southeastern Nigeria, VES was used to assess the subsurface profiles of gully erosion sites. The results indicated that regions with low resistivity values at shallow depths were more prone to erosion due to the presence of loose, water-saturated soils. The study concluded that VES could be effectively used to map erosion sites and guide the design of soil conservation measures.

Similarly, Poesen et al. (2003) used VES to study gully erosion in Mediterranean countries,

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demonstrating that VES could map variations in soil composition and depth to bedrock, which directly influenced gully erosion dynamics. The findings supported the application of VES as a vital tool for identifying subsurface features that contribute to erosion.

2.5 Geotechnical Properties of Soils in Southeastern Nigeria

The soil characteristics of southeastern Nigeria are diverse but are generally susceptible to erosion. The Ameki Formation, which dominates much of the region, consists of sandstones, sands, and silty clays, making it prone to erosion when disturbed. The sedimentary soils in the region are weakly consolidated, with a low cohesion, which increases their vulnerability to water erosion (Nwajide, 2003; Igwe, 2005).

The moisture content of the soil in southeastern Nigeria is generally high, especially during the rainy season, which exacerbates the erosion process. High moisture content reduces soil strength and increases the potential for runoff, leading to gully formation (Lal, 1998). According to Ofomata (1985), the continuous degradation of land in southeastern Nigeria has been linked to the high erosion rates caused by improper land use, such as deforestation and unsustainable agricultural practices.

III. MATERIALS AND METHODS

3.1 Study Area

The study was conducted in the EzeokeNsu area, located in Ehime Mbano Local Government Area (LGA) of Imo State, southeastern Nigeria. The coordinates of the study area are between latitudes 5°42′N and 5°45′N and longitudes 7°10′E and 7°27′E. The area is characterized by significant gully erosion caused by a combination of natural factors, such as soil type and intense rainfall, and anthropogenic factors, including poor land management practices like deforestation, road construction, and farming (Ofomata, 2000; Igwe, 2005).

The erosion site is located near the Ameki Formation, which consists of loose sandstones, sands, and silty clays. The combination of the region's fragile geology, high rainfall, and improper land use has led to severe soil degradation. The gully in the study area is approximately 1 km in length, 5 meters wide, and 27 feet deep, posing a significant environmental hazard to the local communities. The rainy season typically lasts from March to October, with the heaviest rainfall occurring between June and September.

3.2 Fieldwork and Data Collection

Fieldwork for this study involved both geophysical surveys and geotechnical testing. The aim was to collect data that would help map the subsurface profiles of the erosion site and analyze the physical properties of the soil contributing to the gully erosion.

3.2.1 Geophysical Survey (VES Method)

The Vertical Electric Sounding (VES) method was used to measure the apparent resistivity of the subsurface at multiple points across the erosion site. This technique provides valuable information about the subsurface geological layers, depth to water table, and the overall lithology of the area. The following steps were followed:

VES Configuration

The Schlumberger configuration was used, where four electrodes (two current electrodes and two potential electrodes) are placed in a linear arrangement. This configuration was chosen for its ability to provide high-resolution vertical profiling of the subsurface resistivity.

The total electrode spread was 320 meters, and the current electrode spread was varied to measure resistivity at different depths. The current was applied through two current electrodes, and the potential difference was measured between two potential electrodes.

The spread was divided into two halves: one half of the electrodes was placed along the gully to measure the resistivity profile of the erosion site, while the other half was placed on the opposite side to evaluate the surrounding area for comparison.

Data Collection:

OHMEGA-500 Electrical Resistivity Equipment was used to carry out the VES survey. The equipment was connected to a series of electrodes that were placed along the gully and surrounding area at predefined intervals (every 10 meters).At each point, the resistivity values were recorded for varying electrode spacings (ranging from 10 meters to 320 meters) to assess the vertical resistivity distribution of the subsurface.A total of 10 VES stations were established along the gully site to provide a comprehensive assessment of the subsurface conditions.

Data Processing:

The data collected from the field were processed using AGI 1D automatic analysis software. This software helped interpret the

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resistivity data and generate VES curves that represent the resistivity at various depths. The resistivity data were used to derive the lithology of the site, including the depth to the water table, layer composition, and depth to bedrock.

3.2.2 Geotechnical Analysis

In addition to the geophysical survey, geotechnical testing was performed to assess the physical properties of the soil at the erosion site. This testing was important for understanding the moisture content, grain size distribution, and shear strength of the soil, which are critical factors influencing erosion.

Soil Sampling:

A total of three composite soil samples were collected from the site at two different depths: 15 cm and 30 cm.Two of the samples were from the erosive materials (the materials directly involved in gully formation), and the third sample was from a base material layer found below the erosion site.The samples were collected using a manual auger to ensure accurate soil extraction from the identified depths.

Laboratory Testing

After collecting the samples, they were taken to the Federal University of Technology Owerri (FUTO) Erosion Research Laboratory for further analysis. The following laboratory tests were carried out:

Moisture Content Test: The moisture content of each sample was measured using the oven-drying method. This test determined the percentage of water present in the soil, which directly affects its erodibility. Samples were dried at 110°C for 24 hours, and the moisture content was calculated by comparing the weight of the wet sample with the weight of the dry sample.

Grain Size Distribution Test: The sieve analysis method was used to determine the particle size distribution of the soil samples. The samples were washed to remove clay particles, dried in an oven, and sieved using a series of sieves with varying mesh sizes. The amount of material retained on each sieve was weighed and recorded to generate the grain size distribution curve.

Shear Strength Test: The direct shear test was performed to assess the shear strength of the soil. This test measures the resistance of the soil to sliding along a failure plane. A shear box was used, where the soil samples were subjected to a normal load, and the shear force was applied until the sample failed. The shear strength was then calculated using the formula:

Shear Strength=c+σtan⁡(ϕ)\text{Shear Strength} = c + \sigma \tan(\phi)

Where:

cc is the cohesion,

σ\sigma is the normal stress, and

ϕ\phi is the angle of internal friction.

Data Quality Control and Validation

To ensure the reliability of the data. the geophysical measurements were repeated at each station to ensure consistency, the soil samples were carefully preserved in polythene bags to prevent moisture loss before laboratory testing, and the Calibration checks were performed on the VES equipment to ensure accuracy in the resistivity measurements.

3.3 Data Analysis and Interpretation

Once the data were collected, they were analyzed and interpreted in the following steps:

Geophysical Data Interpretation:

The resistivity data were processed to generate resistivity profiles that depicted the variations in subsurface material composition at different depths. This was done using AGI 1D software, which allowed for a detailed analysis of the soil layers, including the depth to bedrock and the presence of water-saturated zones.

Geotechnical Data Interpretation:

The laboratory results were analyzed to determine the moisture content, grain size distribution, and shear strength of the soil samples. These properties were compared to the erosion susceptibility of the materials. For example, soils with high moisture content and low shear strength were identified as being more prone to erosion.

Correlation of Geophysical and Geotechnical Data:

The geophysical and geotechnical findings were correlated to assess the relationship between subsurface conditions and the extent of gully erosion. This correlation helped identify the key factors contributing to erosion in the study area.

IV. RESULTS

4.1 Geophysical Results

The Vertical Electric Sounding (VES) measurements conducted at 10 stations along the erosion site yielded significant findings regarding the subsurface resistivity profiles. The resistivity data helped determine the depth to the bedrock, the water table, and the nature of the subsurface layers, which are key factors influencing the erosion process.

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4.1.1 Resistivity Profiles and Subsurface Lithology

The resistivity values measured during the VES survey varied significantly across the study area, reflecting the heterogeneity of the subsurface materials. The apparent resistivity data from the VES stations were used to model the vertical subsurface layers, including soil, bedrock, and water table.Figure 1 below shows the VES resistivity model for one of the stations, which includes the layered structure of the subsurface and the resistivity values at various depths. The model provides information about the lithology of the subsurface materials, with sandstone, siltstone, and silty sand identified in various layers.

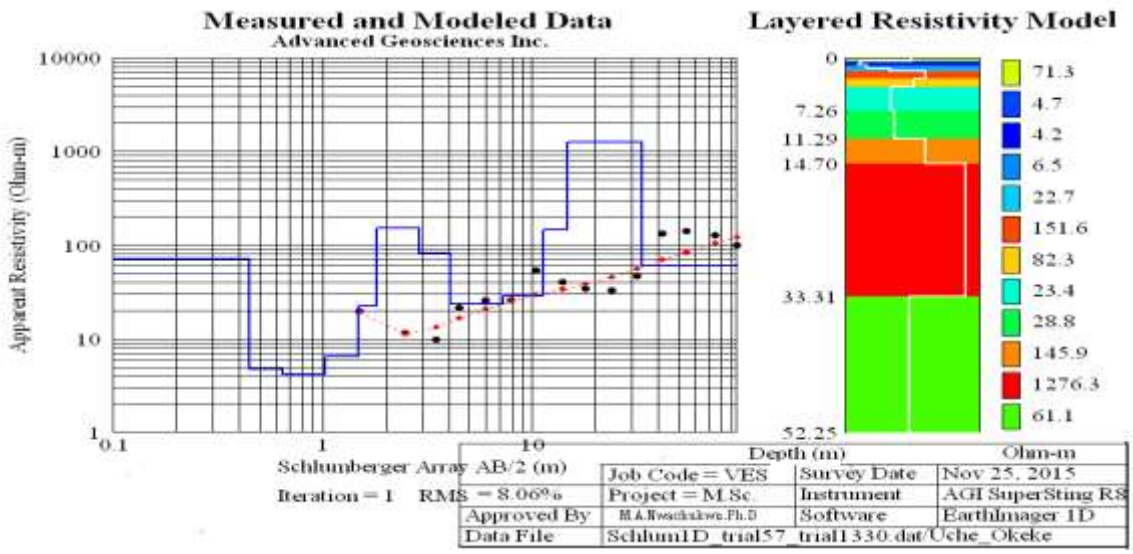


Figure 1: VES Modeled Data.

Depth (m)	Lithology	Resistivity (Ohm-m)	Description
0–9	Sandstone	146	Consolidated bedrock layer
9–18	Siltstone	23	Soft, water-saturated layer
18–27	Silty Sand	28	Loose, erodible material

From the resistivity data, we observed that the sandstone layer had the highest resistivity, indicating that it was more consolidated and resistant to erosion. The siltstone layer, however, had much lower resistivity, indicating that it was weaker and more susceptible to water infiltration, making it prone to erosion. The silty sand layer, with intermediate resistivity, was also prone to erosion, as it is loosely consolidated and easily detached by water.

4.1.2 Depth to Water Table

The depth to the water table varied across the study area, with an average depth of approximately 9 meters. The resistivity values indicated that areas with high water content (low resistivity) corresponded to the presence of shallow water tables. The presence of a shallow water table is a contributing factor to gully formation, as water infiltration weakens the soil structure, making it more prone to erosion.

Table 1: Depth to Water Table Across VES Stations

Station No.	Depth to Water Table (m)	Resistivity (Ohm-m)	Lithology
1	8.5	25	Siltstone, water-saturated
2	9.2	23	Silty sand, high water content
3	10.1	22	Siltstone, saturated layers
4	9.0	24	Sandstone, consolidated bedrock

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These findings highlight the critical role that the water table depth plays in the erosion process. The shallow water table contributes to increased soil moisture content, which weakens the soil and increases the risk of erosion during rainfall events.

4.2 Geotechnical Results

The geotechnical tests conducted on the soil samples from the study area provided further insight into the physical properties of the soil that influence its erodibility. The results of the moisture content, grain size distribution, and shear strength tests are presented below.

4.2.1 Moisture Content and Erosion Susceptibility

The moisture content of the soil was measured at two depths (15 cm and 30 cm) for the erosive materials and the base material. The results indicated relatively high moisture retention in the erosive materials, which contributes to their susceptibility to erosion, especially during heavy rainfall events.

Table 2: Moisture Content of Soil Samples

Sample Location	Depth (cm)	Moisture Content (%)
Erosive Material I	15	10.2
Erosive Material II	30	10.6
Base Material (Control)	15	6.5
Base Material (Control)	30	6.8

The higher moisture content in the erosive materials indicates that these soils are more prone to becoming saturated and less resistant to erosion. This is particularly significant during the rainy season, when the soils' susceptibility to detachment increases.

4.2.2 Grain Size Distribution

The grain size distribution of the erosive materials was dominated by sand particles, with a significant proportion of silt and clay. The sand content ranged from 55% to 70%, and the fine fraction (silt and clay) ranged from 30% to 45%. The loose sandy texture, coupled with high proportions of fines, contributes to the low shear strength of the soil, making it prone to erosion.

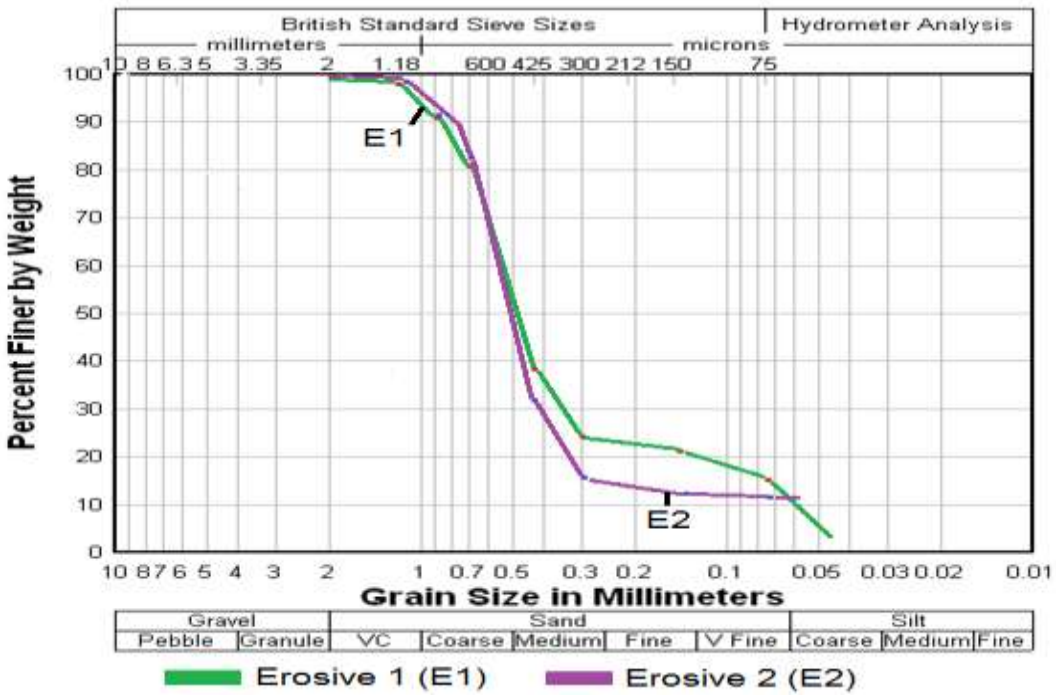


Figure 2: Grain Size Distribution of Erosive Materials

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Graph showing the particle size distribution of the soil samples.

Sieve Size (mm)	Erosive Material I (%)	Erosive Material II (%)
2.0	100	100
1.18	99.5	99.7
0.85	91.3	91.8
0.600	81.0	82.7

The grain size distribution indicates that the erosive materials have a high proportion of fine particles, which reduce their cohesion and increase their susceptibility to erosion by water. These findings align with the VES data, which showed that areas with loose sandy soils are more prone to erosion.

4.2.3 Shear Strength

The shear strength of the soil samples was measured to assess the resistance of the soil to failure due to water infiltration. The results showed that the erosive materials had low shear strength compared to the base material.

Table 3: Shear Strength of Soil Samples

Sample Location	Shear Strength (kN/m²)
Erosive Material I	21.4
Erosive Material II	23.2
Base Material (Control)	45.6

The low shear strength of the erosive materials indicates that these soils are less stable and more prone to being detached by water runoff. This makes them more susceptible to gully erosion, particularly in areas with high rainfall intensity.

4.3 Summary of Results

Geophysical findings from the VES survey revealed that the subsurface layers at the study site consist of sandstone, siltstone, and silty sand. The depth to the water table was found to average 9 meters, and areas with low resistivity indicated the presence of water-saturated, erodible soils.Geotechnical analysis showed that the erosive materials have high moisture content, low shear strength, and a high proportion of sand and fine particles. These factors contribute to the soil's vulnerability to erosion.The combination of high moisture content, low shear strength, and loose, sandy textures in the erosive materials makes these soils particularly susceptible to gully formation, especially during heavy rainfall.



Figure 3: Gully Formation in EzeokeNsu

Photograph showing the gully erosion site, illustrating the exposed soil layers and the erosive materials.

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V. DISCUSSION

5.1 Geophysical Interpretation and Erosion Susceptibility

The results of the Vertical Electric Sounding (VES) survey indicate that the study area is characterized by a layered subsurface profile, with significant variation in resistivity values across the different layers. The sandstone layer at greater depths exhibited the highest resistivity values, suggesting that it is more consolidated and resistant to erosion. Conversely, the siltstone and silty sand layers, with much lower resistivity values, are more susceptible to erosion due to their weaker consolidation and higher permeability.

These findings align with the conclusions of Telford et al. (1990), who stated that subsurface layers with low resistivity, such as siltstone and silty sand, are often more vulnerable to water erosion because they allow for greater water infiltration, which weakens the soil and contributes to gully formation. In contrast, consolidated bedrock layers, such as the sandstone layer, are more resistant to erosion, as water infiltration is limited, and the soil structure is more stable.

The average depth to the water table of approximately 9 meters is significant because a shallow water table increases the moisture content of the soil, reducing its shear strength and making it more vulnerable to erosion. The low resistivity observed in the areas with shallow water tables suggests that these regions have saturated soils, which are particularly prone to erosion during heavy rainfall events, as water infiltration exacerbates soil instability. This is consistent with findings by Abegunde et al. (2003), who noted that areas with high water content in the soil are more susceptible to gully erosion.

5.2 Geotechnical Findings and Soil Vulnerability to Erosion

The moisture content results indicate that the erosive materials have relatively high moisture retention, with 10.2% and 10.6% moisture content at 15 cm and 30 cm depths, respectively. Soils with high moisture content are more prone to erosion because water infiltrates the soil, reducing its shear strength and increasing the likelihood of detachment by runoff. This finding is consistent with the observations of Poesen et al. (2003), who highlighted that soils with high moisture content are more vulnerable to erosion, especially when combined with intense rainfall.

The grain size distribution data further supports this finding, showing that the erosive materials are composed primarily of sand (55%–70%) with a significant proportion of silt and clay (30%–45%). According to Igwe (2005), the presence of a large proportion of fines (silt and clay) makes the soil more susceptible to water-induced erosion, as these fine particles are easily detached and transported by runoff. The high sand content in the erosive materials suggests that the soils are loosely consolidated, which further increases their vulnerability to erosion, as water can easily infiltrate and weaken the soil structure.

The shear strength results, with values of 21.4 kN/m² and 23.2 kN/m² for the erosive materials, are relatively low compared to the base material, which had a shear strength of 45.6 kN/m². This difference highlights the instability of the erosive soils, which are less resistant to shear forces. Soils with low shear strength are more likely to fail under the influence of water, especially when subjected to high runoff during heavy rainfall. This finding is supported by Lal (1998), who emphasized the critical role of shear strength in determining soil stability, particularly in regions with high rainfall intensity.

5.3 Erosion Mechanisms in EzeokeNsu

The combination of loose sandy soils, high moisture content, and low shear strength in the erosive materials makes the area particularly susceptible to gully erosion. The VES data and geotechnical results suggest that these soils are easily eroded, especially in the presence of water-saturated layers, which further weaken the soil structure. This aligns with the work of Igwe (2005), who noted that soils with low cohesion and high permeability are more prone to erosion, particularly in areas with intense rainfall and runoff.

In the EzeokeNsu area, the formation of deep gullies is likely influenced by several factors:

1. High water infiltration into the loose, sandy soils, which increases the moisture content and reduces soil cohesion.
2. The shallow water table and water-saturated soils, which weaken the soil structure, making it more susceptible to detachment by rainfall runoff.
3. The high rainfall intensity in the region, particularly during the rainy season, which contributes to increased surface runoff and accelerates the erosion process.

The VES results provide critical insights into the depth variations in the subsurface, highlighting the potential for gully formation in areas with weak soil layers. This is supported by the findings of Spector et al. (2006), who emphasized that understanding the vertical subsurface structure is key to identifying areas at risk for erosion, as weak

layers in the subsurface provide easy pathways for water to infiltrate and erode the surface.

5.4 Comparison with Previous Studies

The results of this study are consistent with previous research on gully erosion in southeastern Nigeria. Nwajide (2003) and Ofomata (2000) have documented similar erosion mechanisms in regions with high rainfall and weak, unconsolidated soils, such as the Ameki Formation in southeastern Nigeria. These studies found that erosion is exacerbated by poor land management practices, such as deforestation, and the inherent instability of the region's soil.

Abegunde et al. (2003) also used geophysical surveys in southeastern Nigeria to assess erosion-prone areas and found that VES could effectively identify regions with weak, erodible soils. Their findings supported the use of VES as a tool for mapping subsurface layers and guiding the design of erosion control measures.

5.5 Implications for Erosion Control

The findings of this study provide crucial information for designing more effective erosion control measures in the EzeokeNsu area and similar regions affected by gully erosion. The VES and geotechnical data suggest that erosion in the area is primarily driven by shallow water tables, loose sandy soils, and low shear strength. Therefore, erosion control measures should focus on stabilizing the soil and reducing water infiltration.

VI. CONCLUSION

This study highlights the utility of Vertical Electric Sounding (VES) in understanding the subsurface characteristics that contribute to gully erosion. The geophysical and geotechnical data collected from the EzeokeNsu area provide a comprehensive picture of the factors that influence gully formation. The findings indicate that the loose sandy soils, high moisture content, and low shear strength of the erosive materials are the primary factors contributing to the area's vulnerability to erosion. The results underscore the need for targeted erosion control strategies that address both the physical properties of the soil and the hydrological conditions at the site.

Recommendations include:

1. Reforestation and Vegetative Cover: Planting deep-rooted vegetation to stabilize the soil and reduce surface runoff.
2. Terracing and Mulching: Implementing terraces along the gully to slow down water flow and reduce the impact of rainfall on the soil surface.
3. Water Management: Installing proper drainage systems to channel water away from vulnerable areas and reduce water infiltration into the soil.
4. Soil Strengthening: Using soil amendment techniques, such as lime stabilization or geotextile reinforcement, to improve soil cohesion and resistance to erosion.

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