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Assessment of Gully Erosion Through Combined Electrical Resistivity Surveys and Soil Testing in Enugu North, Southeastern Nigeria

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Abstract: *A geophysical investigation was conducted to assess gully erosion in selected parts of the Enugu North zone, Southeastern Nigeria. The study employed the electrical resistivity method alongside soil test analyses to evaluate subsurface conditions contributing to erosion. Four electrical resistivity tomography (ERT) profiles were acquired using the Wenner electrode configuration, with a maximum electrode spread of 200 meters. The resistivity data revealed zones of both low and high resistivity. Low resistivity values are indicative of loosely consolidated, sandy materials, whereas high resistivity values are associated with more compact subsurface features, likely comprising silt, clay, and bedrock. The two-dimensional ERT inversion delineated three distinct subsurface layers: an upper layer of loose, sandy soil; a transitional layer of sandy clay; and a deeper, compacted layer predominantly composed of dry clay. Complementary soil tests further confirmed that the surface materials are primarily composed of loose, non-cohesive soils, including sandy loam, coarse sand, and fine sand. These characteristics suggest a predominance of non-plastic and non-cohesive soils, which significantly contribute to the region's vulnerability to gully erosion.*

Keywords: *Enugu North, Gully Erosion, Electrical resistivity method, Soil test*

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1.0 Introduction

Environmental hazards such as volcanic eruptions, earthquakes, gully erosion, landslides, floods, and geomagnetic storms threaten human life, infrastructure, and socio-economic stability in various regions worldwide. Among these, gully erosion has emerged as a particularly severe and persistent challenge in Nigeria, notably affecting the southeastern region, which includes Enugu, Imo, Anambra, Abia, and Ebonyi States (Egbueri & Igwe, 2020). Scholars like Egbueri *et al*. (2021) and Ofomata (2002) have identified soil erosion as the most formidable environmental threat in Southeastern Nigeria, underscoring its insidious and progressive landscape dissection. In agreement, Nwilo *et al*. (2011) emphasized that gully erosion is a pressing environmental concern in the region.

Gully erosion is characterized by the removal of topsoil along natural drainage pathways due to surface runoff, ultimately leading to the formation of deep and expansive gullies. These erosional features severely degrade the land, diminishing agricultural productivity, contaminating water resources, and disrupting local ecosystems (Poesen *et al*., 2003; Morgan, 2005; Amangabara, 2012). This study focuses on the Enugu North zone within Southeastern Nigeria, a region particularly vulnerable to erosion due to its tropical climate, marked by intense seasonal rainfall and distinct geological conditions. The compounded effects of these natural factors significantly contribute to the acceleration of soil degradation, resulting in far-reaching socio-economic consequences, including the disruption of transport infrastructure, reduced agricultural yields, and threats to local livelihoods (Igwe, 2011).

In response to this pressing environmental issue, the present research conducts a comprehensive investigation employing both geophysical and geotechnical methods, specifically electrical resistivity surveys and soil analysis. Electrical Resistivity Tomography (ERT), a non-invasive geophysical technique, is utilized to probe the subsurface and delineate variations in soil and rock properties. By measuring the resistance of subsurface materials to electrical current, ERT provides valuable insights into moisture content, lithological heterogeneity, and the presence of voids or structural weaknesses, all of which are critical to understanding the genesis and development of gully erosion (Loke *et al*., 2013).

Complementing the geophysical survey, soil test analysis provides a direct evaluation of fundamental soil properties such as texture, composition, permeability, and moisture retention. These parameters are essential for assessing the susceptibility of soils to erosion and identifying the most vulnerable areas (Mossa *et al*., 2012). The integration of both methodologies promises a holistic perspective on the subsurface processes driving gully formation.

Several recent studies have demonstrated the efficacy of these methods in similar contexts. For instance, Igwe (2011) highlighted the utility of electrical resistivity methods in identifying erosion-prone zones within Southeastern Nigeria. Uhegbu & John (2017) applied combined geophysical and geotechnical techniques in Abia State, revealing significant spatial variations in soil resistivity that underscore the influence of both natural and anthropogenic factors. Similarly, John *et al*. (2015) and Igboekwe *et al*. (2012) employed Vertical Electrical Sounding (VES) to evaluate the erosional sensitivity of soils and proposed mitigation strategies such as water harvesting to reduce surface runoff. Additional contributions from Amangabara & Otumchere (2016), Ekwueme (2024), Okoyeh *et al*. (2014), Obi & Okekeogbu (2017), Meindinyo *et al*. (2017), Jatau *et al*. (2013), Olawuyi & Abolarin (2013), and Hassan *et al*. (2017) further attest to the applicability of geophysical techniques in erosion studies, though their investigations predominantly focus on regions outside the present study area. Notably, Ekwueme *et al*. (2021) are the only researchers to have explored this specific region, albeit relying solely on soil testing.

This research, therefore, differentiates itself by integrating electrical resistivity methods with soil analysis within the Enugu North zone, marking the first such endeavor in the area. By doing so, the study seeks to advance a robust analytical framework capable of elucidating the complex subsurface characteristics associated with gully development and assessing the contributory role of soil properties in erosion dynamics.

1.2 Location and Geology of Enugu North

The area of study is located in the Enugu North zone, Southeastern Nigeria. Fig. 1 shows the map of Enugu North comprising four local governments, namely, Udenu, Igbo-Eze South, Nsukka, and Igbo-Eze North. The area studied is bounded by Latitude 6° 40'0"N to 7° 10'0"N and Longitude 7° 15'0"E to 7° 45'0"E. The area studied is about 30 square kilometers. In Udenu, the major gully sites at Obollo-Etiti and Umuitodo are particularly affected by runoff, which is amplified by the area's undulating terrain and the presence of bush-clad ridges that channel water flow into the gullies. Similarly, the major gully points in Igbo-Eze South, such as Ugo-Iheaka and Ekoyi Iheaka, are influenced by the runoff from the surrounding higher grounds, which contributes to the deepening and widening of the gullies. In Nsukka, the runoff from the University of Nigeria secondary school area, Onuiyi Road, and Alor-Uno follows the natural drainage patterns, leading to erosion in vulnerable spots. The gully sites in Igbo-Eze North, including Ugbaike, Olido, Umuida, and Ichi-Unadu, also experience significant runoff, which is a major factor in the development and expansion of the gullies.

The rainfall pattern in this area is characterized by a bimodal distribution, with two distinct peaks occurring between April and October. The region experiences an annual rainfall of approximately 1,500 to 2,000 mm, with the heaviest rainfall typically recorded in July and September. The wet season contributes significantly to surface runoff, which, coupled with the area's topography and soil characteristics, often results in severe gully erosion. The high-intensity rainfall events lead to rapid saturation of the soil, reduced infiltration rates, and increased surface runoff. Consequently, the runoff generated from these rainfall events exacerbates the erosion processes, particularly in areas with minimal vegetation cover and poor land management practices.

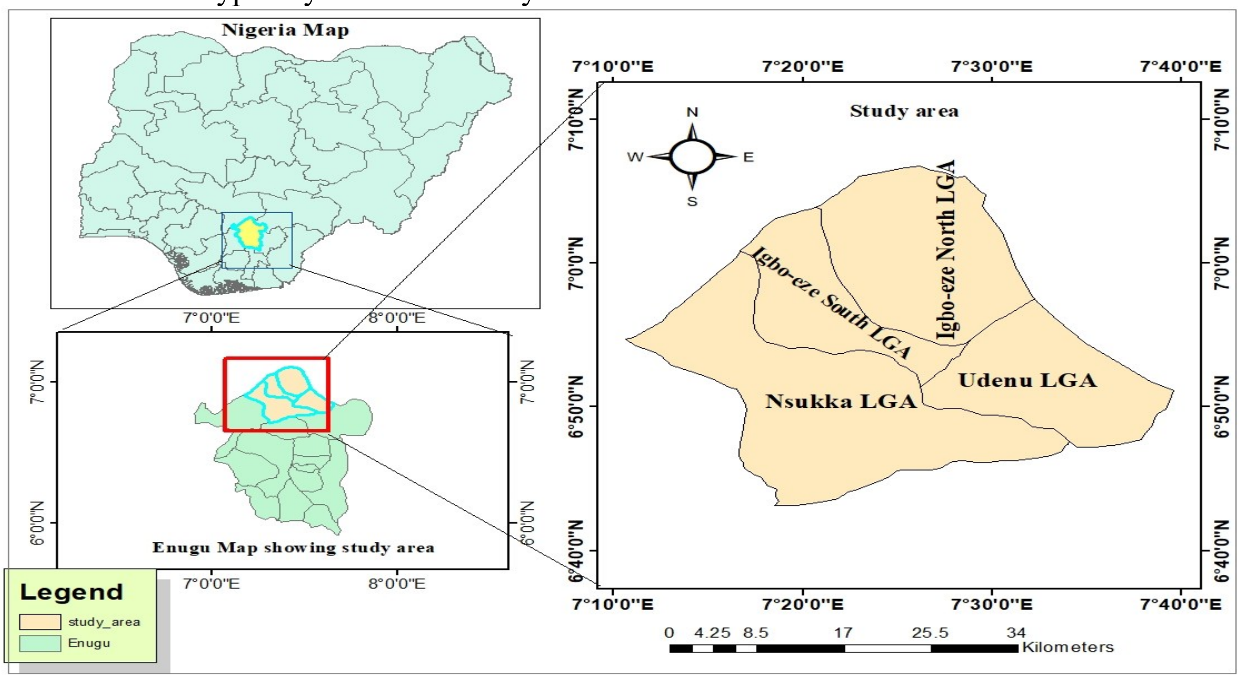

Fig. 1: Location map of Enugu North

The geology of Enugu North forms an integral part of the Anambra Basin (refer to Fig. 2). The Anambra Basin encompasses six principal lithological units: the Enugu Shale, Mamu Formation, Agwu Shale, Ajali Formation, Nsukka Formation, and the Imo Shale Formation. These units are more broadly grouped into four key formations, namely, the Ajali Sandstone, Mamu Formation, Nsukka Formation, and Imo Shale Formation (Nwajide & Reijers, 1995).

The depositional products of this geologic era are distributed across four distinct physiographic provinces: the Cross River Plains, the Escarpment, the Plateau, and the Anambra Plains. These sedimentary units are known to host a variety of economically significant mineral resources, including coal, natural gas, glass sands, and liquid hydrocarbons (Obiora *et al*., 2015).

Topographically, the region is characterized by undulating terrain shaped by the Nsukka–Okigwe cuesta. Elevations ascend from Eha-Alumona to Obollo-Afor, while lower altitudes prevail toward Eha-Amufu. Pedological investigations reveal that the predominant soil type is loose, sandy ferrallitic soil, interspersed with lesser quantities of loamy clay. The prevailing vegetation is composed of derived Guinea woodland savanna and grass tufts. According to Kowal and Kassam (1978), the land is primarily utilized for subsistence agriculture, infrastructure development, and settlement construction. Fig. 2 presents a geological map illustrating the lithological framework of Enugu North and its surrounding regions.

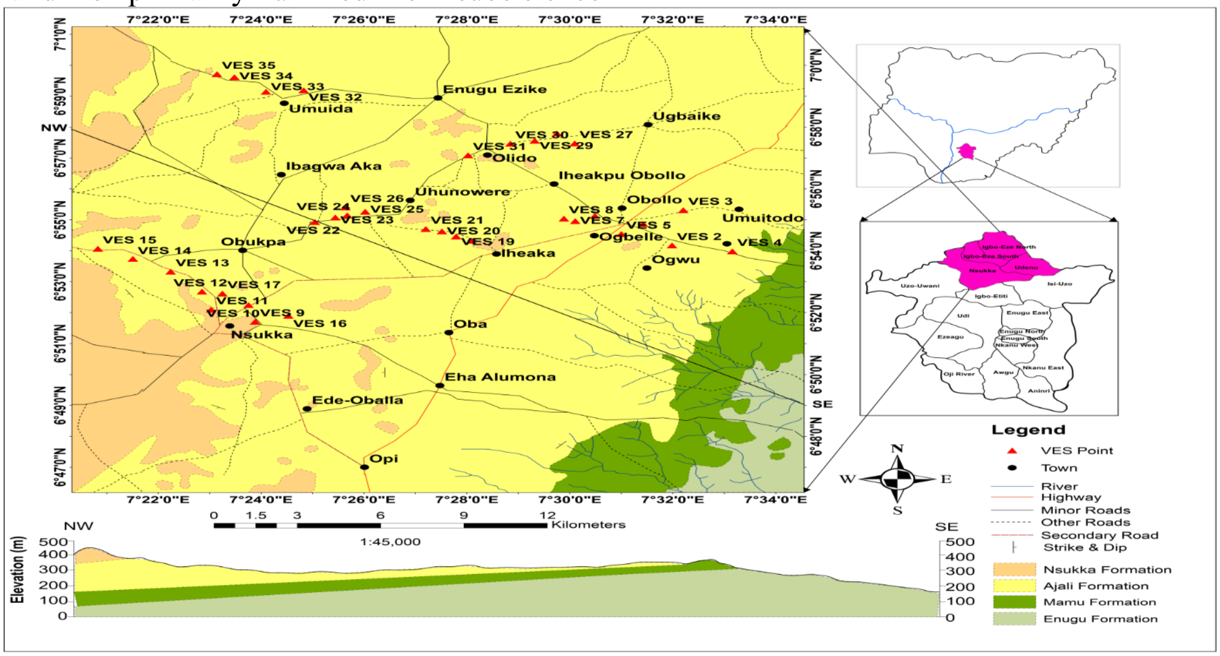

Fig. 2: Geology map of Enugu North

2.1 Materials and Methods

In the course of this Electrical Resistivity Tomography (ERT) survey, an electric current was introduced into the subsurface via the current electrodes, designated A and B (Fig. 3), utilizing a direct current supplied by a 24 V battery connected to the resistivity meter. The Wenner electrode configuration was employed, as illustrated in Fig. 3. The resulting electrical potential was measured through two potential electrodes, M and N. At greater electrode spacings, the positions of the potential electrodes were also adjusted, ensuring that the separation between M and N did not exceed one-half the distance between A and B (i.e., MN ≤ AB/2). At each sounding, the resistivity meter recorded the corresponding resistance values. The Wenner array configuration facilitates straightforward computation of the apparent resistivity (ρ_a) directly in the field. Accordingly, the apparent resistivity is expressed as:

$$\rho_a = 2\pi a \frac{\Delta V}{I} \quad (1)$$

Where a is the electrode spacing, $\frac{\Delta V}{I}$ = R (Ohms) is the field resistance.

Therefore, equation 5 can be written as;

$$\rho_a = GR \quad (2)$$

Where G is the geometric factor given by;

$$G = 2\pi a \quad (3)$$

2.2 Soil test

Soil testing was undertaken utilizing samples collected from four principal gully erosion sites, each situated within the Local Government Areas of Udenu, Igbo-Eze South, Nsukka, and Igbo-Eze North. The suite of analyses performed included evaluations of hydraulic conductivity, particle size distribution, Atterberg limits (comprising the plasticity index, liquid limit, and plastic limit), total porosity, bulk density, moisture content, degree of soil saturation, and infiltration characteristics. Undisturbed core samples were extracted from the gully erosion sites at an approximate depth of 0.6 meters and subsequently conveyed to the laboratory for detailed examination. To assess infiltration capacity, a double-ring infiltrometer measuring 30 cm and 60 cm in diameter, respectively, was employed.

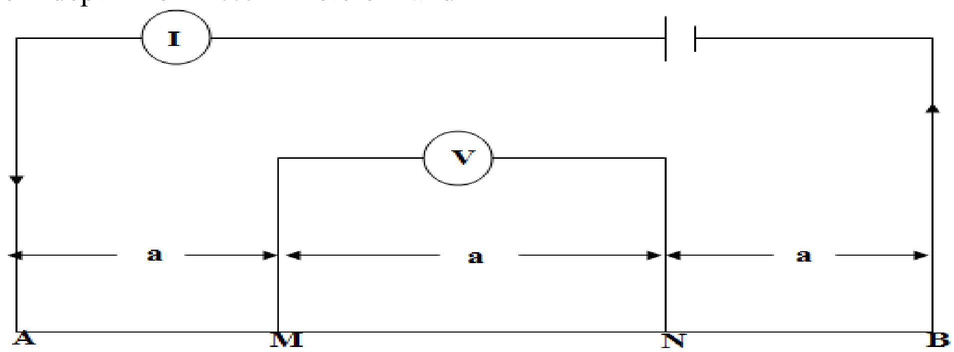

Fig. 3: Wenner electrode configuration (after Lowrie, 1997)

3.1 Results and Discussion

3.1.2 Electrical Resistivity Tomography

Four (4) electrical resistivity tomography (ERT) surveys were conducted across the principal gully erosion sites, each situated within one of the four local government areas encompassed by the study region. The Wenner array configuration was employed, utilizing a maximum current electrode spacing of AB = 200 meters. Two-dimensional (2D) resistivity data were acquired and subsequently processed using the RES2DINV software package. The resulting inversion models were systematically presented and interpreted.

The inversion model for the Obollo-Etiti gully site, located in the Udenu Local Government Area (Fig. 4), reveals a tripartite subsurface structure. The uppermost layer, characterized by notably low resistivity values ranging from 1.16 to 9.07 Ωm, extends from a depth of approximately 3.75 meters to a maximum of 9.26 meters. This stratum is presumed to consist predominantly of saturated sandy or silty materials, known for their high porosity and permeability, thereby exhibiting minimal resistance to erosive forces.

Beneath this lies the intermediate or diffused layer, exhibiting moderate resistivity values between 25.4 and 198 Ωm, and occurring at depths from 9.26 to 12.4 meters. It is inferred that this layer comprises a heterogeneous mixture of sandy clay and loamy clay soils, which confer a moderate degree of protection against surface runoff due to their comparatively reduced permeability. The basal layer, referred to as the compact or bedrock zone, displays high resistivity values ranging from 198 to 1546 Ωm and is encountered at depths of 12.4 to 19.8 meters. This layer is interpreted to be composed of well-consolidated soil or lithified rock material, possessing considerable resistance to erosional processes, an interpretation consistent with the findings of Telford *et al*. (1990), who affirm that bedrock typically exhibits the highest resistivity values.

An additional observation from the inversion model in Fig. 4 indicates elevated resistivity values in the superficial layers. This anomaly is attributed to the constraints encountered during fieldwork, wherein direct access to the gully point at Obollo-Etiti was restricted. Consequently, the ERT survey was conducted along an adjacent roadway. The compact nature of the road surface likely contributed to the higher resistivity values observed in the uppermost strata of the inversion model.

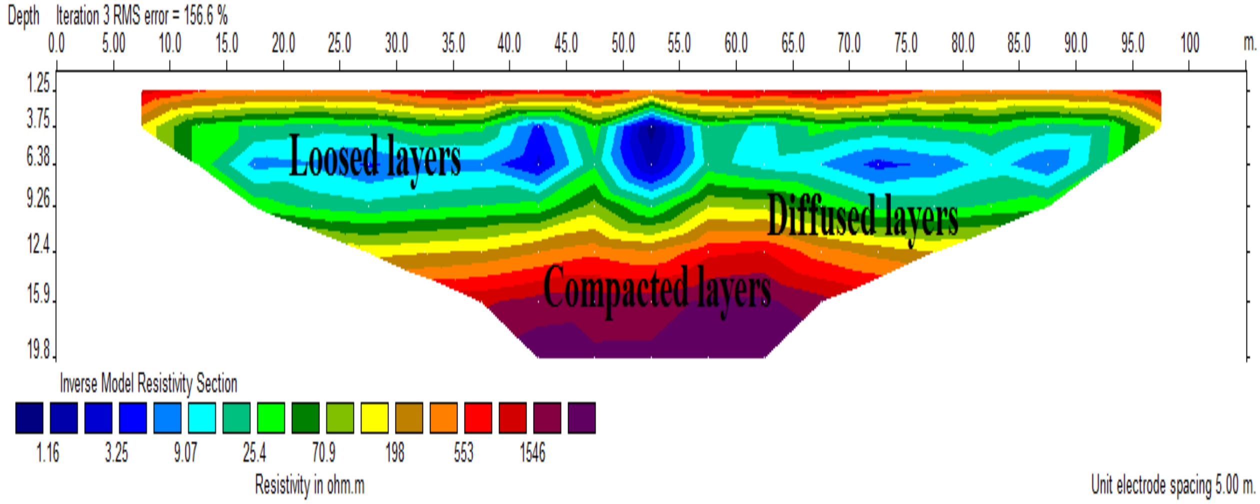

Fig. 4: Inverted resistivity-depth model profile for Obollo-Etiti ERT gully site

At the Ugbaike gully site, situated within the Igbo-Eze North Local Government Area, the results of the two-dimensional resistivity inversion model are presented in Fig. 5. The model reveals that the uppermost portion of the subsurface consists of loosely bound materials, interpreted as soft and unconsolidated soil layers. These layers exhibit relatively low resistivity values, ranging from 6.52 to 106 Ωm, and extend to depths between approximately 1.25 and 9.26 meters. Beneath this, a series of more diffused layers is observed, characterized by resistivity values between 429 and 6987 Ωm, spanning depths of 9.26 to 12.4 meters. At greater depths, more compacted strata emerge, displaying a broader spectrum of resistivity values, from 6987 to 113,822 Ωm, and extending down to a depth of 19.8 meters. Both the diffused and compacted layers are marked by significantly elevated resistivity values, indicative of bedrock zones predominantly composed of massive quartzite formations. As noted by Telford *et al*. (1990), such lithological compositions are known for their high resistivity and are typically less susceptible to soil erosion.

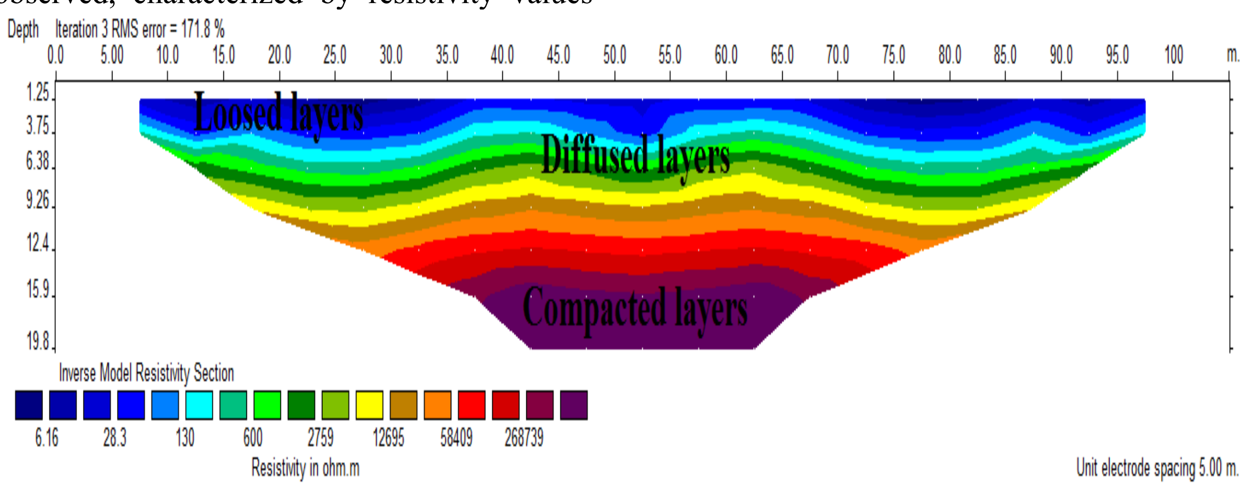

Fig. 5: Inverted resistivity-depth model profile for Ugbaike ERT gully site

The two-dimensional (2D) inverse resistivity model of the Ugo Iheaka gully site, situated along the major road in Igbo-Eze South Local Government Area, is presented in Fig. 6. The western and eastern portions of the study area are characterized by loose soil layers, exhibiting resistivity values ranging from 2.68 to 15.0 Ωm and occurring at depths between 3.75 and 9.26 meters. These values are indicative of sandy soils composed of materials with low resistance to erosional processes. Beneath these zones, diffuse layers with resistivity values varying from 35.5 to 199 Ωm and depths ranging between 3.75 and 12.4 meters appear in a sandwiched formation, truncated at both the western and eastern flanks of the area. These transitional layers lie between the overlying loose sediments and the underlying compacted materials.

The compacted layer, which extends from the top northern section down towards the southern part of the profile where it becomes increasingly dominant, exhibits significantly higher resistivity values, ranging from 199 to 1112 Ωm. This layer occurs at variable depths, reaching a maximum of approximately 19.8 meters. It is inferred to consist of highly compacted soils and resistant lithological units, possibly including rock materials less susceptible to erosion. These observations are in agreement with the findings of Kumar *et al.* (2014), who reported that resistivity values exceeding 1000 Ωm typically correspond to the presence of massive quartzite formations or similarly resistant geological structures.

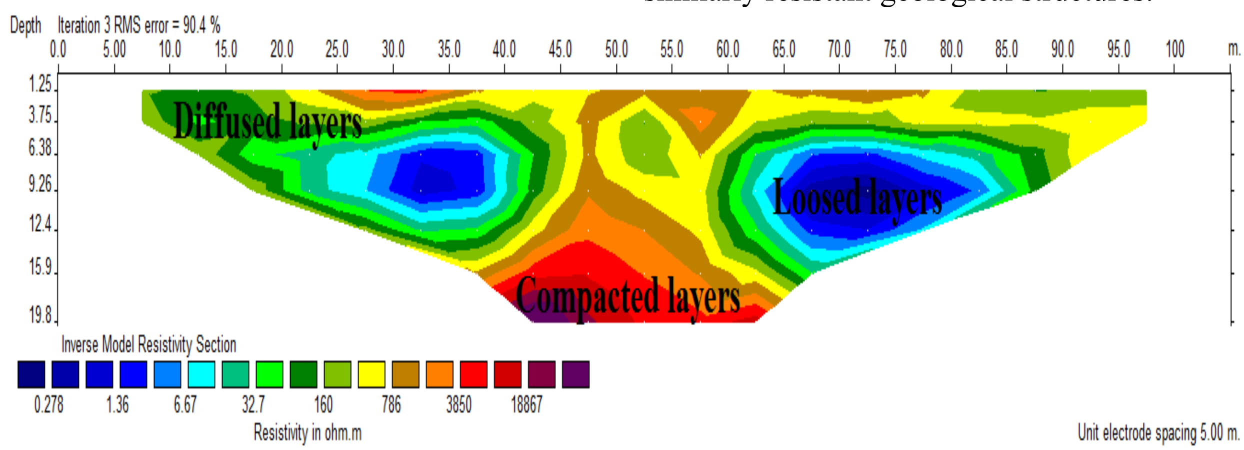

Fig. 6: Inverted resistivity-depth model profile for Ugo Iheaka ERT gully site

Fig. 7 presents the two-dimensional Electrical Resistivity Tomography (ERT) subsurface image of the gully site in the University Secondary School in Nsukka Local Government Area. Compact layers, primarily composed of dry clay soils, are visible from the topsoil and are intermittently identified at greater depths. These compacted strata exhibit resistivity values ranging from 406 to 2810 Ωm, occurring at depths of approximately 1.25 to 3.75 meters below the surface. In contrast, the western and eastern sections of the site are predominantly characterized by loosely bound sandy soils, which display significantly lower resistivity values, ranging from 3.21 to 22.3 Ωm, and extend to depths of 6.38 to 15.9 meters. Between the compacted and loose layers, there exists a diffused zone containing a mixture of sand, clayey sand, and silt soils, as noted by Loke (2009). This transitional layer, with resistivity values from 58.6 to 406 Ωm and a maximum depth of 15.9 meters, forms a relatively thin band of medium resistivity material that trends laterally from the western to the eastern portion of the area.

3.1.3 Soil Test

A soil investigation was conducted using samples collected from four principal gully sites within the study area, specifically from Igbo-Eze South, Igbo-Eze North, Nsukka, and Udenu Local Government Areas. The laboratory analysis was carried out at the Soil Science Department of the University of Nigeria, Nsukka. Table 1 presents a summary of all the soil test analyses. The results revealed that the liquid limit (LL) of the samples ranged from 16.67% to 46.89%. The plastic limit (PL) was recorded as 33.45% for the sample from Igbo-Eze South and 22.38% for Nsukka. Notably, no plastic limit (NP) was observed in the samples from Igbo-Eze North and Udenu. The plasticity index (PI) values were 13.44% for Igbo-Eze South and 9.90% for Nsukka, whereas both Igbo-Eze North and Udenu exhibited zero plasticity index, consistent with their non-plastic classification.

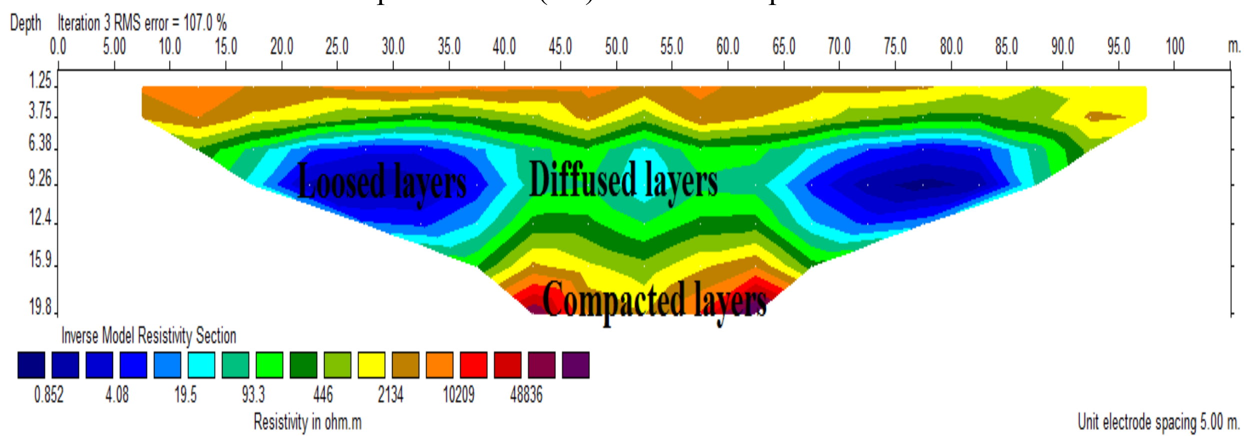

Fig. 7: Inverted resistivity-depth model profile for University Secondary School, Nsukka ERT gully site

The absence of plasticity in the samples from Igbo-Eze North and Udenu, along with the relatively low PL and PI values observed in the Nsukka and Igbo-Eze South samples, suggests a predominance of soils with limited cohesion and plastic behavior. Specifically, the Nsukka and Igbo-Eze South samples exhibit low to medium plasticity, indicative of weak structural integrity. Overall, the findings imply that the soils in all four zones are largely non-cohesive and non-plastic, characteristics that significantly contribute to the susceptibility of the area to gully erosion.

The soil classification results indicate that the textural composition of the samples predominantly comprises sandy, loamy, and clayey soils (Fig. 1). The clay content ranges from 8% to 18%, silt from 3% to 9%, fine sand from 20% to 38%, and coarse sand from 29% to 69%. The particle size distribution reveals that the study areas are largely characterized by sandy soils, both fine and coarse, with only minor proportions of clay and silt present.

Hydraulic conductivity, which reflects the ease with which water permeates soil pores and fractured substrates, was observed to range from 8.89 to 22.73 m/day. Lower conductivity values were generally associated with soils containing higher proportions of silt and clay, whereas higher conductivity was indicative of loose, sandy soils with more permeable structures.

The total porosity of the soil samples ranged between 41.13% and 47.55%. Samples obtained from Igbo-Eze South and Nsukka Local Government Areas demonstrated moderate porosity, consistent with sandy soils containing a high proportion of macropores. In contrast, soils from Igbo-Eze North and Udenu exhibited slightly lower porosity, suggestive of finer-textured materials such as clay and silt with predominantly microporous structures.

Table 1: Summary of the results of the soil test

Sample Description	Igbo-Eze South L.G.A	Igbo-Eze North L.G.A	Nsukka L.G.A	Udenu L.G.A	
Liquid Limit (LL) %	46.89	15.88	32.28	16.67	Particle Size Distribution
Plastic Limit (PL) %	33.45	NP	22.38	NP	
Plasticity Index (PI) %	13.44	0	9.90	0	
Textural Class	Sandy Loam	Loam Sand	Sandy Loam	Loam Sand	Particle Size Distribution
Clay (%)	14	8	18	8	
Silt (%)	3	3	9	3	
Fine Sand (%)	38	22	44	20	
Coarse Sand (%)	45	67	29	69	
Total Porosity (%)	47.55	41.13	45.28	41.51	
Hydraulic Conductivity (m/day)	8.89	16.16	14.14	22.73	
Bulk Density (g/cm³)	1.39	1.56	1.45	1.55	
Moisture Content (%)	24.38	7.07	31.73	8.34	
Saturation Test (%)	23	20	21	22	
Infiltration Test (mm/hour)	25.05	23	20	24	

Moisture content analyses revealed medium values of 31.73% and 24.38% for Nsukka and Igbo-Eze South, respectively, implying the presence of modest clay fractions capable of retaining water. However, significantly lower moisture content values were recorded for Igbo-Eze North (7.07%) and Udenu (8.34%), indicative of loosely structured soils with limited water retention capacity.

4.0 Conclusion

The findings from the electrical resistivity surveys, alongside the results of soil testing conducted across selected locations within the study area, reveal several underlying factors contributing to the prevalence of gully erosion in the region. Chief among these is the predominance of coarse and fine sand fractions, coupled with a notably low presence of clay and silt. This textural composition significantly undermines soil cohesion and stability, thereby facilitating erosive processes. Furthermore, the inherently loose and friable nature of the soil, characterized by minimal binding agents and poor structural integrity, exacerbates susceptibility to erosion. The observed low moisture retention capacity further diminishes the soil's resistance to displacement, accelerating gully development throughout the area.

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Declaration

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Competing Statement

There are no competing financial interests in this research work.

Ethical considerations

Not applicable

Data availability

The microcontroller source code and any other information can be obtained from the corresponding author via email.

Authors' Contribution

All components of the work were carried out by the author