

Geo-Electric Characterization and Slope Stability Analysis of Ekoli Eda, Southeastern Nigeria: Implications for Landslide Risk under Climate-Induced Saturation

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Orcid.org/0000-0002-2825-0074

Abstract

This study integrates Vertical Electrical Sounding (VES) data with geotechnical slope analysis to assess subsurface conditions and landslide susceptibility in Ekoli Eda, Southeastern Nigeria. Four VES stations—Elugwu-Nguzu, Okpocha, Letu, and Ugwuelu—were analyzed to delineate subsurface lithology and model potential failure zones. Combined resistivity modeling, shear strength analysis, and slope safety evaluations reveal that saturated silty and clayey beds overlying consolidated sandstone at Letu and Ugwuelu significantly reduce Factor of Safety (Fs), particularly under rainfall-induced saturation. Ugwuelu exhibits the highest risk due to a 19.88 m thick saturated clayey sand layer and steep elevation gradient. The study recommends site-specific slope management strategies, including surface drainage systems, re-vegetation, and structural reinforcements. These findings highlight the urgent need for proactive slope stability measures in humid tropical terrains increasingly exposed to extreme weather events.

Keywords: VES, Landslides, geotechnical, slope, subsurface, factor of safety, rainfall, Ekoli Eda

1. Introduction

Geo-environmental hazards have been a significant threat to both human life and the natural environment for many years. These hazards range from floods, landslides, earthquakes, tsunamis,

soil erosion, wildfires, and more. A landslide is the movement of rocks, detritus, or soil caused by the action of gravity (De Blasio, 2011). It also involves rapid displacement of rock mass, residual soils, or sediments adjoining a slope (Malamud *et al.*, 2004; Terzaghi, 2015). Landslides are classified according to the type of movement (topples, slumps, sags, flow, slides, falls), material composition (silt, rock, unconsolidated sediments), and speed (slow, moderate, fast) (Clague, 2013).

Landslides, have resulted in numerous deaths worldwide and account for 9% of the natural disasters in the world (Gomez *et al.*, 2023; Remondo *et al.*, 2025; Kanwal *et al.*, 2016; Galli *et al.*, 2008), hence, making it crucial to study this natural phenomenon. Several works have shown the temporal and spatial distribution of landslide occurrences around the world, indicating that landslides are a major global hazard, with large human and economic losses every yearly (Gomez *et al.*, 2023). According to a study conducted by Froude and Petley (2018), between 2004 and 2016, more than 55,000 people lost their lives globally as a result of landslides. Research findings by Nsengiyumva *et al.*, (2019) recorded that in 2014 alone, about 174 landslides occurred worldwide resulting in devastating consequences for humans as well as natural resources. Landslides are responsible for an average of 25-50 deaths per year in the United States, while the global death toll caused by landslides reaches thousands. The majority of landslide fatalities are due to rock falls, debris flows, and lahars, which are volcanic debris. On January 9, 2018, debris flows occurred in Montecito, Santa Barbara County, California, resulting in 23 fatalities, at least 167 injuries, and more than 400 damaged homes. In Colombia, landslides are common due to the country's mountainous terrain and heavy rainfall. In 2017, a landslide in Mocoa, Southern Colombia, killed over 300 people and displaced thousands. The event was triggered by heavy rainfall, which caused several rivers to overflow and led to massive amounts of debris being carried downstream (Cheng *et al.*, 2018).

Landslides have also occurred in Ethiopia, Nigeria, Tanzania, Uganda, and more. In 2010, a landslide in Uganda's Bududa district killed over 400 people and displaced an estimated 5,000 people (Atuyambe *et al.*, 2011) later in 2018, heavy rainfall in Ethiopia resulted in a landslide that led to the unfortunate loss of 62 lives, with 30 individuals sustaining injuries. Additionally, around 5,091 households were forced to leave their homes, and significant damage occurred to houses, as well as cultivated and non-cultivated land in various regions of the country (Wubalem, 2020). Tanzania is also vulnerable to landslides, especially in its mountainous regions, such as the Usambara and Uluguru mountains. On May 4, 2016, a landslide event took place in the Lwangwa and Lupata Wards, located in the Rungwe district of the Mbeya region in Tanzania. This incident involved rotational slumps, resulting in the unfortunate loss of five lives and the significant destruction of numerous homes and structures (Tegeje, 2017).

Landslides are increasingly prevalent in humid tropical regions of Nigeria due to changes in rainfall intensity and poor land-use practices leading to significant consequences. In Nanka, Orumba North L.G.A, Anambra State, a major landslide took place, necessitating the evacuation of 50 families (Okagbue, 1992). In September 1997, heavy rainfall triggered two distinct landslides

on the slopes of the Akovolwo Mountains near Jato-Aka, located in the Kwande Local Government area of Benue State (Agbor *et al.*, 2014). Another distressing example of the destructive nature of landslides occurred in Calabar, Cross River State, in 2013, when nine individuals lost their lives due to landslides (Channels Television, September 9, 2013). Similarly, in 2015, Ugwelu Ekoli Edda, Ebonyi State, experienced a landslide, and another occurred in Amuzukwu, Umuahia North, on October 29, 2019. These incidents highlights the devastating impact of landslides in Nigeria. The causes of landslides in Nigeria are diverse, but several common factors contribute to their occurrence.

The occurrence of landslides is influenced by both causal and triggering factors. Causal factors contribute to the creation of favorable conditions for landslides and include slope, elevation, aspect, geology, and land use/land cover. On the other hand, triggering factors are responsible for initiating landslides and can occur naturally due to snow melting, volcanic activity, groundwater pressure, and prolonged rainfall. Additionally, human activities such as excavation, deforestation, land-use change, hillslope cutting, construction of roads, and subsequent excessive vibration by traffic and agricultural cultivation can also trigger landslides. (Guzzetti *et al.*, 2012; Althuwaynee *et al.*, 2014; Chen *et al.*, 2018; Ahmed, 2015).

Southeastern Nigeria is geologically situated between two major tectonic trends. The first has a NW – SE direction expressed as the Okitipupa Basement Complex of Western Nigeria and the Oban massifs and Mamfe embayment in the southeast. The second has a direction which is approximately SW- NE and is expressed in the trend of the Cameroon volcanic zone, the Benue trough, the Abakiliki Anticlinorium and the Afikpo Syncline (Amangabara, 2023). Between these two Precambrian Basement areas, sediments of Cretaceous, Tertiary and Quaternary ages occur and it is within this geologic setting that the greatest threat of gully erosion and landslides occur. In Southeastern Nigeria, the Ekoli Edda area has exhibited signs of slope failure, necessitating a detailed geophysical and geotechnical investigation. This study combines VES data and geotechnical analysis to understand subsurface conditions and determine the most critical factors contributing to landslide risk (Nwachukwu *et al.*, 2014; Igwe, 2015).

2. Materials and Methods

Geophysical Survey: Four VES representative locations were selected for the resistivity survey namely: Amanta (VES 1), Okpocha (VES 2), Elugwu-Nguzu (VES 3) and Letu (VES 4). To complement surface studies, OHMEGA-500 Allied Associates geophysical equipment was used to conduct a Vertical Electric Sounding (VES). At each of the 4 locations. Schlumberger configuration was used for a total spread (L) of 150 m. VES stations were located in a central point along a pre-determined traverse. A distance of 75 m ($L/2$) was covered on the right and another 75 m ($L/2$) was run on the left.

Data were processed using AGI EarthImager to produce 1D resistivity models. Field data was subjected to automatic analysis based on the Schlumberger apparent resistivity equation:

$$\rho_a = \frac{\pi(AB/2 + MN/2)^2}{MN} \times R \quad (\text{Ohm-m})$$

Where AB = Current electrode spread (m)

MN = Potential electrode spread (m)

R = Measured field resistance (Ohm)

$$\frac{\pi(AB/2 + MN/2)^2}{MN} \times R = \text{Geo-electric constant (L)}$$

Thus $\rho_a = LR$ (Ohm-m)

Apparent resistivity generated automatically using the Advanced Geophysics Incorporation (AGI) 1D inversion resistivity analytical software to obtain the subsurface model of each location

Geotechnical Investigation: The investigation involves selecting appropriate methods for data collection, such as drilling, sampling, and in-situ testing. Drilling obtains subsurface soil and rock samples, while sampling collects samples for laboratory testing. In-situ testing measures properties directly in the ground. Laboratory testing determines physical and mechanical properties like grain size distribution, moisture content, shear strength, and permeability. Field tests like the CPT, and SRT assess density, resistance, permeability, and seismic velocity. The analysis identifies potential failure modes and calculates safety factors. Geotechnical data, including cohesion, angle of internal friction, shear stress, and Factor of Safety (Fs), were used to evaluate slope stability. A rainfall simulation was conducted by reducing soil cohesion by 50% to assess the impact of saturation on slope failure.

3. Results and Discussion

3.1 Subsurface Interpretation

The Vertical Electrical Sounding (VES) data from Ekoli-Eda provide a detailed profile of subsurface geologic layers, resistivity values, and lithology. The primary goal is to understand soil characteristics, identify subsurface instability, and assess landslide susceptibility. Fig 1 is a summary for each VES site

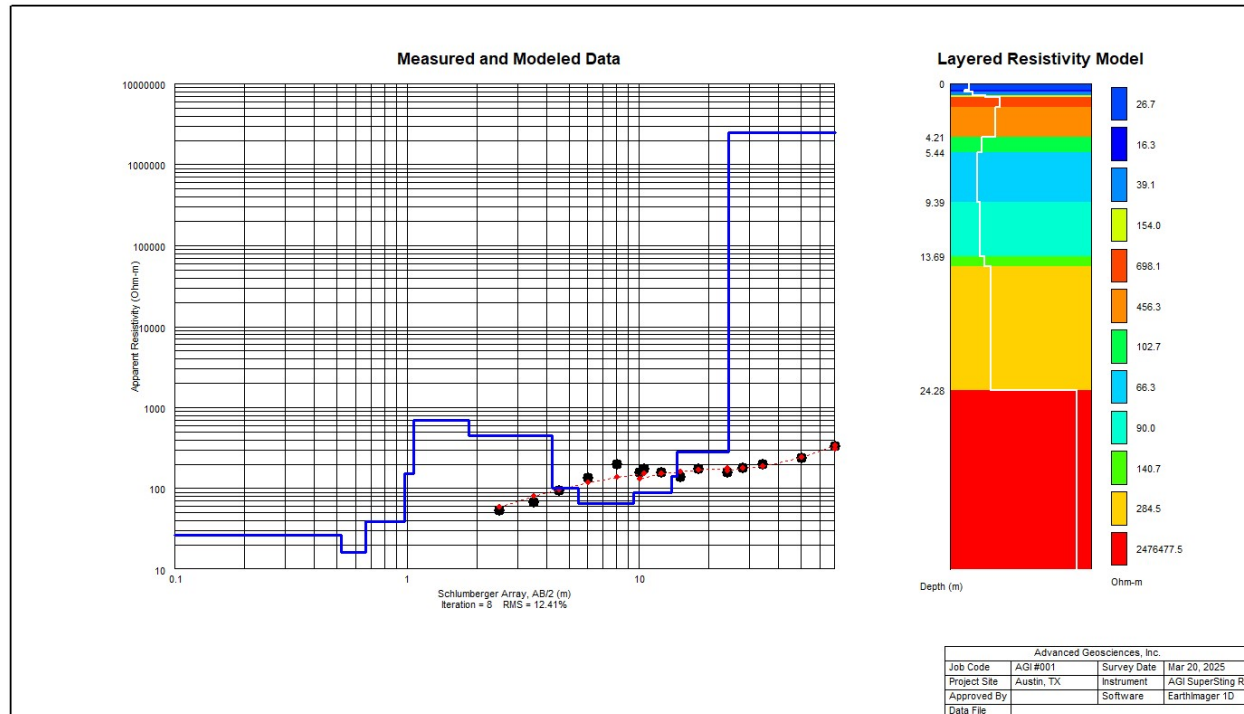


Fig 1 ELUGWU-NGUZU EDA VES; Coordinate N 05.45.24 E 07.49.21.4; Elevation 725ft

Measured Resistivity Data

; Data#	V (mV)	I (mA)	MN (m)	AB/2 (m)	Ohm-m
1	280.000	100	1.000	2.500	52.78
2	180.000	100	1.000	3.500	67.86
3	150.000	100	1.000	4.500	94.25
4	120.000	100	1.000	6.000	134.77
5	100.000	100	1.000	8.000	200.28
6	50.000	100	1.000	10.500	172.79
7	785.018	100	11.000	10.000	156.38
8	433.987	100	11.000	12.500	156.17
9	250.000	100	11.000	15.000	139.05
10	210.000	100	11.000	18.000	176.18
11	99.864	100	11.000	24.000	155.65
12	423.471	100	30.000	24.000	155.65
13	303.527	100	30.000	28.000	177.68
14	202.010	100	30.000	34.000	196.95
15	100.000	100	30.000	50.000	238.24
16	68.250	100	30.000	70.000	334.13
17	159.534	100	60.000	70.000	334.13

Modeled Resistivity Layers

; Layer#		Ohm-m	Thickness (m)	Depth (m)
1	26.69	0.517	0.517	
2	16.33	0.144	0.661	
3	39.14	0.308	0.969	
4	153.96	0.096	1.065	
5	698.10	0.783	1.848	
6	456.26	2.358	4.206	
7	102.68	1.233	5.439	
8	66.27	3.955	9.394	
9	89.96	4.299	13.694	
10	140.66	0.783	14.476	
11	284.53	9.799	24.275	
12	2476477.50			

Constrained Geo-Electric Layers

; Layer#		Ohm-m	Thickness (m)	Depth (m)	Lithology
1	153.96	0.096	1.065		Top soil
2	456.26	2.358	4.206		Siltstone
3	66.27	3.955	9.394		Sandy-clay bed
4	140.66	0.783	14.476		Sand
5	284.53	9.799	24.275		Mixed sand (Top of Bedrock)
6	2476477.50				Sandstone Bedrock, highly consolidated; deep red color

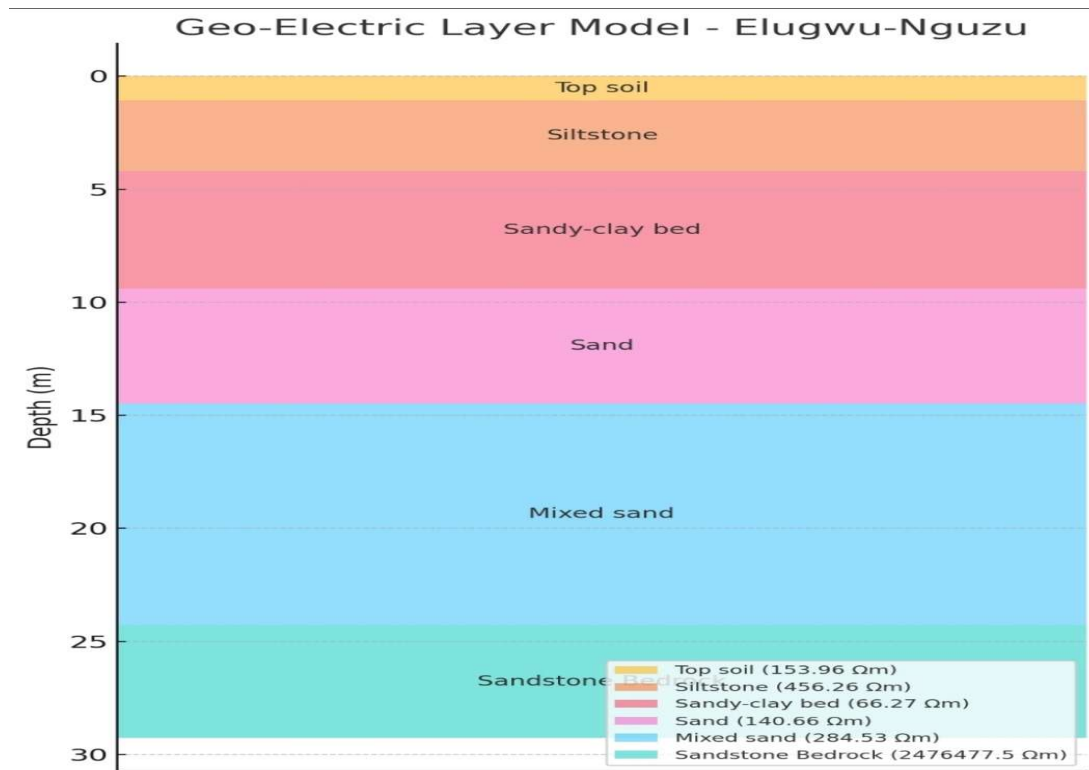


Fig 2 virtual diagram for the interpreted subsurface layers at Elugwu-Nguzu, showing depth, lithology, and resistivity

The result shows that the Topsoil of Elugwu-Nguzu slope is very thin (0.096 m) with moderate resistivity (153.96 Ωm). The Intermediate Layers indicates an alternating sandy-clay and siltstone layers with varied resistivity. While the Bedrock is extremely high resistivity (2,476,477.50 Ωm), indicating highly consolidated sandstone. The implication is that the presence of several intermediate low-resistivity layers (e.g., 66.27 Ωm sandy clay) over bedrock suggests possible water retention zones. Risk of slope instability if saturated.

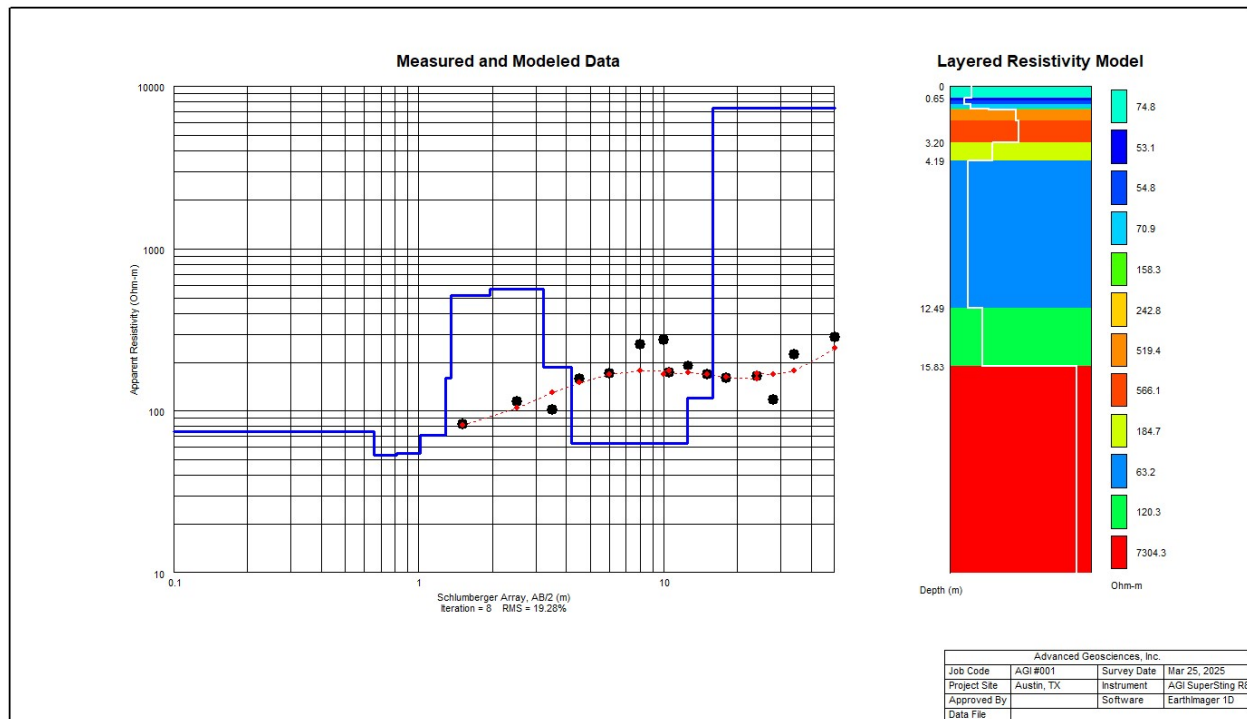


Fig 3 OKPOCHA EDA; Coordinates: N05.45.57; E07.51.2.1. Elevation: 716ft.

Measured Resistivity Data

; Data#	V (mV)	I (mA)	MN (m)	AB/2 (m)	Ohm-m
1	1320.000	100	1.000	1.500	82.94
2	600.000	100	1.000	2.500	113.10
3	270.000	100	1.000	3.500	101.79
4	250.000	100	1.000	4.500	157.08
5	150.000	100	1.000	6.000	168.47
6	130.000	100	1.000	8.000	260.36
7	50.000	100	1.000	10.500	172.79
8	1390.000	100	11.000	10.000	276.90
9	530.000	100	11.000	12.500	190.72
10	300.000	100	11.000	15.000	166.86
11	190.000	100	11.000	18.000	159.40
12	104.510	100	11.000	24.000	162.90
13	443.174	100	30.000	24.000	162.90
14	200.000	100	30.000	28.000	117.08
15	230.000	100	30.000	34.000	224.24
16	120.000	100	30.000	50.000	285.88

Geo-Electric Model Layers

; Layer#	Ohm-m	Thickness (m)	Depth (m)
1	74.84	0.653	0.653
2	53.14	0.153	0.806
3	54.75	0.200	1.007
4	70.87	0.279	1.285
5	158.28	0.058	1.343
6	242.82	0.007	1.350
7	519.43	0.595	1.945
8	566.06	1.258	3.202
9	184.69	0.992	4.195
10	63.18	8.292	12.486
11	120.28	3.345	15.831
12	7304.30		

Constrained Geo-Electric layers

; Layer#	Ohm-m	Thickness (m)	Depth (m)	Lithology
1	158.28	0.058	1.343	Topsoil
2	566.06	1.258	3.202	Siltstone
3	63.18	8.292	12.486	Sandy-clay bed
4	120.28	3.345	15.831	Sand (Top of Bedrock)
5	7304.30			Consolidated Bedrock; Shaly Sandstone

From the Geo-electric model above fig 4 (a generalized virtual diagram of the Okpocha) Vertical Electrical Sounding (VES) was drawn. The generalized shows Topsoil as Thin (0.058 m) and moderately resistive (158.28 Ω m). Middle Layers: Thick sandy-clay bed (~8.29 m, 63.18 Ω m). Bedrock: High resistivity (7304.30 Ω m) consistent with shaly sandstone. This is an indication that the slope is homogeneous, generally stable and consistent subsurface with good consolidation; there is a lower landslide susceptibility unless external loads are applied with respect to this slope at Okpocha Eda

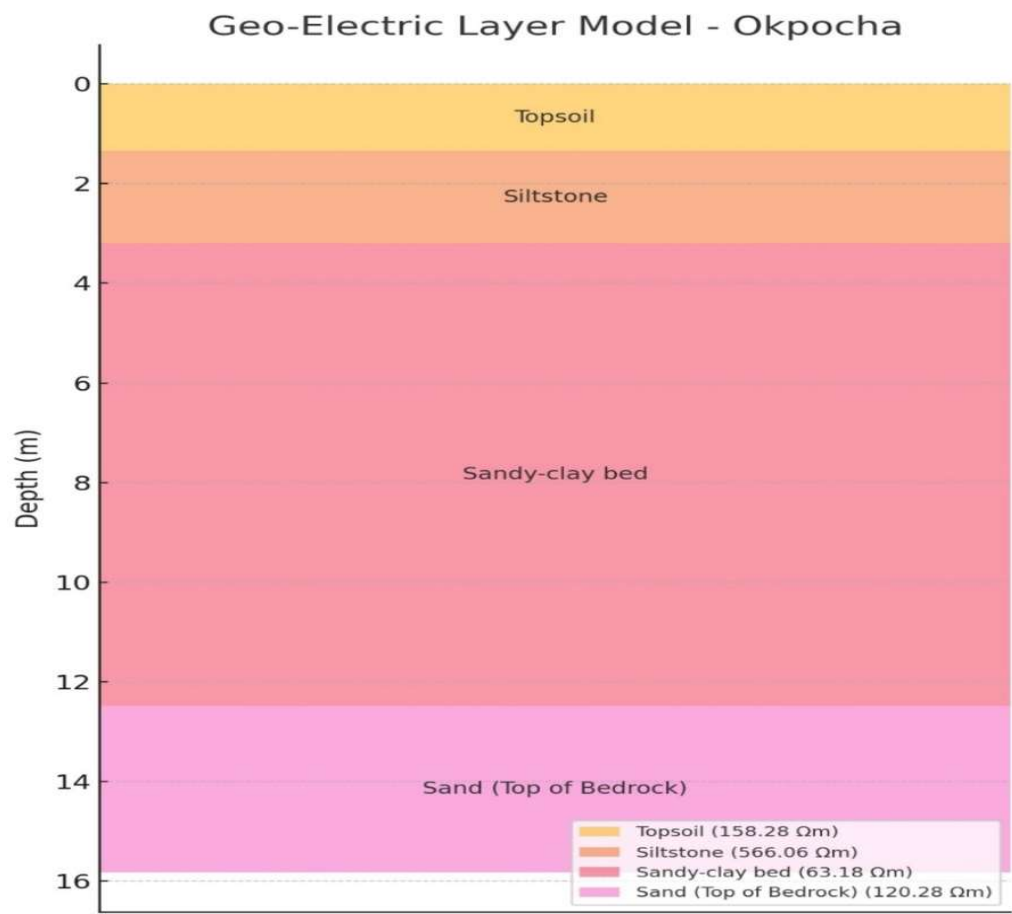


Fig 4 Virtual subsurface diagram for Okpocha Eda

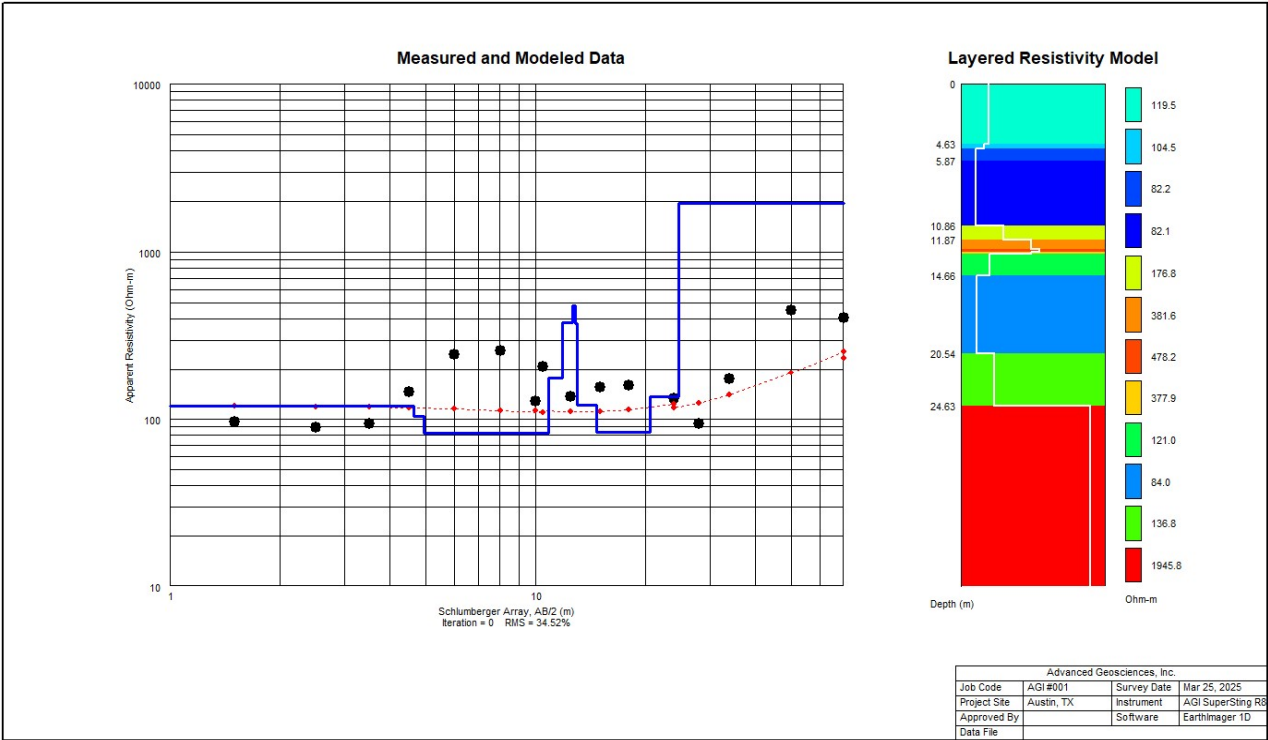


Fig 5 LETU EDA Coordinates N05. 46. 52. E 07. 02. 52. Elevation: 674ft
Measured Resistivity Data

; Data#	V (mV)	I (mA)	MN (m)	AB/2 (m)	Ohm-m
1	1530.000	100	1.000	1.500	96.13
2	470.000	100	1.000	2.500	88.59
3	250.000	100	1.000	3.500	94.25
4	230.000	100	1.000	4.500	144.51
5	220.000	100	1.000	6.000	247.09
6	130.000	100	1.000	8.000	260.36
7	60.000	100	1.000	10.500	207.35
8	640.000	100	11.000	10.000	127.4
9	380.000	100	11.000	12.500	136.74
10	280.000	100	11.000	15.000	155.74
11	190.000	100	11.000	18.000	159.40
12	84.948	100	11.000	24.000	132.40
13	360.220	100	30.000	24.000	132.40
14	160.000	100	30.000	28.000	93.66
15	178.000	100	30.000	34.000	173.54
16	190.000	100	30.000	50.000	452.65
17	82.734	100	30.000	70.000	405.04
18	193.391	100	60.000	70.000	405.04

Modeled Geo-Electric Layers

; Layer#	Ohm-m	Thickness (m)	Depth (m)
1	119.51	4.629	4.629
2	104.53	0.310	4.939
3	82.16	0.935	5.874
4	82.07	4.984	10.858
5	176.81	1.010	11.868
6	381.63	0.738	12.606
7	478.24	0.206	12.812
8	377.86	0.153	12.965
9	121.04	1.691	14.656
10	84.00	5.886	28.542
11	136.80	4.085	34.627
12	1945.84		

Constrained Geo-Electric Layers

; Layer#	Ohm-m	Thickness (m)	Depth (m)	Lithology
1	119.51	4.629	4.629	Extended Topsoil
2	82.07	4.984	10.858	Sandy-Clay Bed
3	478.24	0.206	12.812	Siltstone
4	121.04	1.691	14.656	Sand
5	84.00	5.886	28.542	Silty-Sand
6	136.80	4.085	34.627	Sand
7	1945.84.....			Consolidated Sandstone Bedrock

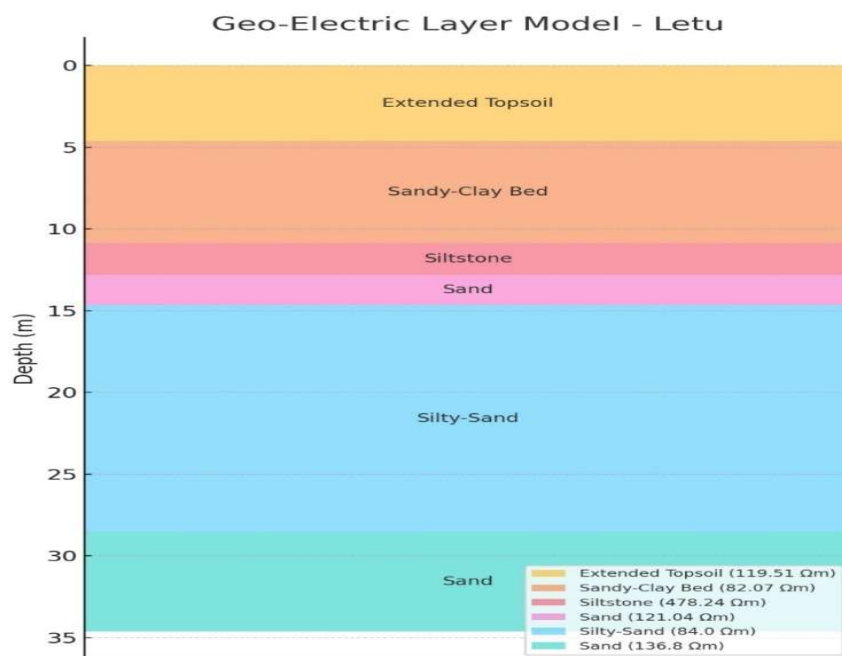


Fig 6 Generalized model of Letu Eda

The generalized model (Fig 6) of Letus Eda Slope has Topsoil: Thickness of (4.629 m), moderate resistivity. The intermediate Layers is composed of Sandy-clay and silty sand over consolidated sandstone bedrock. Generally, Silty-sand and sandy-clay beds (low-moderate resistivity) are potential slip planes, especially under saturation or slope stress. This is an in indication for moderate-high landslide potential, especially in zones with extended topsoil and loose materials. The layered structure with clayey and silty materials, indicate potential instability.

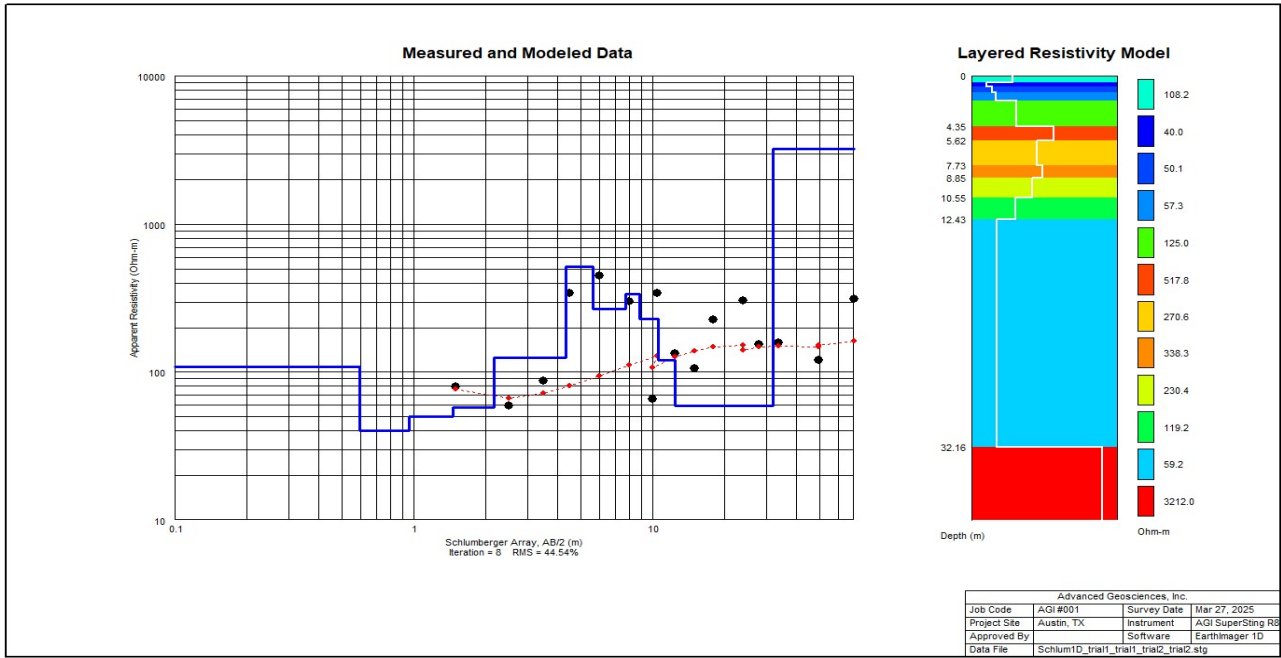


Fig 7 UGWUELU (Ogwuma Landslide). Coordinates N 05. 45. 47.9; E 01. 51. 11.9. Elevation Top (722ft) Bottom (555ft)

Measured Resistivity Data

; Data#	V (mV)	I (mA)	MN (m)	AB/2 (m)	
Ohm-m					
1	1260.000	100	1.000	1.500	79.17
2	315.000	100	1.000	2.500	59.38
3	230.000	100	1.000	3.500	86.71
4	550.000	100	1.000	4.500	345.58
5	400.000	100	1.000	6.000	449.25
6	150.000	100	1.000	8.000	300.41
7	100.000	100	1.000	10.500	345.58
8	330.000	100	11.000	10.000	65.74
9	370.000	100	11.000	12.500	133.15
10	190.000	100	11.000	15.000	105.68
11	270.000	100	11.000	18.000	226.52
12	195.758	100	11.000	24.000	305.12
13	830.108	100	30.000	24.000	305.12
14	260.000	100	30.000	28.000	152.20
15	160.000	100	30.000	34.000	155.99
16	50.318	100	30.000	50.000	119.88
17	143.091	100	60.000	50.000	119.88
18	150.000	100	60.000	70.000	314.16

Modelled Geo-Electric Layers

; Layer#	Ohm-m	Thickness (m)	Depth (m)
1	134.84	0.511	0.511
2	35.26	0.372	0.883
3	51.45	0.470	1.353
4	65.31	0.709	2.062
5	117.42	2.693	4.755
6	533.06	1.326	6.081
7	318.86	1.940	8.020
8	402.16	1.123	9.143
9	248.15	1.481	10.624
10	100.08	0.627	11.250
11	54.05	19.883	31.133
12	523014.63		

Constrained Geo-Electric layers

; Layer#	Ohm-m	Thickness (m)	Depth (m)	Lithology
1	51.45	0.470	1.353	Lateritic Topsoil
2	117.42	2.693	4.755	Sand
3	533.06	1.326	6.081	Siltstone
4	318.86	1.940	8.020	Sandy shale
5	248.15	1.481	10.624	Mixed sand
6	54.05	19.883	31.133	Saturated clayey sand horizon
7	523014.63			Highly Consolidated Sandstone Bedrock

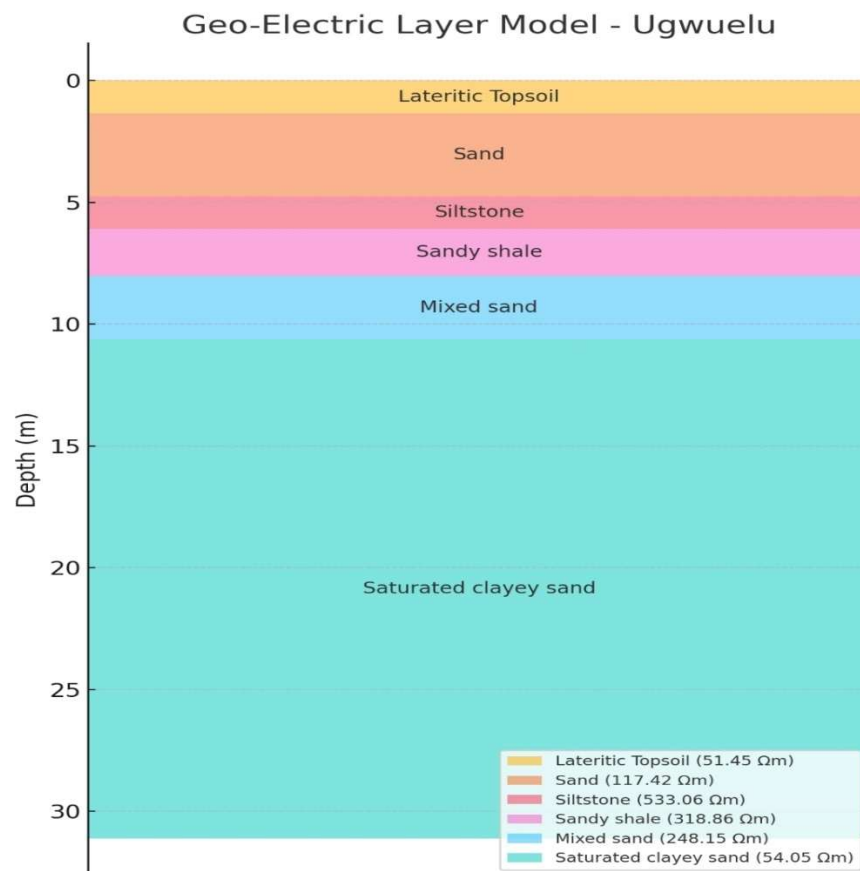


Fig 8 Generalized diagram Ugwuelu Slope

Topsoil of this slope is characterized by lateritic soil over sandy-shale and saturated clayey sand. Underneath is mixed sand. Beneath this layer is very thick saturated clayey sand layer (19.883 m, 54.05 Ω m). While Bedrock with extremely high resistivity (523,014.63 Ω m). The result shows that the saturated horizon acts as a potential failure plane—high risk of landslide especially under increased overburden pressure or intense rainfall.

Elugwu-Nguzu slope (fig2) exhibits a consolidated profile with no saturated weak layer—resulting in low landslide risk. Okpocha (Fig3) shows moderate risk, especially at points with negligible cohesion. Letu Eda (fig 6) features silty sand over bedrock and extensive topsoil, posing moderate-to-high risk. Ugwuelu (Fig 8) displays the most critical condition with a thick, saturated clayey sand layer overlying bedrock and a steep slope—indicating high landslide potential.

Table 1: Geotechnical Property of Soil on each of the four Slopes

SLOPES POSITION S	COHESION (KN/m ²)	ANGLE OF INTERNAL FRICTION Φ (°)	SHEAR STRENGTH τ (KN/m ³)	SHEAR STRESS	MAXIMUM NORMAL STRESS σ_n (KN/m ³)	SAFETY FACTOR (Fs)
S1p1	10.03	19.24	87.07	55.48	333.96	2.20
S1p2	10.77	20.20	91.28	63.36	349.95	2.21
S1p3	10.51	19.25	86.01	56.61	337.62	2.15
S2p1	11.61	17.00	76.21	44.57	314.60	2.27
S2p2	11.89	25.20	121	103.07	422.72	2.04
S2p3	0	18.75	69.89	45.74	304.97	2.20
S3p1	11.48	20.01	91.22	33.06	349.46	3.93
S3p2	33.83	10.35	73.28	26.04	303.80	2.33
S3p3	31.78	12.50	66.89	34.37	163.66	1.97
S4p1	28.34	8.90	60.68	18.89	276.93	2.59
S4p2	29.75	17.38	101.59	60.59	367.55	2.03
S4p3	40.8	4.31	56.15	8.27	260.22	2.91

S1 = ELUGWU-NGUZU EDA, S2= OKPOCHA EDA S3=5 LETU EDA, S4 = UGWUELU (Ogwuma)

3.2 Factor of Safety and Rainfall Simulation

Computation of slope models and Factor of Safety ($F = C/D$) for each site.

Consideration for slope model is based on:

1. Slope angles at each Vertical Electric Sounding (VES) site (top and bottom elevations and horizontal distances).
2. Cohesion or resisting force (C)
3. Unit weights of soil and water if known (we used standard values).

Here are the standard values commonly used for unit weights of soil and water in geotechnical engineering:

1. Unit Weight of Water

- γ_w (Water):
 - 9.81 kN/m³ (standard at 4°C)
 - Often approximated as 10 kN/m³ for simplicity in field calculations

2. Unit Weight of Soil

Unit weight depends on the soil type and condition (dry, moist, saturated).

Soil Type	Dry Unit Weight (γ_d)	Saturated Unit Weight (γ_{sat})
Loose sand	14–17 kN/m ³	18–20 kN/m ³
Dense sand	16–20 kN/m ³	20–22 kN/m ³
Silty sand / sandy silt	14–18 kN/m ³	18–21 kN/m ³
Clay (soft to stiff)	14–18 kN/m ³	18–22 kN/m ³
Gravel	18–22 kN/m ³	20–24 kN/m ³
Organic soils/Peat	8–14 kN/m ³	10–16 kN/m ³

Typical Assumptions:

- Dry soil: 16–18 kN/m³
- Saturated soil: 18–22 kN/m³
- Water: 9.81 or 10 kN/m³

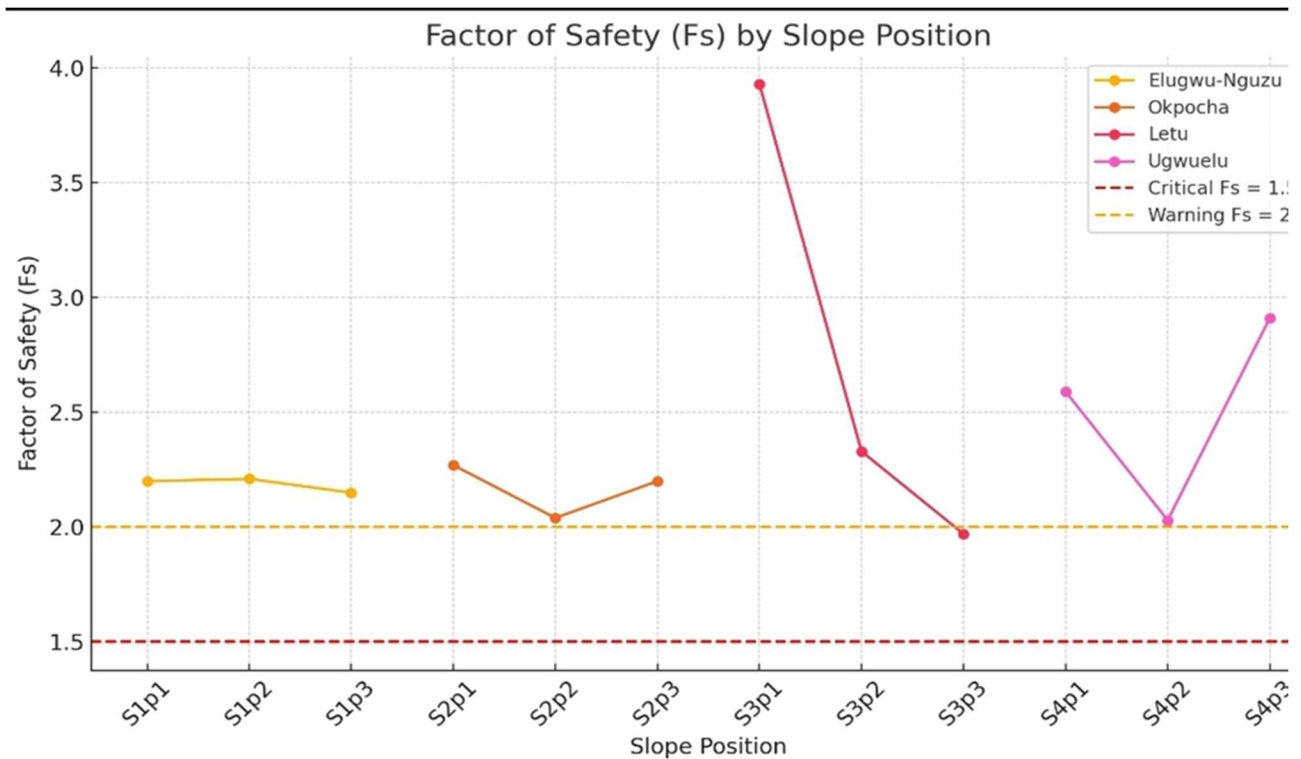
From the Table 1 (Geotechnical data) supplied from the lab which includes cohesion values, internal friction angles, shear strength and stress, and safety factors (F_s) for different slope positions labeled S1p1 to S4p3. We proceeded by:

1. Match slope points (S1–S4) to VES locations:

- S1 → Elugwu-Nguzu
- S2 → Okpocha
- S3 → Letu
- S4 → Ugwuelu

2. Visualize Factor of Safety at each slope point (p1–p3 per site).
3. Highlight critical zones ($F_s < 2.0$) indicating higher landslide risk.

Simulated saturation resulted in F_s dropping below critical levels ($F_s < 1.5$) in Letu and Ugwuelu, confirming vulnerability under intense rainfall or groundwater infiltration.



This graph shows the Factor of Safety (F_s) for each slope position across the four VES sites:

- $F_s < 2.0$ (below the orange line): indicates potential instability or concern under certain conditions.
 - Notably, Letu (S3p3) has a F_s of 1.97 – indicating moderate landslide risk.
- $F_s > 2.0$: generally considered stable, though conditions like saturation or seismic activity can change this.
- Highest stability is seen at Letu S3p1 ($F_s = 3.93$) and Ugwuelu S4p3 ($F_s = 2.91$).

We proceeded to generate a combined site map with slope stability zones and also simulate effect of rainfall/saturation by reducing cohesion values to show safety degradation.

1. Combined Site Map:

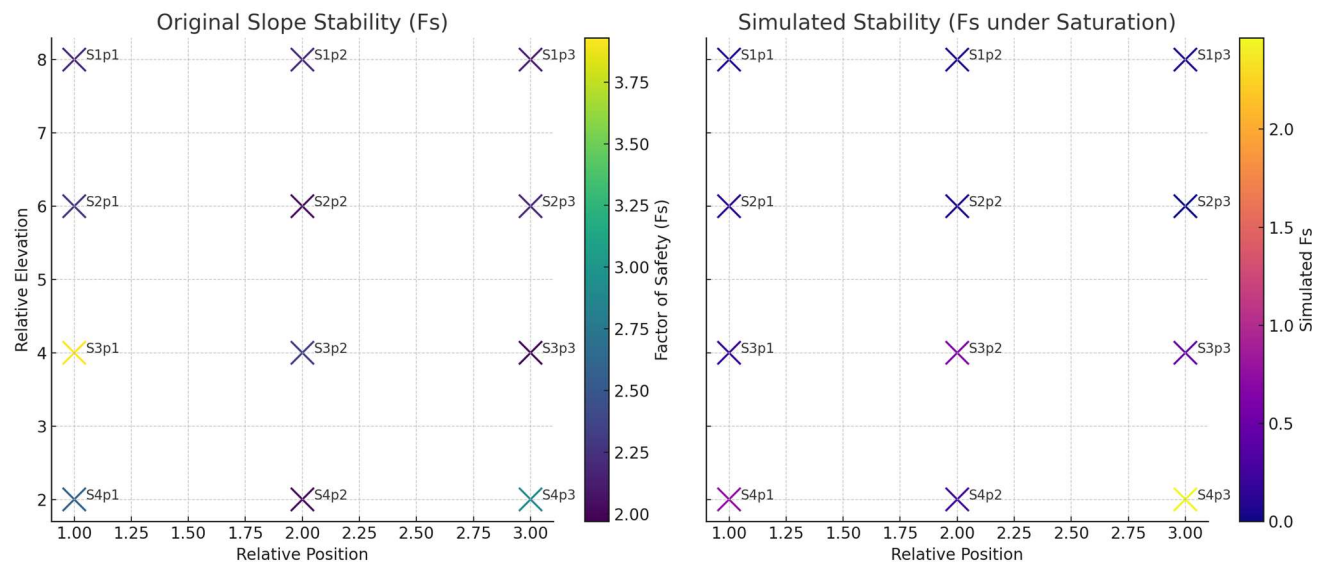
- Each slope position (S1p1 to S4p3) is plotted with a color scale based on the original Factor of Safety (Fs).
- Locations with $F_s > 2.0$ appear in green to blue (safe), while those approaching or below 2.0 trend toward yellow and red (less stable).

2. Rainfall Simulation:

- To model the impact of saturation, cohesion values are halved, simulating weakened soil bonding due to water.
- The recalculated $F_s = C/D$ shows visibly lower values—locations previously marginally stable might now fall below the safety threshold ($F_s < 1.5$), especially where cohesion was already low (e.g., Letu S3p3 or Ugwuelu).

Combined Site Map with Slope Stability Zones

The diagram below shows the distribution of Factor of Safety (F_s) across 12 slope positions under normal and rainfall-simulated conditions. Sites with $F_s < 2.0$ are considered more vulnerable to sliding.



From the stability analysis, most slope sites demonstrate acceptable stability under normal conditions. However, simulated rainfall significantly reduces the Factor of Safety, especially in

areas with low cohesion or silty-clayey overburden. Simulated saturation resulted in F_s dropping below critical levels ($F_s < 1.5$) in Letu and Ugwuelu, confirming vulnerability under intense rainfall or groundwater infiltration. While Okpocha exhibited higher sensitivity to saturation.

Based on the VES and the geotechnical data presented, the most critical factors contributing to landslide susceptibility in the four locations sampled are:

1. **Presence of Saturated Clayey or Silty Layers:** Letu and Ugwuelu have thick clayey-silty layers (e.g., saturated clayey sand and silty sand) immediately overlying bedrock. These layers have low shear strength and may become incompetent when saturated—essentially acting as slip planes. VES at Ugwuelu shows 19.88 m of saturated clayey sand above bedrock—a classic landslide-prone profile. Water saturation reduces cohesion and increases pore pressure, dramatically lowering Factor of Safety (F_s).
2. **Weak Topsoil and Overburden:** Thin, low-resistivity topsoil layers (like those in Okpocha and Letu) suggest lateritic or loose materials, which have limited cohesion. These are vulnerable to erosion and downward stress from overburden or development. Shallow failure surfaces develop easily under load or saturation.
3. **Steep Slope Gradients:** Elevation differences (e.g., Ugwuelu: 722 ft to 555 ft) indicate significant slope. When combined with soft layers, slope angle increases shear stress beyond resisting capacity. High slope angles amplify driving forces, pushing unstable materials downslope.
4. **Low Cohesion in Critical Points:** From geotechnical data: Some sites like S2p3 (Okpocha) show 0 kN/m² cohesion—meaning soil strength relies only on internal friction. Under wet conditions, friction is reduced, further lowering F_s .
5. **External Loads / Land Use:** Though not detailed in the data, factors like: buildings, deforestation, heavy machinery, seismic activity or vibrations (during the time of the construction of Ekoli Eda bridge) may trigger or accelerate slope failure, especially where underlying soil is weak.
6. **Most Contributing Factor (Combined):** > Saturation of weak subsurface layers (especially silty/clayey beds) combined with steep slope gradients are the primary triggers for landslides in these locations.

The table below presents a ranked risk assessment of landslide susceptibility in the Ekoli Eda area based on the Vertical Electrical Sounding (VES) interpretation and geotechnical data. It includes key risk factors for each site and proposes specific mitigation strategies.

Table 2 Ranked Landslide Risk

Site	Key Risk Factors	Overall Risk
Ugwuelu	-Thick Saturated Clayey-sandy layer (19.88m) -High slope gradient (Elevation drop: 722ft to 555ft) -Moderate Fs under saturation	High Risk
Letu Eda	-Silty sand over bedrock -Variable Resistivity & extended topsoil - Fs drops below 2.0 in some zones	Moderate - Risk
Okpocha Eda	- Slope zone with 0 kN/m ² Cohesion (S2p3) -Risk increases under Saturation	Moderate
Elugwu – Nguzu	-Consolidated subsurface - No clayey saturation horizon - Stable under most conditions	Low

4. Conclusion

This study demonstrates that combining VES and geotechnical data provides valuable insights into slope behavior. The results underscore the need for proactive, localized interventions in communities like Ekoli Eda, where rainfall-induced saturation can significantly increase landslide risks. These findings are crucial for regional planning, disaster risk management, and infrastructure development.

5. Competing interests/Funding.

There is no competing interest. The manuscript has not been submitted to any journal other than Landslide which in the opinion of the Researchers is the best option to publish the research findings

This research was funded by the Institutional Bases Research Grant from the Federal University of Technology, Owerri under the Tertiary Education Trust Fund of Nigeria (TETFUND). Researchers are required to publish with any Scopus indexed journal to access balance on funding.

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