Effects Of Slope Segments On Physical, Hydraulic, and Structural Stability Properties at Three Soil Depths in Amachalla, Awka, Nigeria

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ABSTRACT

This study examines the effects of slope segments in gully site at three depths on soil physical, hydraulic and structural stability properties at Amachalla, Awka, Southeastern Nigeria. A total of 36 soil samples were collected from three different slope segments (upper, middle and lower) at three depths (0–15 cm, 15–30 cm, and 30–45 cm) with four replications. These samples were prepared and taken to the laboratory for analysis using standard procedures to determine some soil parameters. The laboratory data were analyzed using Genstat Statistical Package and means were separated by Fisher's Least Significant Difference (F-LSD) at P<0.05. Results showed that soils in the study area were predominantly loamy sand, with the upper slope containing the highest sand fraction (86.91%) at 15–30 cm depth, while the lower slope recorded the highest silt content (12.27%) at the same depth. The middle slope recorded the highest clay fraction (4.08%) at 0–15 cm. Bulk density values ranged from 1.47 to 1.48 g/cm³, with no significant differences across slopes. Total porosity decreased with depth, ranging from 18.16 to 44.65%. Moisture content was highest (24.55%) in lower slopes at 30–45 cm. Saturated hydraulic conductivity varied from 10.49 to 13.54 cm/hr. Aggregate stability was highest (34.77%) at the lower slope (0–15 cm). Erosion ratio was highest at 263.14 in lower slopes. Based on the findings, emphasis should be placed on slope-specific soil conservation strategies to mitigate erosion risks.

INTRODUCTION

Soils in Southeastern Nigeria exhibit high erodibility and are classified as structurally unstable (Idowu and Oluwatosin, 2008). The prevalence of soil erosion, particularly gully erosion, poses a significant ecological threat to various states in the region, including Anambra, Imo, Ebonyi, and Abia, as well as other regions within Nigeria's humid tropical zones (Ume *et al.*, 2014). This persistent erosion contributes to soil degradation, resulting in the loss of fertile topsoil and significantly impacting agricultural productivity and food security in the region. The degradation of arable land due to erosion reduces soil fertility and negatively affects crop yields, necessitating urgent soil conservation interventions (Okogbue and Anomohanran, 2015).

Understanding the physical properties of soils across different slope segments and depths can provide critical insights into erosion vulnerability and soil stability. Such knowledge is essential for designing effective land management strategies aimed at mitigating erosion and sustaining agricultural productivity (Brady and Weil, 2016). Sloping terrains exhibit variations in soil characteristics due to differences in erosion intensity and sediment deposition (Liu *et al.,* 2020). Upper slopes tend to experience higher erosion rates due to steep slopes, gravitational force and minimal organic matter accumulation, whereas middle slopes act as transition zones with relatively balanced soil properties (Behr *et al.*, 2022). Conversely, lower slopes accumulate more organic matter and moisture, making them susceptible to waterlogging and structural instability (McKenzie *et al.,* 2004). Soil properties such as bulk density, porosity, and aggregate stability vary across slope segments. In contrast, higher porosity in upper slopes improves aeration but may heighten erosion susceptibility (Sari, 2017). Aggregate stability, a key determinant of soil resistance to erosion, tends to be highest in lower slopes due to increased organic matter and finer soil fractions (USDA-NRCS, 2014). Water retention parameters, including Field Capacity (FC), Permanent Wilting Point (PWP), and Available Water Capacity (AWC) exhibit notable variations across slope segments. Research suggests that middle slopes offer optimal conditions for agriculture due to their balanced water retention and drainage properties (Liu *et al.*, 2020). Upper slopes characterized by rapid water loss require conservation techniques like mulching and cover cropping to enhance moisture retention (Wang *et al.*, 2020). Conversely, lower slopes, which are prone to waterlogging, may necessitate improved drainage systems to maintain soil stability (Pulido Moncada *et al.,* 2015).

Saturated Hydraulic conductivity (Ksat) plays a crucial role in water movement within the soil profile with variations influenced by soil texture and organic matter content. Coarse-textured soils in upper slopes often exhibit higher Ksat values, facilitating rapid drainage (Sharma *et al.,* 2017). In contrast, fine-textured soils in lower slopes restrict water movement, increasing retention while simultaneously elevating erosion risks (Mukherjee and Lal, 2014). The erosion ratio (ER) is a critical indicator of landscape stability, with higher values observed in lower slopes due to prolonged runoff and sediment deposition. Implementing erosion control measures such as vegetative barriers and contour farming can significantly mitigate erosion risks (Brady and Weil, 2016). Effective land management strategies tailored to slope-specific soil properties are crucial for enhancing soil stability, agricultural productivity, and environmental conservation.

As Southeastern Nigeria particularly, Anambra State experiences severe gully erosion, leading to topsoil loss, reduced agricultural productivity, and environmental hazards it is pertinent to understand soil properties across slope segments which will help in erosion control and proper land management strategies. Therefore, this study aimed at assessing the effects of slope segments on soil physical, hydraulic, and structural stability properties at different depths in the gully site at Amachalla, Awka, Southeastern Nigeria.

MATERIALS AND METHODS

The study was conducted in a gully site at Amachalla, Awka, Anambra State, South Eastern, Nigeria. It is characterized by an undulating terrain with latitudes and longitudes ranging from 6˚07' to 6˚17'N and 7˚00' to 7˚10'E. The area has a humid tropical climate with a mean annual rainfall of 1824 mm and relative humidity of 80%. Geologically, over 80% of the soil of the area are derived from Imo Shale, while a small band of Nanka sands are seen in the western parts of the region (Orajiaka,1975). The climate is wet equatorial with average maximum and minimum temperatures of 29˚C and 23˚C, respectively. The vegetation is rainforest which has largely been disturbed by urbanization and other anthropogenic activities, thus leaving a derived vegetation as outliers within the region. The region is well-drained by such rivers as Mamu and Obibia in the East, Obizi in the North and Idemili River and Agulu Lake in the South (Ezenwaji *et al*., 2014).

Soil Sampling and Laboratory Analysis

A total of 36 disturbed soil samples were collected from three different slope segments (upper, middle and lower) in a gully site at Amachalla Awka at three varying depths (0–15 cm, 15–30 cm, and 30–45 cm) with four replications. These samples were collected with soil auger 15 metres apart from each sampling point to check for variabilities. The samples were prepared by air-drying, crushed with mortar and pestle and passed through 2mm sieve mesh before taken to laboratory for analysis using standard procedures to determine the following soil parameters: Particle Size Distribution using the Bouyoucos hydrometer method (Day, 1965), Soil Organic Carbon (SOC) determined using Walkley and Black method as described by Nelson and Sommer (1982). Percentage organic matter was calculated by multiplying the value of percentage organic carbon with Van Domelen’s correction factor 1.724 Emeka (2014), Water Stable Aggregates (WSA) by Kemper and Chepil (1965) method, Critical level of soil organic matter by Pieri (1991), Erosion Ratio by Middleton (1930), Bulk Density, Porosity, Hydraulic Conductivity, Field Capacity, Permanent Wilting Point, and Available Water Capacity were determined using pedotransfer functions (Saxton *et al.,* 1986) and analyzed with SPAW software (Saxton and Rawls, 2006).

Statistical Analysis

The data were analyzed using Genstat Statistical Package and means were separated by Fisher's Least Significant Difference (F-LSD) at $P<0.05$ to determine statistical significance between treatments.

RESULTS AND DISCUSSIONS

1.0 The effects of slope Segments in a gully across selected Depths on the Particle Size Distribution

The particle size distribution (Table 1) shows that the soils in the study area are predominantly loamy sand. The sand, silt and clay whose values across the depths ranged between 84.24% and 86.91%, 9.59% and 12.27% and 2.33% and 4.08 showed no level of significance among the mean values across the slope segments and depths with an exception to silt which showed significance at the depth of 15-30 cm depth. The upper slope segment showed highest sand fraction (86.91%) and lowest percent silt and clay when compared to the middle and foot slopes at the depth of 15-30cm, while least sand fraction (85.43%) was obtained at the depth of 0-15cm, suggesting that surface erosion has detached finer particles, leaving behind coarser fractions. This is in conformity with the findings by Sharma *et al.*, (2017), who reported that sandy soils are more prone to particle sorting due to water infiltration. Studies by Liu *et al*. (2020) confirm that upper slopes often lose finer particles (silt and clay) due to increased runoff and reduced deposition rates. Conversely, the lower slope has the highest percent silt (12.27%) at the depth of 15–30 cm, indicating a deposition zone where transported sediments, particularly silt and possibly clay, accumulate. The highest silt fraction observed on the surface soil indicates an initial accumulation of finer materials which are often removed by surface runoff over time (Liu *et al.*, 2020). Behr *et al.*, (2022) reported that lower slopes act as sediment traps leading to an increase in silt and organic matter content. The middle slope has the highest percent clay (4.08%) at the surface layer (0-15 cm), which may be attributed to moderate water infiltration and deposition of finer particles as observed by Wang *et al.*, (2020). Middle segment recorded highest per cent clay (4.08%) at the depth of 15-30 cm. This could be as a result of elluviation as suggested by U.S. Army Corps of Engineers (n.d.), while the least (2.33%) was observed at the upper segment at the surface soil depth of 0-15cm.

Table 1: Effect of slope Segments in a gully across selected Depths on the Particle Size Distribution of the Soil at Amachalla, Awka

SS	%Sand	%Silt	%Clay	Textural Class
		0-15cm Depth		
Upper	86.08	11.60	2.33	LS
Middle	84.24	11.68	4.08	LS
Lower	85.97	11.27	2.79	LS
$LSD_{(0.05)}$	NS	NS	NS	
		15-30cm Depth		
Upper	86.91	9.49	2.97	LS
Middle	85.42	10.95	3.03	LS
Lower	84.69	12.27	3.59	S
$LSD_{(0.05)}$	NS	1.616	NS	
		30-45cm Depth		
Upper	85.86	11.35	2.79	S
Middle	86.05	11.28	3.33	LS
Lower	85.91	10.59	2.60	LS
$LSD_{(0.05)}$	NS	NS	NS	

SS= Slope Segment, LS=Loamy Sand, LSD=Least Significant Difference, S=Sandy, NS= Not significant

Effect of slope Segments in a gully on the soil physical properties of eroded site at different depths.

Bulk Density (BD)

Bulk Density (BD) showed no significant difference across different gully segments. Its values ranged from 1.47 to 1.48 g/cm^3 with middle and lower slopes having highest value (1.48 g/cm^3) showing relatively low value which better soil aeration and root penetration (Brady and Weil, 2016. The non-significant differences across slope segments suggest that erosion and deposition processes have not significantly altered soil compaction, but ongoing land use practices could impact future BD trends (McKenzie *et al.,* 2004).

Total Porosity (Ft)

There was no significant difference in total porosity across the slope segments and depths under study. The total porosity values had range of 18.16 to 44.65% (Table 2) with higher value recorded at the upper slope (44.65%). This was likely due to vegetation cover and the subsequent deposition of leaves droppings that lower compaction as reported by (Wakene, 2001; Brady and Weil, 2016). This lowers BD and results in higher porosity. As recorded, its value tends to decrease down the depth. The declining porosity with depth is consistent with findings by Sari (2017), who linked compaction to reduced pore spaces which negatively affect water infiltration.

Moisture Content (MC)

Table 2 shows that there is significant difference on the M.C of the soil across the slope segments and depths under study. The soil moisture content value ranged from 7.87 to 24.55% where the lower slope segment had the highest percentage of moisture content (24.55%) at depth of 30-45 cm. This high M.C value recorded at the lower slope segment may be due to runoff and sediment deposition (Liu *et al.*, 2020). High moisture content recorded on the lower slope shows that it is prone to waterlogging and reduced soil stability (Behr *et al.,* 2022).

Saturated Hydraulic conductivity (Ksat)

The saturated hydraulic conductivity (Ksat) showed no significant effect across the depths and slope segments. The values ranged from 10.49 to 13.54 cm/hr. There was an increase in Ksat of the soil at the upper slope at 0-15cm and 15-30cm depths, but highest at the lower slope at the depth of 30-45cm. These differences in hydraulic conductivity with depth could align with the soil texture influence on permeability where coarser soils at upper slopes facilitate faster drainage, while finer-textured soils in lower slopes slow down water movement (Sharma *et al*., 2017).

Table 2: Effects of Slope Segments and depths on the soil physical properties and structural indices

SS	BD (g/cm^3)	Ft	MC	FC (%)	PWP	AWC	Ksat (cm/hr)	Aggregate Stability (%)	St (%)	ER
					0-15 cm Depth					
Upper	1.47	44.65	18.16	7.87	2.30	5.57	13.54	19.74	12.66	118.66
Middle	1.47	44.53	21.72	9.43	3.70	5.73	10.49	28.77	12.01	170.96
Lower	1.47	44.53	25.03	8.39	2.70	5.67	12.58	34.77	11.59	254.99
LSD$_{(0.05)}$	NS	NS	0.876	NS	NS	NS	NS	5.36	NS	57.82
					15-30 cm Depth					
Upper	1.47	44.65	17.72	8.43	3.10	5.33	11.99	18.78	10.20	129.03
Middle	1.48	44.03	21.52	9.07	3.17	5.90	11.12	26.27	11.39	178.87
Lower	1.47	44.53	24.12	9.27	3.50	5.77	10.82	30.79	12.44	241.09
LSD$_{(0.05)}$	NS	NS	1.50	NS	NS	NS	NS	5.05	1.60	57.19
					30-45 cm Depth					
Upper	1.47	44.53	18.84	8.40	2.90	5.50	12.18	19.90	12.08	137.03
Middle	1.48	44.28	22.34	8.40	2.90	5.50	12.23	24.70	11.70	139.56
Lower	1.48	44.28	24.55	8.30	2.70	5.60	12.65	28.70	10.85	263.14
LSD$_{(0.05)}$	NS	NS	0.90	NS	NS	NS	NS	NS	NS	63.10

SS = Slope Segments, St = Critical level of soil organic matter, ER = Erosion Ratio, NS = Not Significant

Field capacity (FC)

Table 2 showed that FC value ranged from 7.87 to 9.43% with highest percent recorded at middle slope with value of 9.43%, but fluctuated across depths probably as a result of variations in clay content and evaporation effects that influenced water retention in the soil (lgwe *et al.*, 2011).

Permanent Wilting Point (PWP)

There was no significant difference in PWP across slope segments. The permanent wilting point ranged between 2.30% to 3.70% across the slope segments and depths. However, variations in depth may be attributed to differences in soil properties that affect water retention capacities (Wang *et al.*, 2020).

Available water capacity (AWC)

The value of AWC ranged between 5.33% – 5.90% with the middle segment recording highest (5.73% and 5.90%) at the depths of 0-15 and 15-39 cm respectively (Table 2). These ranges of values support the findings of Liu *et al.* (2020) who reported that moderate slopes act as water retention zones before excess water drains downslope. It also aligns with agricultural land suitability studies, which suggest that middle slopes are ideal for crop cultivation due to balanced drainage and moisture availability (Liu *et al.* 2015).

Aggregate Stability

Soils of the lower slope across all depths (0-15, 15-130, and 30-45 cm) recorded the highest (34.77%, 30.79% and 28.70%) aggregate stability with the surface depth recording the highest value (34.77%) (Table 2). This could be as a result of higher organic matter content and clay fraction (USDA-NRCS, 2014) indicating greater resistance to erosion. The gravitational force acting on water runoff and sediment transport is typically higher compared to lower slopes. The upper slopes had lower aggregate stability, making them more prone to erosion, a trend widely observed in soil degradation studies (Behr *et al.,* 2022).

Critical level of Soil Organic Matter Content (St)

Organic matter improves soil water retention capacity by increasing water-holding capacity and reducing surface runoff and soil erosion.

The effects of slope segments across all depths on the critical level of soil organic matter as shown in Table 2 indicates that there was no significant difference in St. The Critical level of Soil Organic Matter Content value ranged from 10.2 to 12.66%, with the upper segment recording the highest (12.66%) at 0-15cm depth followed by 12.44% at 15-30cm depth, and 12.08% at 30-45cm depth. This range of value in St could be as a result of high organic matter accumulation that gave rise to highly stable soil. This accumulation of organic matter in different depths suggests erosion transport effects, where finer particles and organic residues are washed down the slope but accumulate at specific depths due to changes in infiltration rates (Wang *et al.*, 2020). However, when compared to the report of Mukherjee and Lal (2014), Pulido Moncad *et al.* (2015) and Pieri (1992); < 5% as structurally degraded soil, 5-7% as soil with high risk of degradation, and > 9% as soil with high stability. Therefore, soils of the study area are structurally stable.

Erosion Ratio (ER)

High erosion ratios indicate elevated soil erosion risk and decreased landscape stability. Table 2 shows higher values of erosion ratio in the lower slope across the three different depths (0-15,15-30 and 30-45cm) at 254.99, 241.09 and 263.14 where the highest was obtained at the depth of 30-45 cm. This could be as a result of lower slopes having a gentler gradient and longer slope length compared to upper slope. This also confirms that lower slopes experience significant sediment deposition due to prolonged runoff flow. The longer slope length on lower slopes allows water to flow with greater momentum and erosive force, leading to increased soil erosion as reported by *Liu et al.*, (2020) who emphasized that longer slope lengths in lower segments increase water velocity and erosive force, leading to higher sediment transport. The high erosion risk at these segments suggests a need for erosion control strategies, such as vegetative barriers and contour farming (Brady and Weil, 2016).

CONCLUSION

This study highlights the significant influence of slope segments in three soil depths on the physical, hydraulic and structural stability properties of soils in Amachalla, Awka. The results show that the soil is predominantly loamy sand, with particle distribution varying across slope segments in a gully site. The upper slope had the highest sand fraction (86.91%), while the lower slope exhibited the highest silt content (12.27%) and aggregate stability (34.77%), indicating sediment accumulation in the deposition zone. The middle slope had the highest clay content (4.08%), showing moderate water infiltration and partial deposition. Soil bulk density ranged from 1.47 to 1.48 g/cm³, showing no significant difference across slope segments. Highest Moisture content value was recorded as 24.55% in the lower slope at 30–45 cm depth, while saturated hydraulic conductivity varied from 10.49 to 13.54 cm/hr. The erosion ratio was highest (263.14) in the lower slope, indicating higher vulnerability to soil loss.

These findings highlight the importance of implementing slope-specific soil conservation practices, including contour farming, vegetative barriers, and enhanced drainage systems, to reduce erosion risks, improve soil stability, and promote sustainable land management and agricultural productivity in the region.

RECOMMENDATIONS

Based on the above results the following recommendations are proposed:

i. Upper slopes, showing high sand content (86.91%) and low moisture retention, should be protected by mulching, contour farming, and cover cropping to reduce erosion and improve water retention.

ii. Middle slopes, with the highest clay content (4.08%), are ideal for crop production due to their balanced water retention and drainage. Conservation tillage and crop rotation should be adopted to maintain soil structure.

iii. Lower slopes, with the highest moisture content (24.55%) and erosion ratio (263.14), require vegetative barriers, terracing, and drainage systems to prevent waterlogging and sediment accumulation.

iv. Incorporation of organic matter through compost and green manure to enhance aggregate stability, particularly in upper slopes with lower stability is recommended for soil structure improvement

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