Available online www.unicrossjournals.com

UNICROSS JOURNAL OF SCIENCE AND TECHNOLOGY, UJOST

RESEARCH ARTICLE VOL. 1(2) SEPTEMBER, 2022 ISSN:2814-2233

Date Approved September 30, 2022 Pages 259 – 276

ECO-ENGINEERING FOR ENVIRONMENTAL PROTECTION: VETIVER GRASS AS A SUSTAINABLE SOLUTION FOR SLOPE STABILISATION IN NIGERIA

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Abstract

Slope failure remains one of Nigeria's most persistent environmental hazards, causing destruction of infrastructure, displacement of communities, and loss of agricultural land. Conventional slope protection methods, such as concrete revetments and boulder pitching, are often expensive and prone to failure due to poor design and lack of maintenance. In response, eco-engineering approaches that incorporate vegetation into geotechnical engineering have gained attention as sustainable alternatives. This study evaluates the effectiveness of vetiver grass (Vetiveria zizanioides) as a bioengineering solution for slope stabilisation at the Ikot Uduak gully erosion site in Calabar, Nigeria. Soil samples were collected from the site and tested, including Atterberg limits, particle size distribution, specific gravity, and direct shear tests. A slope model was developed to compare soil strength parameters before and after introducing vetiver grass. The results show that shear strength increased from 25 to 26 kPa at 50 kPa normal stress, from 34.4 to 37.5 kPa at 100 kPa, and from 48.4 to 54 kPa at 200 kPa after eight weeks of vegetation growth. While soil cohesion slightly decreased from 18.0 to 17.8 kPa, the angle of internal friction (φ) increased from 8.7° to 10.4°, confirming the reinforcing role of vetiver roots. The study emphasises vetiver grass as a cost-effective, climate-resilient, and environmentally sustainable method for erosion control. Beyond its engineering benefits, vetiver offers additional ecological services such as soil conservation, runoff reduction, and ecosystem restoration. These findings support the integration of bioengineering approaches into Nigeria’s erosion management strategies and highlight the global importance of vegetation-based slope stabilisation in combating land degradation under changing climate conditions.

Keywords: *Vetiver grass, Eco-engineering, Slope stability, Direct shear test, Soil shear strength parameters, Gully erosion, Bioengineering for erosion control, Sustainable land management*

1.0 Introduction

Slope instability and soil erosion continue to be urgent global challenges with severe environmental, social, and economic impacts. Landslides, gully formation, and embankment failures not only damage infrastructure but also displace communities, diminish agricultural output, and increase poverty in vulnerable areas. According to the Internal Displacement Monitoring Centre (2015), over 26 million people were displaced worldwide in 2008 alone due to disaster-induced land degradation, highlighting the need for effective slope management strategies. The effects of climate change, such as increased rainfall intensity and variability, further elevate the risks of slope failures, especially in developing countries where adaptive capacity is limited.

In Nigeria, erosion has become a major environmental threat, with Calabar in Cross River State experiencing some of the worst cases of gully erosion in West Africa. Research has documented the collapse of residential buildings, the loss of farmland, and damage to vital urban infrastructure as typical consequences of uncontrolled soil erosion in this region (Imoke et al., 2021; Okpiliya et al., 2017). The main causes of slope and embankment failures include heavy rainfall, storm surges, riverbank undercutting, and poor maintenance of protective structures. Traditional slope protection methods, such as concrete revetments, boulder pitching, dredging, and channelisation, have been widely employed. However, these approaches are costly, susceptible to design errors, and often not sustainable in the long term (Abramson et al., 2002; Nazrul, 2000).

In response to the constraints of purely structural methods, greater emphasis has been placed on eco-engineering solutions that integrate vegetation into geotechnical practice. Vegetation influences slope stability through root reinforcement, hydrological regulation, and surface protection from rainfall impact (Roering et al., 2003). Vetiver grass (Vetiveria zizanioides), in particular, is recognised worldwide as a promising bioengineering resource. Its deep and fibrous root system provides exceptional tensile strength, anchoring soil layers while enhancing shear resistance. Moreover, vetiver thrives in a wide range of climatic and soil conditions, making it a resilient and adaptable species for erosion-prone environments (Jerome, 2011). Despite these advantages, the role of vegetation in slope stability analysis is often overlooked in engineering design, resulting in a research gap in quantifying its geotechnical contributions.

This study addresses this gap by examining the effectiveness of vetiver grass as a sustainable alternative for slope stabilisation in Nigeria. Using the Ikot Uduak gully erosion site in Calabar as a case study, the research assesses soil properties before and after establishing vetiver grass through standard geotechnical tests, including Atterberg limits, particle size distribution, specific gravity, and direct shear tests. By comparing changes in shear strength, cohesion, and internal friction angle, this study provides empirical evidence of vetiver's contribution to slope stability. The findings not only enhance understanding of vegetation-based slope reinforcement but also inform policy and practice for cost-effective, environmentally sound, and socially inclusive erosion control strategies in Nigeria and beyond.

2.0 Material and Methods

This chapter describes the experimental program that will be carried out to conduct the research. It will show the locations of the tests for the research. Then, all the field and laboratory test procedures will be discussed. During the field investigation, disturbed and undisturbed samples will be collected. Laboratory tests and all model tests will be performed on the collected samples at the Geotechnical Laboratory of the Civil Engineering Department of the University of Cross River State (UNICROSS), Calabar, Nigeria.

2.1 Study Area

Ikot Uduak is a street located within the State Housing Estate district in Calabar municipality, Cross River State, Nigeria. Calabar had a population of 328,878 in 1991 and 375,196 in 2006, according to the National Population Commission, as shown in Figure 1. With ongoing development in the city, the projected population for 2015 was estimated at 529,362, with a growth rate of 2.54 (World Bank, 2015). It is situated in the southern senatorial district of the state, between longitudes 8°18′00″E and 8°24′00″E, and latitudes 4°54′00″N and 5°04′00″N. The area is bounded by Calabar River to the west, Kwa River to the east, Odukpani L.G.A to the north, and the creeks of the Atlantic Ocean to the south. Covering about 406 square kilometres, Calabar’s coastal areas are low-lying, with an average altitude of 10 metres above sea level, while areas further inland to the north range between 40 and 80 metres above sea level. The undulating terrain of Calabar contributes to the rapid development of gully erosion agents (Okpiliya et al., 2016). Figure 1 illustrates the study area along with several other gully sites in Cross River State, Nigeria.

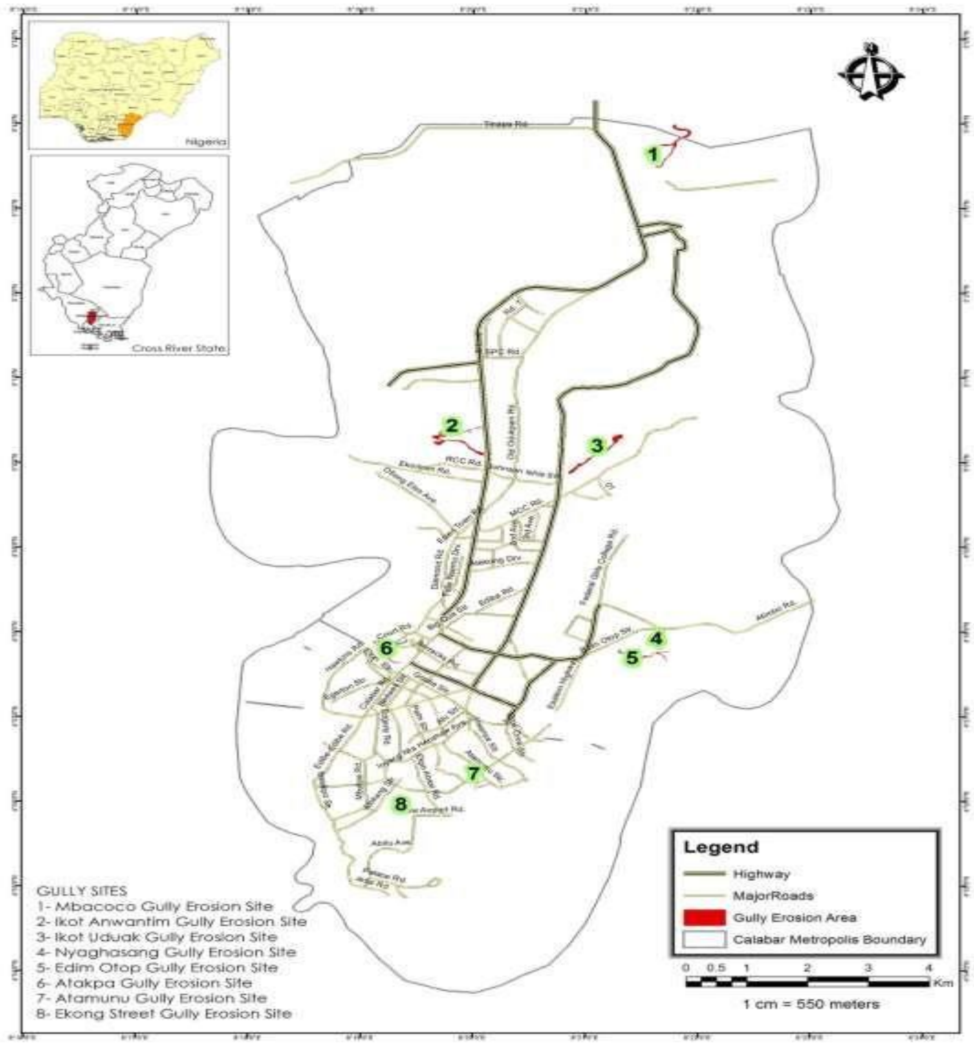

Figure 1: Map of gully sites in Calabar Metropolis (Source: Okpiliya et al., 2016

2.2 **Plant Selection and Collection**

Considering the physical, biological, morphological, ecological, and experiential aspects of previous applications and research, Vetiveria zizanioides appears to be the ideal plant for this study. In addition to its root morphology, vetiver is a grass capable of surviving under extreme soil conditions. To ensure the experiments are rational for studying the characteristics of vetiver grass at different slope levels in the study area, sources of these grasses were kept consistent. Plants used in this study were collected from a specific location. The grasses were placed in sack bags, then transported to the laboratory. They were kept under a shed and watered to maintain moisture.

2.3 Soil Sample Collection

Two types of soil samples were used for laboratory tests: disturbed and undisturbed soil samples. Undisturbed soil samples were collected using a garden hoe. Polythene bags were employed to store these samples to retain moisture. A PVC pipe with a diameter of 7.5 cm and a length of 45 cm was used for collecting undisturbed soil samples by driving the pipe into the soil. Subsequently, the surrounding soil was excavated to extract the pipe along with the undisturbed soil inside.

2.4 Laboratory Analysis

Index and strength properties tests, including Atterberg Limits, Grain Size Distributions, Specific Gravity, and Direct Shear tests, were conducted on soil samples to assess the subsoil conditions of the study area. The following tests will be performed on the soil in the study area.

3.0 Results and Discussion

Tables 1 to 3 give direct shear test results for 50, 100, and 200kPa loads.

Table 1: Result for Direct Shear Strength of 50 kPa

50KPA

TIME	VERT.DIAL	VERT.DISP.	Strain	HOR.DIAL	HOR.DISP.	COR.A	LOAD RING.DIAL	HOR.SHEAR	SHEAR STRESS
0	100	0	0	0	0	0.0036	0	0	0
15	85	-0.015	0.15	75	0.075		18	5.625	1.40625
30	78	-0.022	0.22	140	0.14		20	6.25	1.5625
45	68	-0.032	0.32	187	0.187		24	7.5	1.875
60	57	-0.043	0.43	258	0.258		25	7.8125	1.953125
75	49	-0.051	0.51	320	0.32		28	8.75	2.1875
90	43	-0.057	0.57	389	0.389		31	9.6875	2.421875
105	38	-0.062	0.62	456	0.456		32	10	2.5
120	34	-0.066	0.66	524	0.524		32	10	2.5
150	31	-0.069	0.69	664	0.664		32	10	2.5
180				790	0.79		27	8.4375	2.109375

Table 2: Result for Direct Shear Strength of 100 kPa

100KkPa

TIME	VERT.DIAL	VERT.DISP	Starin	HOR.DIAL	HOR.DISP.	COR.A	LOAD RING DIAL	HOR.SHEAR	SHEAR STRESS
0	100	0	0	0	0	0.0036	0	0	0
15	84	-0.016	0.16	82	0.082		26	8.125	2.03125
30	75	-0.025	0.25	151	0.151		29	9.0625	2.265625
45	62	-0.038	0.38	197	0.197		33	10.3125	2.578125
60	57	-0.043	0.43	267	0.267		38	11.875	2.96875
75	40	-0.06	0.6	320	0.32		39	12.1875	3.046875
90	38	-0.062	0.62	392	0.392		43	13.4375	3.359375
105	35	-0.065	0.65	483	0.483		44	13.75	3.4375
120	35	-0.065	0.65	562	0.562		44	13.75	3.4375
150	32	-0.068	0.68	628	0.628		44	13.75	3.4375
180				784	0.784		42	13.125	3.28125

Table 3: Result for Direct Shear Strength of 200 kPa

200kPa									
TIME	VERT.DIAL	VERT.DISP	Strain	HOR.DIAL	HOR.DISP.	COR.A	LOAD RING.DIAL	HOR.SHEAR	SHEAR STRESS
0	100	0	0	0	0	0.0036	0	0	0
15	81	-0.019	0.19	84	0.084		36	11.25	2.8125
30	71	-0.029	0.29	162	0.162		40	12.5	3.125
45	68	-0.032	0.32	230	0.23		48	15	3.75
60	62	-0.038	0.38	256	0.256		51	15.9375	3.984375
75	42	-0.058	0.58	357	0.357		55	17.1875	4.296875
90	28	-0.072	0.72	420	0.42		58	18.125	4.53125
105	28	-0.072	0.72	467	0.467		62	19.375	4.84375
120	28	-0.072	0.72	542	0.542		62	19.375	4.84375
150	21	-0.079	0.79	630	0.63		62	19.375	4.84375
180				788	0.788		57	17.8125	4.453125

A summary of the direct shear strength test results is given in Figure 1.

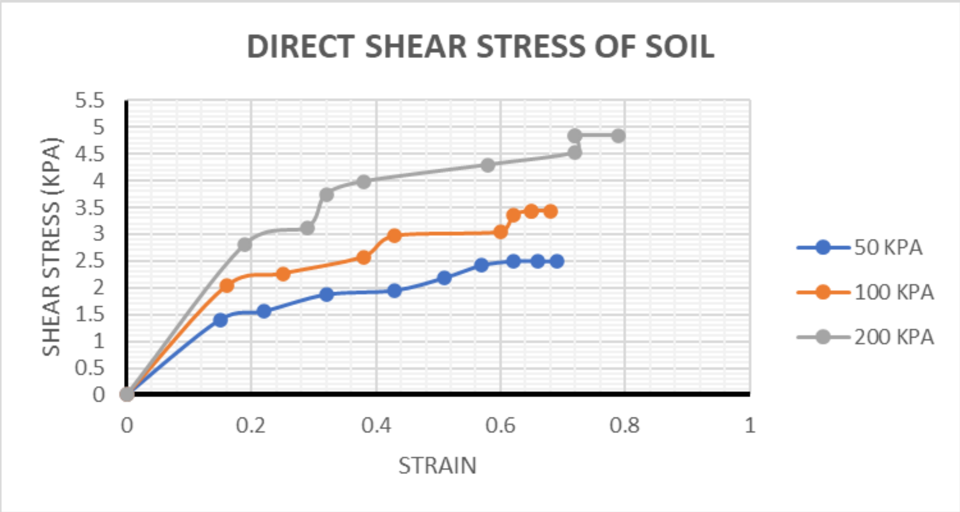

Figure 2: Graph of Direct Shear Strength of Soil

3.1 Cohesion and Angle of Internal Friction

To determine the cohesion and internal friction angle of the soil, a graph of shear stress against normal stress was plotted as shown in table 4 and Figure 3.

Table 4: Shear stress against normal stress

Normal Stress (kPa)	Shear Stress (KPa)
50	25
100	34.4
200	48.4

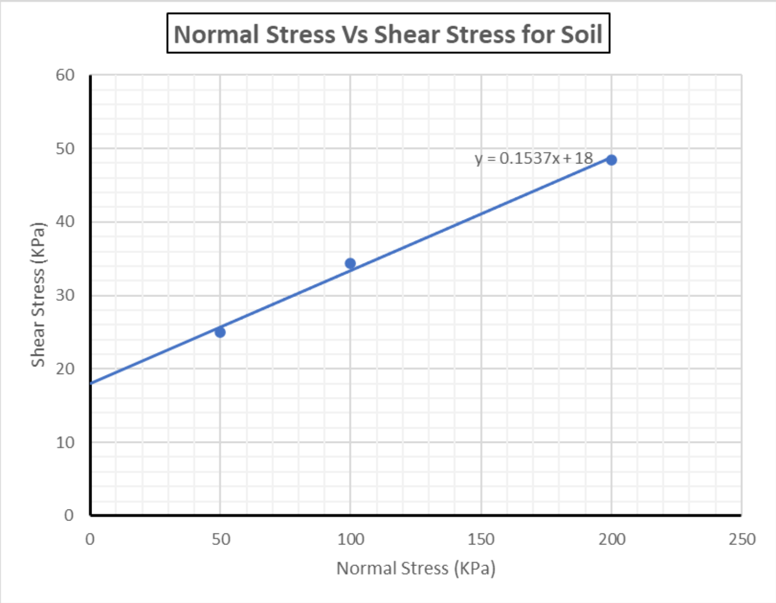

Figure 3: Graph of Shear Stress Vs Normal Stress of the Soil

It can be obtained from the plot that the cohesion of the soil, $C^!$ is 18 kPa while the angle of internal friction,$\emptyset$ is 8.74°. This is demonstrated in the table 5 below

Table 5: Cohension and angle of internal friction

Property	Value	Unit
Cohesion, $C^!$	18	kPa
Angle of Internal Friction, $\emptyset$	0.152506551 8.737980739	Rad Degrees

3.2 Direct Shear Strength for Soil with Vetiver Grass

To achieve the research aim, vetiver grass was planted and allowed to grow in the soil for approximately 2 months. Samples were then obtained and transported to the laboratory for testing. The following shows the results obtained from the experiment performed.

Table 6: Result for Direct Shear Strength Test of 50 kPa

50kPa

TIME	VERT.DIAL	VERT.DISP.	HOR.DIAL	HOR.DISP.	COR.A	LOAD RING.DIAL	HOR.SHEAR.	SHEAR STRESS
0	100	0	0	0	0.0036	0	0	0
15	89	-0.011	60	0.06		22	6.875	1.71875
30	80	-0.02	120	0.12		27	8.4375	2.109375
45	70	-0.03	179	0.179		29	9.0625	2.265625
60	59.5	-0.0405	238	0.238		30	9.375	2.34375
75	52	-0.048	299	0.299		31	9.6875	2.421875
90	46.5	-0.0535	361	0.361		33	10.3125	2.578125
105	42.5	-0.0575	423	0.423		34.5	10.78125	2.695313
120	39	-0.061	485	0.485		34.5	10.78125	2.695313
150	38	-0.062	512	0.512		34.5	10.78125	2.695313
180			740	0.74		33	10.3125	2.578125

Table 7: Result for Direct Shear Strength Test of 100 kPa

100kPa								
TIME	VERT.DIAL	VERT.DISP	HOR.DIAL	HOR.DISP.	COR.A	LOAD RING DIAL	HOR.SHEAR	SHEAR STRESS
0	100	0	0	0	0.0036	0	0	0
15	90	-0.01	65	0.065		30	9.375	2.34375
30	79	-0.021	125	0.125		35	10.9375	2.734375
45	65	-0.035	182	0.182		38	11.875	2.96875
60	60	-0.04	240	0.24		40	12.5	3.125
75	50	-0.05	300	0.3		42	13.125	3.28125
90	45	-0.055	360	0.36		45	14.0625	3.515625
105	40	-0.06	420	0.42		48	15	3.75
120	40	-0.06	490	0.49		48	15	3.75
150	35	-0.065	515	0.515		48	15	3.75
180			755	0.755		45	14.0625	3.515625

Table 8: Result for Direct Shear Strength Test of 200 kPa

200kPa								
TIME	VERT.DIAL	VERT.DISP	HOR.DIAL	HOR.DISP.	COR.A	LOAD RING.DIAL	HOR.SHEAR	SHEAR STRESS
0	100	0	0	0	0.0036	0	0	0
15	85	-0.015	70	0.07		40	12.5	3.125
30	75	-0.025	140	0.14		50	15.625	3.90625
45	70	-0.03	200	0.2		55	17.1875	4.296875
60	65	-0.035	220	0.22		58	18.125	4.53125
75	45	-0.055	320	0.32		65	20.3125	5.078125
90	30	-0.07	380	0.38		68	21.25	5.3125
105	30	-0.07	440	0.44		70	21.875	5.46875
120	30	-0.07	500	0.5		70	21.875	5.46875
150	25	-0.075	550	0.55		70	21.875	5.46875
180			760	0.76		65	20.3125	5.078125

The direct shear strength of the soil with vetiver plant is plotted on a graph to visually demonstrate the effect of vetiver on the sample's shear strength. This graph shows shear strength against strain, as illustrated in Figure 4.

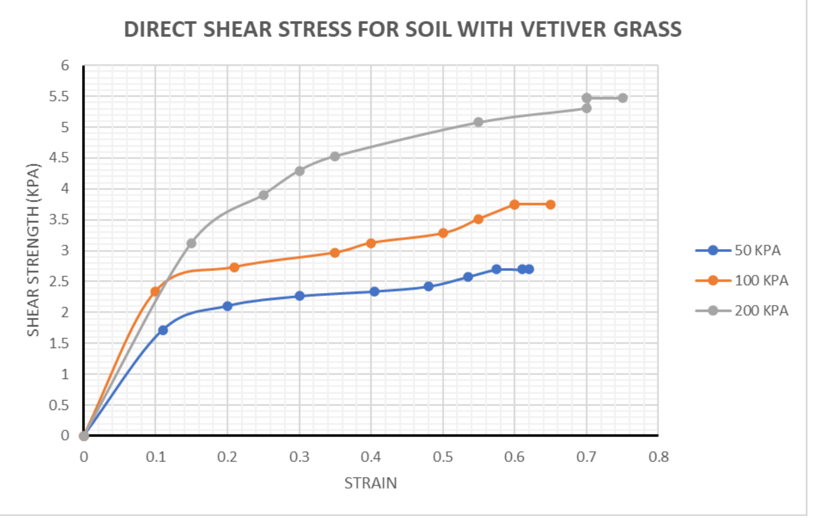

Figure 4: Graph of Direct Shear Stress for soil with Vetiver grass

3.3 Cohesion and Angle of Internal Friction for Soil with Vetiver Grass

To obtain the cohesion and the angle of internal friction of the soil with vetiver grass, the graph of shear stress against the normal stress was plotted as shown below.

Table 9: Normal stress and shear stress

Normal Stress (kPa)	Shear Stress (kPa)
50	26
100	37.5
200	54

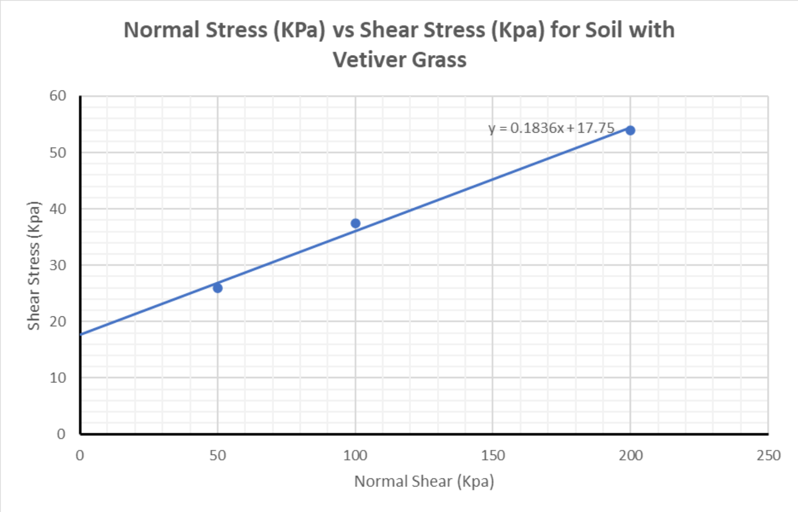

Figure 5: Graph of Shear Stress Vs Normal Stress of the Soil with Vetiver Grass

It can be obtained from the plot that the cohesion of the soil, $C^{!}$ is 18 kPa while the angle of internal friction,∅ is 8.74°. This is demonstrated in the table below

Table 10: Cohesion and angle of internal friction

Property	Value	Unit
Cohesion, c	17.75	kPa
	0.1836	
Angle of Internal Friction, ∅	0.181578	Rad
	10.40364	Degrees

3.4 Effects of Vetiver grass on the Shear strength of the soil

The introduction of vetiver grass (Vetiveria zizanioides) into the soil significantly improved slope stability by enhancing shear strength and the angle of internal friction, while only slightly reducing cohesion. After eight weeks of growth, shear strength increased from 25 to 26 kPa at 50 kPa normal stress, from 34.4 to 37.5 kPa at 100 kPa, and from 48.4 to 54 kPa at 200 kPa. At the same time, the angle of internal friction rose from 8.7° to 10.4°, whereas cohesion decreased marginally from 18.0 to 17.8 kPa.

These results confirm that vetiver roots contribute substantially to soil–root reinforcement, improving inter-particle bonding and resistance to shear deformation. This aligns with earlier findings that vegetation enhances slope stability primarily by increasing frictional resistance rather than cohesion (Roering et al., 2003; Nazrul, 2000; Jerome, 2011). The outcomes also correspond with studies in Bangladesh and Southeast Asia, where vetiver grass has been successfully applied to embankment and dyke stabilisation projects (Shahriar, 2015).

From an engineering standpoint, these findings emphasise the potential of integrating vegetation into slope stability models. Traditional geotechnical design tends to overlook root reinforcement, resulting in conservative and expensive solutions. By accounting for vegetation effects, engineers can develop cost-effective, resilient, and environmentally sustainable alternatives to conventional structural approaches.

Beyond its geotechnical function, vetiver grass provides wider ecological and socio-economic benefits. It reduces runoff, controls erosion, restores degraded land, and enhances biodiversity, making it more advantageous than conventional methods such as concrete revetments or boulder pitching, which lack ecological value (Abramson et al., 2002). Its low cost and suitability for community participation further strengthen its relevance in resource-constrained contexts like Nigeria.

Nonetheless, this study was limited to laboratory-based analysis with an 8-week growth period, which may not reflect long-term field performance. Extended field trials under varying climatic, hydrological, and slope conditions are necessary to capture seasonal variations and hydrological interactions. Coupling field research with hydrological modelling and cost–benefit analysis would provide a more comprehensive understanding of vetiver systems for large-scale application.

4.0 Conclusion

This study demonstrated that vetiver grass can serve as an effective eco-engineering solution for slope stabilisation in erosion-prone areas of Nigeria. Laboratory tests at the Ikot Uduak gully erosion site showed that shear strength improved under everyday stresses of 50, 100, and 200 kPa, while the angle of internal friction increased from 8.7° to 10.4°. Although cohesion declined slightly, the overall improvement in soil stability highlights the reinforcing role of vetiver roots.

The findings establish vetiver grass as a sustainable, low-cost, and environmentally beneficial alternative to conventional slope protection methods. In addition to strengthening soil mechanically, vetiver contributes to broader ecological services, including erosion mitigation, runoff reduction, and soil conservation. This dual function positions it as a valuable bioengineering tool that can complement Nigeria's erosion management efforts while supporting global goals for sustainable land use and climate resilience.

Recommendations

Policy Adoption: Government agencies should integrate vetiver-based eco-engineering into national erosion control and land management programs.

Field Validation: Large-scale demonstration projects should be conducted under diverse soil and climatic conditions to confirm long-term performance.

Economic Evaluation: Comparative cost–benefit analyses should be undertaken to assess the financial advantages of vetiver systems over conventional methods.

Public Engagement: Awareness campaigns should be launched to promote community involvement in vetiver planting and maintenance for slope protection.

Research Expansion: Further studies should investigate hydrological impacts, climate resilience, and potential applications of vetiver in soil reclamation.

Community-Based Implementation: Local communities should be empowered to adopt vetiver systems, ensuring ownership and sustainability of erosion control initiatives.

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