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Geological and Geotechnical Evaluation of Gully Erosion at Nguzu Edda, Afikpo Sub-Basin, Southeastern Nigeria

Amagu, A. C. (Corresponding author)
Division of Sustainable Resources Engineering, Graduate School of Engineering, Hokkaido University
N13W8, Kita-ku, Sapporo, 060-8628, Japan; E-mail: amaguclementglk@gmail.com

Eze, S. N.
Department of Geology and Exploration Geophysics, Ebonyi State University Abakaliki, Nigeria; E-mail: nkemakoname@gmail.com

Jun-ichi Kodama
Division of Sustainable Resources Engineering, Graduate School of Engineering, Hokkaido University
Sapporo, 060-8628, Japan; e-mail: N13W8, Kita-ku, Sapporo, 060-8628, Japan
Phone: +81-11-706-6300, E-mail:kodama@eng.hokudai.ac.jp

Nweke, M. O
Department of Geology and Exploration Geophysics, Ebonyi State University Abakaliki, Nigeria; E-mail: nwaekeoby@yahoo.com

Abstract

A detailed geological field mapping of Nguzu Edda has revealed that gully erosion and landslides have remained active over the years, posing serious threats to human life, agricultural land, infrastructure and socio-economic activities within the area. Consequently, twelve true representative soil samples from different locations within gully sites have been analyzed based on ASTM and British Standards, to evaluate geologic conditions and geotechnical parameters that influence the gullies problems. The results of the laboratory tests revealed that the soil at the gully sites are predominantly sands (57~99.5 % with mean of 69.7%) with low amount of fines (silt; 0.3~ 22% with average value of 14.6% and clay: 0.2 ~ 21% with average value of 13.9%). The liquid limit (LL) ranged from 15 ~ 31.50 % with mean of 23.32% and the plasticity index (PI) ranged from 2.92~14.42% with mean of 8.95%. The moisture content, permeability, bulk density, porosity, organic matter and pH have average values of 25.31%, 6.04×10^{-4} cm/sec, 1.55 kg/m^3, 40.40, 1.26% and 5.12, respectively. The cation exchange capacity (CEC) is low, which could be attributed to low organic matter, pH and non active clay minerals. With regard to the aforementioned characteristics, the soils at gully sites are loose sands with low amount of fines fraction, hence cohesionless, and are easily exposed to agents/factors of gully erosion. Thus, provides insights about the vulnerable causes of gully erosion and landslides problems that are prevalent in the area. This research addresses, to a great extent the effects of local geology, geotechnical properties of the underlying soil and associated human activities on the formation of gully erosion, in-turn results to landslides within in the study area. Engineering-geologic aspects of soil erosion control were also recommended.

Keywords: Afikpo Sub-basin, Geologic conditions, Geotechnical analysis, Gully erosion and Erosion control measures.

1. Introduction

Among the geohazard, gully erosion has been considered as one of the most fatal hazard posing a serious threat to human existence, agricultural land, infrastructure and socio-economic activities (Amah et al., 2008). Generally, it could occur either as sheet, rill or gully erosion (Okeke & Enwelu, 2010) and is a clear form of soil degradation and destruction, which occurs where surface water flow become trapped in a small concentrated stream, and begins to erode channels in the ground surface, making it wider and deeper (Chikwelu & Ogbuagu, 2014). Significantly, uncontrolled progressing gully erosion results in the loss of biological and economic productivity of terrestrial ecosystem, including soil nutrients, vegetation (Carter & Bentley, 1991). In order to mitigate these gullies there is increased need for soil investigations to obtain information and adequate understanding of the geotechnical properties of the sandy soil

In South eastern Nigeria, field geological studies have revealed that gully erosion has remained active over many years, ravaging the physical ecology of the landscape. These have led to geotechnical and engineering geological interest due to its effect on structures, natural resources and foundations. Some of these investigation revealed that the major landslides and gully erosion sites in south eastern Nigeria are localized within areas where there are predominantly sandy soils.

Recently, studies have attributed the formation and growth of gullies to the influence of human activities on geomorphologic processes. However, investigations carried out by previous researchers on these soils have shown that the primary causes of the gully erosion lie in the hydrogeological and geotechnical properties of the soils in the area. Research works have been carried out by Ofomata (1988), Floyd (1965), Nwajide &Hoque (1979), Okagbue & Uma (1987), Akpokodje et al. (1986), Okagbue (1986); Akpokodje (2001); Okagbue & Aghamelu, (2010a), Teme (2001), Okeke & Enwelu (2010) and Okagbue &Ezechi (1988) on the sandy soils in South eastern Nigeria. They stated that all previous works on the soils seem to agree that soil/gully erosion is more severe in areas of rugged terrain underlain by friable sandy soils with high fines content and unconsolidated sandy bedrock. Okengwo et al. (2015) studied the factors that gives development of gully erosion and landslides in southeastern Nigeria, suggested that gully erosion is controlled by physiography, hydrogeology, and engineering properties of the soil materials. Osadebe and Akpokodje (2007) remarked that the soil erodibility index is influenced by both physical and chemical properties of soil. Bocco et al. (1990) concluded that gullies erosion is triggered by many factors, but largely by rainfall, slope of the land surface, and human activities (Okengwo et al., 2015). Akpokodje (2001) stated that the mechanical behaviour of a sandy soil changes depending on its grain size distribution due to particle crushing during loading, unloading and reloading during tectonic activities, the soil could behave as either cohesive or cohesionless because of changes in the coarse/fine grains content ratio. Chien (2002) stated that textural properties play an important role in the mechanical response of soils, especially when the soils are subjected to loading. Hudec et al. (2005) noted that the textural properties of these soil deposits determine their mechanical response to the erosive action of surface runoff. The geotechnical properties of sandy soils in Southeastern Nigeria has been investigated and documented but there is still limited understanding on how a low amount of fines particles affect the overall geotechnical behavior of sandy soils.

Although much work has been done on gully erosion site soils in Southeastern Nigeria, but the geotechnical evaluation of the sandy soil deposit in the study area has not been investigated. Given the above, the detailed geologic and geotechnical test were carried out within Nguzu Edda, which have revealed that gully erosion remained active, causing large-scale landslide within the area (F.g.1). Therefore, in this study, an attempt has been made to employ applicable laboratory tests to evaluate geotechnical properties of the soil within the gully site. The assessment mainly intended to provide insight on the geologic conditions and geotechnical parameters that contribute immensely to gully development and to study the influence of the fines content on the mechanical/geotechnical behaviour of the sandy soil in the study area. This knowledge may be useful in controlling gully erosion and landslides in the area.

Figure 1: Gully erosion sites within the study area

2. Physiography, climate and geology of the study area

2.1 Physiography and climate of the study area

The study area, Nguzu Edda in Afikpo South Local Government Area, Ebonyi State is geographically bounded by longitude $7^0 49'$ E to $7^0 54'$ E and latitude $5^0 45'$ N to $5^0 50'$ N. The mapped area covers Owutu-Edda, Ebonwana-Edda, Ekoli-Edda, Amaigbo Edda, Ekeje and Amaiyi Edda of about 62 km^2 (Fig.2). The study area can be accessed by major roads of Owutu – Nguzu Edda and Owutu – Ekoli Edda road and minor roads include Achara, Amanyi, Ebuwana, Ekeje, and Amaiyi. Nguzu Edda lies on the Cross River Basin with an irregular and undulating topography (Okoro and Igwe, 2014). The hills in the area are very steep and rocky, making the soils very susceptible to erosion irrespective of its nature. The south westerly winds bring the rain from April to October while the north east trade winds are responsible for the hammattan with low humidity from December to February. The hottest periods are February and March with mean annual temperature of over 27^0 C. During the rainy season the temperature ranges from 16° to 28° C. The predominant vegetation visible along these zones is the grasslands, with scattered forests and woodland areas as well as tropical rainforest which comprise tall trees with thick undergrowth with fewer branches. However, these zones have been seriously affected by erosion as a result of natural and human influences

2.1 Geology of the study area

Nguzu Edda lies within Afikpo Sub-basin (Fig. 2), which is one of the Upper Cretaceous sub-basins which make up the Anambra Basin (Reijers et al., 1997, Okoro and Igwe, 2014). The Afikpo Sub-basin is considered as the southeastern depression of the Anambra Basin of (Nwajide, 2013). The sediment fill is a succeeding post-Santonian facies though to be completely accommodated within the Anambra Basin (Nwajide, 2013) Based on the lithologic, structural and stratigraphic of the study area, three component lithostratigraphic units of the Upper Campanian-Maastrichtian were identified: the Afikpo sandstone, Nkporo and Mamu Formation (Fig.3). The Afikpo sandstone is the oldest lithostratigraphic unit, consists mainly of fine to very coarse ferruginized sandstone and shale. The Nkporo Formation overlies the Afikpo sandstone and consists of thick succession of fossiliferous dark-grey to black shales with intercalations of sandstone and ironstone. The Mamu formation is made up of coal, shale and sandstone.

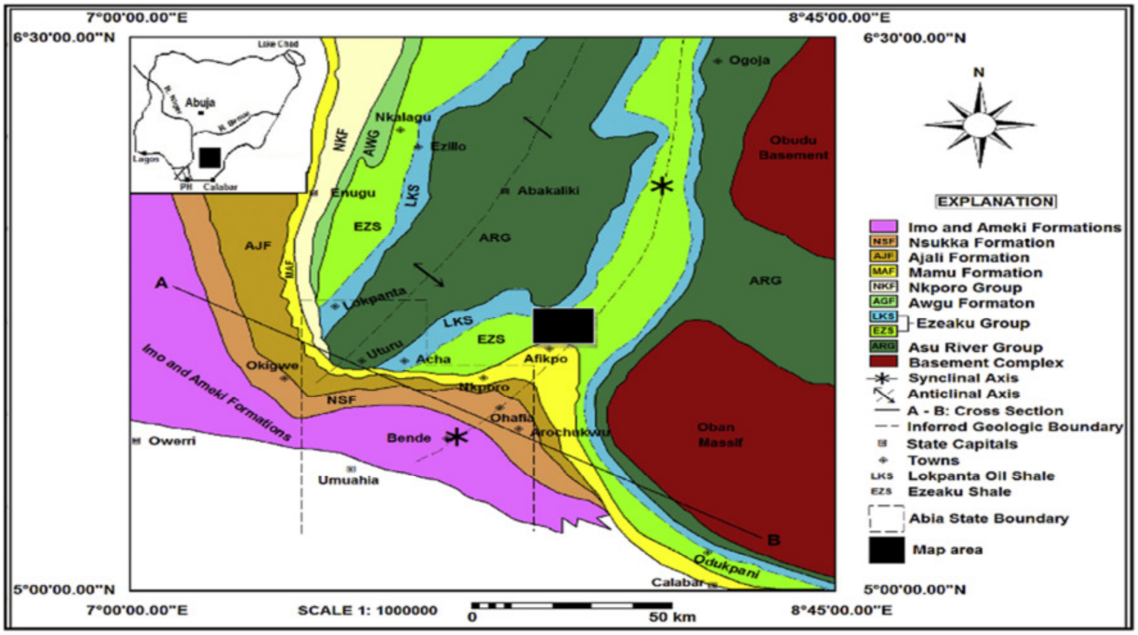

Figure.2: Regional geologic map of Southern Benue Trough showing the study area (Nwajide, 2013)

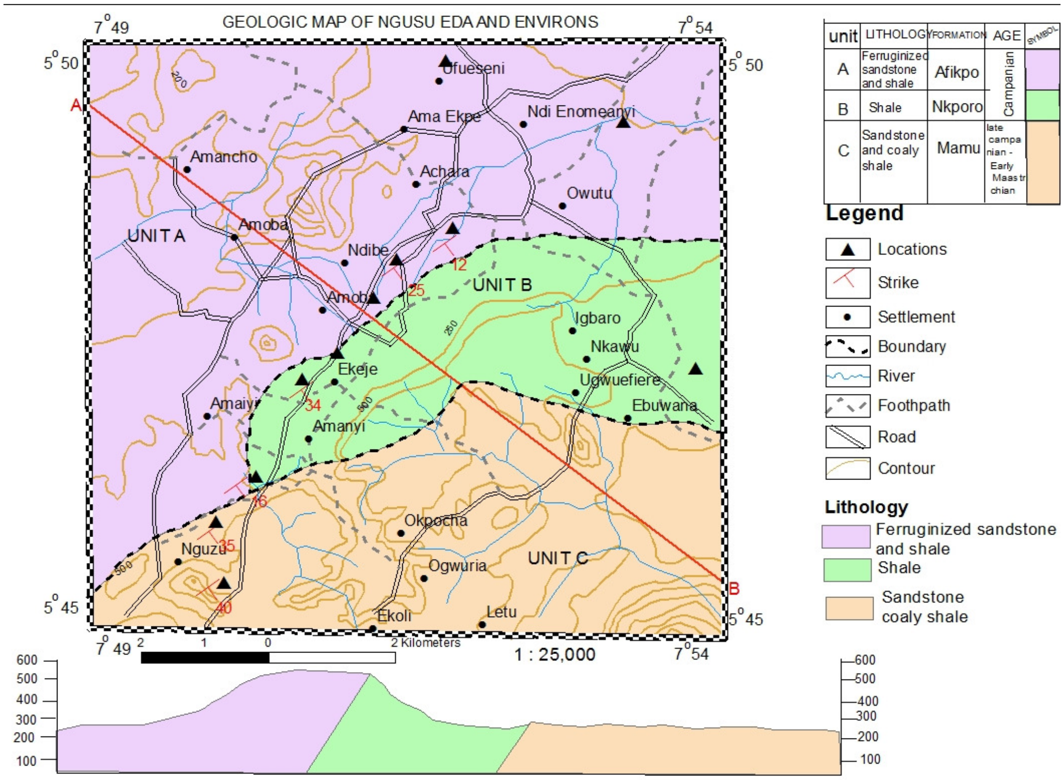

Figure 3: Geologic map of Nguzu Edda and its Environs

3. Methods

3.1 Sampling

The soil investigation, which comprised field study and laboratory analyses were carried out. The field investigation for the soil data collection included sampling and measurement in twelve different gully erosion sites (Fig. 3 and Table 1), with the aid of Global Positioning System (GPS). Twelve (12) true soil representative samples, designated as SML_1-SML_12 were randomly collected from active erosion sites as well as areas considered to be potential future erosion sites for laboratory analysis. The soil samples were subjected to geotechnical Basic Index Property Tests at laboratory of National Steel Raw Materials Exploration, Malali village, Kaduna Nigeria, to determine the physical and chemical properties of the soil that facilitates its prone to gully erosion in accordance with standardized methods specified by the American Society for Testing and Materials (ASTM) and the British standard (BS).

Table.1: Sample collection points of the Erosion Areas

Sample ID	Locations	Latitude (North)	Longitude East)	Current Erosion state
SML-1	Echara	05048'46"	007050'19."	Partially Active
SML-2	NdiEba	05048'24"	007050'11"	Partially Active
SML-3	Amoba	05047'40"	007049'49"	Partially Active
SML-4	Ekeje	05047'0.2"	007049'29"	Partially Active
SML-5	Uniglobe Const. Site	05046'38.2"	07049'29.2"	Very active
SML-6	Iyiasa stream Nguzu	05045'52.9"	007049'49.1'	partially active
SML-7	St.Peters Nguzu Edda	05045'06.0"	07049'17.0"	Active
SML-8	LGA hqtrs Nguzu	05045'04.5"	07049'17.5"	very active
SML-9	Ekoli Edda	05044'56"	007050'4''	Active
SML-10	Letu Edda	05045'30.6"	007050'33.8"	Partially active
SML- 11	Ugwuifere	05046'53"	007050'42"	Partially Active
SML-12	Ndiologhu	05046'03"	007051'12"	Partially Active

3.2 Laboratory analyses

The Laboratory tests carried out on the soil samples include Index Tests such as Atterberg limits (liquid and plastic limits), particle size distribution, natural moisture content, bulk density test, permeability, porosity, organic matter and pH test. The sample laboratory tests for the geotechnical parameters followed standardized methods specified by the American Society for Testing and Materials (ASTM) and the British standard (BS) of testing soil for civil engineering purposes.

The Atterberg limits for measuring properties and behaviors of soil in respect with critical water content that include liquid limit, plastic limit and plasticity index were calculated according to ASTM D 4318-00 (ASTM, 2000). The particle distribution test was determined using the hydrometer which was done in accordance with BS 1377 (BSI, 1990). Natural moisture content test was done in accordance with BS 1377 (BSI, 1990), to determine the water content of the soil. Coefficient of permeability test was done in accordance with BS 1377(BSI, 1990), to estimate water inflow and seepage through the soil. Bulk density test was done in accordance with BS 718 (BSI, 1991), to determine the weight per unit volume of loose dry material carried out. Organic content test and cation exchange capacity test followed the procedure specified by Nelson and Summers (1982).and Hendershot and Duquette (1986), respectively.

The laboratory tests carried out on the soil samples include; particle size analysis, standard compaction and shear strength test. These tests were carried out in accordance with the British Standard (BS 1377, 1975) laboratory test procedures.

3.3 Statistically

Total Dissolved Solute

Total dissolved solute (TDS) is a property used to govern the susceptibility of clayey soils to dispersion. Where TDS is given as

$$TDS = Na^{+} + K^{+} + Ca^{2+} + Mg^{2+} \quad (1)$$

Exchangeable Sodium Percentage

The presence of exchangeable sodium percentage (ESP) is the main chemical factor contributing towards dispersive clay behavior. This is expressed in terms of exchangeable sodium percentage, measure in mg/100g and is given by

$$ESP = \frac{Na^+}{TDS} \times 100 \quad (2)$$

Sodium Adsorption Ratio

The sodium adsorption ratio (SAR) is used to quantify the role of sodium where free salts are present in the pore water and is defined as

$$SAR = \frac{Na}{\frac{(Ca^{2+} + Mg^{2+})}{2}} \quad (3)$$

It is expressed as milli-equivalent per litre.

4. Results

4.1. Atterberg limit

Table 2 shows the underlying soil recorded values of liquid limit (LL), which ranged from 15 to 31.50 % with mean value of 23%, plastic limit (PL) ranged from 11.18 to 17.73 % with mean value of 14% while the plasticity index (PI) ranged from 2.92 to 14.42 % with a mean value of 8%. Clayton and Juckes (1978) pointed out that PI<35 should be considered low plasticity due to low content of fine materials, which indicates that such soil may change from one state of consistency to another with less change in water content (Akpokodje, 2001).

Give the above, the underlying soil strata of Nguzu Edda could be classified as low plasticity soil, thus, highly susceptible to erosion. This is because the soil is friable and therefore results to ease of water flow, moving the soil particles down slope with increase in velocity of motion of the water (Okengwo et al., 2015). The relative consistency shows that the soil cannot be remoulded, indicating low plasticity, consequently due to low amount of fines, which would have cemented the sand particles; and thereby suggests high susceptibility of the soils to erosion. Furthermore, the calculated value of the Skempton activity of the soil implies that the area is dominated by more of inactive to normal soil (Skempton, 1953).

Table.2: Summary of Geotechnical properties of soil samples in the study area

Sample ID	Plastic limit	Liquid limit	Plasticity index	Skempton Activity	Relative consistency
SML-1	15.54	18.46	2.92	0.14	0.43
SML-2	12.47	17.79	5.32	0.27	0.00
SML-3	16.74	27.40	10.66	0.59	0.03
SML- 4	13.58	28.00	14.42	1.97	0.00
SML- 5	17.73	20.82	3.09	0.44	0.00
SML- 6	11.73	15.00	3.27	0.36	0.00
SML- 7	12.20	21.10	8.90	0.99	0.00
SML- 8	14.33	22.25	7.92	0.88	0.06
SML-9	15.98	29.47	13.49	0.79	0.41
SML-10	17.42	27.00	9.08	1.01	0.00
SML-11	11.18	31.50	20.32	101.6	0.15\
SML-12	12.90	21.00	8.05	0.45	0.00
Min	11.18	15.00	2.92	0.14	0.03
Max	17.73	31.50	14.42	101.6	0.41
Mean	14.32	23.32	8.95	9.12	0.09

4.2. Particle size distribution

Table 3 shows the textural characteristics of the soils, among these are the sand fraction, which ranges from 57 to 99.5% with mean of 69.7% and fines (silt; 0.3~ 22% with average value of 14.6% and clay: 0.2 ~ 21% with average value of 13.9%). The particle size distribution result shows that the underlying soil strata in the study area consist of cohesionless sand with low amount of fines. Thus, the soils are generally poorly sorted and also poor drained material (Akpokodje, 2001), suggesting a decrease in cohesion and resistance to soil cracking.

Table 3: Grain size distribution of Nguzu Edda soil

Sample ID	Sand%	Silt%	Clay %	Texture class
SML- 1	57	22	21	SaL
SML- 2	58	22	20	SaL
SML- 3	70	21	9	SaL
SML- 4	56	23	21	SaCL
SML- 5	82	11	7	Lsa
SML- 6	79	12	9	Lsa
SML- 7	80	11	9	Lsa
SML- 8	61	21	18	SaL
SML- 9	60	22	18	SaL
SML- 10	62	21	17	SaL
SML- 11	99.5	0.3	0.2	SaL
SML- 12	72	10	18	SaL
Min	57	0.3	0.2	
Max	99.5	22	21.0	
Mean	69.7	14.6	13.9	

4.3. Physical properties: moisture content, permeability, bulk density, porosity, organic matter and pH

The summary of the physical properties of the underlying soil strata of Nguzu Edda is presented in Table 4. The moisture content, permeability, bulk density, porosity, organic matter and pH have average values of 25.31%, 6.04×10-4 cm/sec, 1.55 kg/m3, 40.40, 1.26% and 5.12 respectively.

In this study, the Coefficient of permeability of the soil could be classified as low to medium according to Carter and Bentley (1991), indicating there are low to medium base flows, consequently could result in the collapse of river bank and advance the growth of gully erosion (Nwajide and Hoque, 1979; Egboka and Nwankwor, 1986; Onwuemesi and Egboka, 1991). It is shown in Fig. 4 that the permeability declines with increase in the fines content. The permeability decreases gradually with increase in fines content, could be explained by the fact that fine grain particles are being suspended in the pores water and they physically block the drainage path as they are moved along the flow path. These permeability properties of the soil samples indicate that the sandy soils with low amount of fines will have high flow rate of pore water and seepage pressure; implies that less water will move underground and more runoff will be generated to induce erosion.

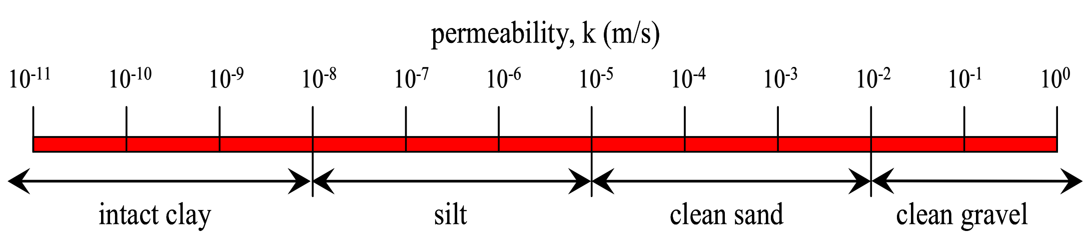

Figure: 4 A modified classification chart showing relationship between permeability and soil grain size (Carter and Bentley, 1991)

The high bulk density of the soil could be attributed to high sand fraction and high rainfall witnesses, therefore causes leaching of organic content which could bind the sand grain. The high bulk density also reduces the rate of infiltration rate, causing water logging and run off and in turn reduces the stability and resistance of the soil to erosion, thus triggering to high intensity of the gullies in the area (Enyankwere et al., 2015). Organic matter affects both the chemical and physical properties of the soil and also increases soil porosity (Lal et al., 1998). Boyle (2002) remarked that the organic carbon content within the erodible fine surface fraction is usually 1 to 2%, these may result to low porosity with greater runoff as applied within the study area. Generally, soils with <2% of organic matter content by weight are highly erodible (Fullen and Catt, 2004), and susceptible to erosion with long lasting secondary consequence (Ezemonye and Emeribe, 2012). Interestingly, the low organic content of the underlying soil in the study is due to high rate of erosion.

Table 4: Physical properties of Nguzu Edda Soil

Sample ID	NMC (%)	Permeability (cm/sec)	Bulkdensity (Kg/m3)	Porosity (%)	Organic Matter (%)	pH (%)
SML- 1	24.44	7.34×10-4	1.54	37.00	1.83	5.50
SML- 2	33.42	6.42×10-4	1.53	40.21	2.08	5.30
SML- 3	27.11	6.44×10-4	1.62	41.50	1.37	5.30
SML- 4	28.95	4.87×10-4	1.59	37.30	1.46	5.80
SML- 5	17.19	4.94×10-4	1.59	44.71	0.38	4.50
SML- 6	20.92	5.55×10-4	1.44	44.50	0.37	4.40
SML- 7	23.18	4.99×10-4	1.61	37.80	0.71	5.80
SML- 8	21.79	6.34×10-4	1.58	43.00	1.18	4.90
SML- 9	23.94	6.25×10-4	1.45	41.61	1.15	4.80
SML- 10	28.02	6.62×10-4	1.52	41.66	1.39	5.40
SML- 11	28.49	6.42×10-4	1.53	39.61	1.84	4.80
SML- 12	26.25	6.28×10-4	1.59	41.50	1.37	4.80
Min	17.19	4.87×10-4	1.40	37.00	0.37	4.40
Max	33.42	7.34×10-4	1.62	44.71	1.84	5.80
Mean	25.31	6.04×10-4	1.55	40.46	1.26	5.12

Natural Moisture content (NMC)

4.4. Cation Exchange Capacity

The results of the cation exchange capacity (CEC) are shown in Table 5. However, the probable sources of the ions include dissolution of calcite as well as mica and organic matters within sandstone, siltstone, limestone and ironstone. The results indicate that the CEC of sodium ranged from 0.83 ~ 1.11 meq/100g with average value of 1.09 meq/100g while the CEC of calcium ranged from 3.42 ~ 4.51 meq/100g with an average value of 3.88 meq/100g. The CEC of the soils tested reflect the type of predominant clay minerals present (Sheard et al., 1976). Monovalent exchangeable cations such as Na^+, cause more swelling with water addition than divalent exchangeable cations such as Ca^{2+} and Mg^{2+} (Bell and Maud, 1994). The low CEC can be attributed to low organic matter, pH and non active clay minerals. Basis on the result, these soils are likely non dispersive.

The calculated value of sodium adsorption ratio (SAR) of the sampled soils ranged from 0.37~ 0.65 meq/liter with average value of 0.57meq/liter. Fetter (1990) considered a SAR value >10 Meq/liter as indicative of dispersive soils, 6 ~10 as intermediate while <6 Meq/litre as non-dispersive. Fig.4 shows that the soil is non dispersive as a result of low sodium adsorption ratio. This implies that the Nguzu Edda soil with an average value of 0.57 meq/liter is non dispersive.

The calculated value of exchangeable sodium percentage (ESP) of Nguzu Edda area ranged from 10.72~12.86 meq/100g with an average value of 12.05 meq/100g (Table 5). Above a threshold value of ESP of 10 meq/100g, soils have their free salt leached by seepage of relatively pure water and are prone to dispersion. Give the above reason, Exchangeable the soils are non dispersive (Sheard et al., 1976).

5. Implication of the study

The geotechnical properties of the soils from the predominantly gully erosion sites make the study area susceptible to gully erosion. The chemical analyses showed that soils of Nguzi Edda are non dispersive as a result of low cation exchange values and hence, less expandable. The erodibility of these soils may then be attributed as a result of the grain size distribution which is predominantly sand; that are cohesionless and poorly sorted. They contain low amount of clay materials (0.2 to 21%) which would serves as a binding material.

The fine particle contents in the soil establish the presence of silts and clay sediments. Sediments with high sand or silt contents with less clay particle erode easily under a flat terrain. Hence, any runoff on the surface would less resistance resulting in the intensity of the gully erosion in the area. These can also be attributed to high annual rainfall amounting to 2000 mm (Hulme & New, 1997). The coefficient of permeability of the soil is low, implying that low infiltration and more runoff inducing gully erosion. Soil pH, organic matter and exchangeable cation were low indicates that the soils are quite below their potential productivity level and hence less dispersive.

Table 5: Chemical properties of Nguzu Edda soil; all in meq/100g

Sample ID	Na^+	K^+	Ca^{2+}	Mg^{2+}	Fe^{2+}	TDS	SAR	ESP
ML- 1	0.85	1.15	3.46	1.15	1.70	6.61	0.56	12.86
SML- 2	0.83	1.48	3.42	1.15	1.69	5.73	0.55	14.49
SML- 3	0.98	2.91	3.97	1.28	1.64	9.14	0.37	10.72
SML- 4	1.11	3.01	4.41	1.47	2.41	10.00	0.65	11.10
SML- 5	1.02	2.03	4.01	1.34	1.87	8.40	0.62	12.14
SML- 6	0.92	1.63	3.97	1.26	1.59	7.78	0.57	11.83
SML- 7	0.91	1.49	3.70	1.25	1.40	7.35	0.58	12.38
SML- 8	1.08	2.23	4.20	1.40	1.10	8.91	0.65	12.12
SML- 9	1.11	2.24	4.51	1.43	1.12	9.29	0.65	11.95
SML- 10	0.86	1.59	3.65	1.17	1.80	7.27	0.55	11.83
SML- 11	0.85	1.55	3.62	1.58	1.27	7.60	0.53	11.18
SML- 12	0.87	1.61	3.60	1.19	1.72	7.27	0.56	11.97
Min	0.83	1.48	3.42	1.15	1.10	5.73	0.37	10.72
Max	1.11	3.01	4.51	1.8	2.40	10.00	0.65	12.86
Mean	1.09	1.92	3.88	1.31	2.61	7.94	0.57	12.05

6. Conclusion and Recommendations

From the above discussions and analysis: the following conclusions can be drawn:

1. The underlying soil strata in the study area consist of cohesionless sand with low amount of fines, which would have cemented the sand particles, thus, in-sufficient binding materials and hereby suggests high susceptibility of the soils to erosion. The soils are generally poorly graded, suggests a decrease in cohesion and resistance to soil cracking.

2. The underlying soils have low value of LL and PI of the underlying soil. These could be attributed to low amount of fines fraction. It indicates that the soil may change from one state of consistency to another with minimum change in water content. Thus, soil unit with the least plasticity index will have the highest instability.

3. Conclusively, the relationship observed among the soils properties and its erodibility could not have occurred by chance. Erodibility of soils is therefore significantly influenced by engineering-geologic properties of the soil. Thus, the erodibility of the soil in the study area is high.

4. Consequently, the following engineering-geologic aspect of soil erosion control should be adopted towards changing the slope characteristics of the gullies in Nguzu Edda area, namely:

i. Techniques such as grouting, construction of concrete structures, installation of check-dams and dewatering should be applied to reduce seepage force and pores water pressures.
ii. Agro-forestry enlightenment and awareness of erosion control should include discouraging villagers from bushing-burning, overgrazing, over-cultivation and deforestation to protect vegetation cover of the soil, in-turn improve the binding characteristics and compensate soil nutrient loss, caused by high intensive raindrops and leaching.
iii. Proper drainage channels and indiscriminate dumping of wasted at gullies sites should be enlightened.
iv. Subsurface horizontal drains, drainage galleries, well point systems or intensive groundwater abstraction through deeper boreholes should be adopted to stabilize the soil by lowering the level of groundwater in the gullies sites.
v. Continuous geotechnical evaluation should be carried on the soil to assess changes in the soil and the environment.

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