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Evaluation of Geotechnical Properties on the Development of Gully Erosion

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Abstract

This studyexamined the effects of Geotechnical properties on the development of gully erosion in Auchi Metropolis of Edo State, Nigeria.Soil samples were collected from the gully site of the study area using disturbed sampling method and were taken to Geotechnical Laboratory of Civil Engineering Department,University of Beninfor various tests.The tests,which includedspecific gravity, particle size distribution, Atterberg limit, compaction and permeability,were carried out in accordance with the British Standard (BS) Method of testing Soil for Civil Engineering Purposes, BS 1377.The results of the specific gravity of the soils at the gully erosion siterange from 2.56 to 2.72, while that of percentage sieve sizes of 0.075mm and 1.18mm range from 5.18% to 26.58% and 95% to 99.84% respectively. The coefficient of Uniformity (C_u) and Coefficient of Curvature (C_c) were 2.83 and 0.039 respectively. The Optimum Moisture Content(OMC) ranges from 9.60% to 14% while the values of Maximum Dry Density (MDD) were between1.58% to 1.99%. These results indicate the abundance of coarse particles in the study area. The soils are predominantly sandy with a mixture of coarse to fine grains, non-plastic, poorly graded, high porosity, very susceptible to soil erosion, highly erodible by water erosion. These results are in conformity with the results of other researchers on related subject matters.

Keywords: Gully erosion,Soilerodibility, Surface runoff, Consistency test, Compaction.

1.0 Introduction

One of the major causes of land degradation in most urban areas in Edo state of Nigeria is Gully erosion[1].Soil erosion, the detachment and transportation of soil by natural agents such as gravity, ice mass, running water and wind, is classified as sheet, rill and gully erosion.Gully erosion has attracted a growing interest because of its devastating effect on man and properties worldwide[2].Gullies have three –dimensional nature affected by a variety of processes such as surface hydrology, soil, topography and land use. These processes are usually the main sources of sedimentation [3].

Several soil erosion studies have suggested that a number of factors contribute to gully erosion, including rainfall energy, the resistance to erosion offered by the ground surface and the way in which ground cover and terrain characteristics affect runoff and soil erodibility [4]. Many national and international research projects have focused on the impacts of climatic and land use changes on rates of soil erosion by water [5,6]. However, over the last decades, most research dealing with soil erosion by water has mainly focused on sheet and rill erosion processes [5].Researchers in Nigeria have also shown that gully erosion represent one of the most soil degradation process in Nigeria as it causes considerable soil loss and produces large volume of sediment [1].Gullying, which is rapidly developing in many areas in Nigeria due to urbanization and civilization, has been identified mostly in terrain covered by friable and highly erodible soil deposits [7].

The contents of soils have significant effect on soil erodibility. The properties of soils play important roles on soil erosion.The textural properties of soils, sediments and sedimentary rocks are among the defining elements of a sensitive ecosystem, which undergoes rapid degradation, in response to surface runoff and human disruption.The destruction caused by gully erosion is influenced by the geotechnical properties of the soil. There is need for appropriate site investigation for a good understanding of the soil properties and its strength stability which differs from one location to another[8]. Areas with high-intensity precipitation, more frequent rainfall, more wind, or more storms are expected to have more erosion. Sediments with high sand or silt contents and areas with steep slopes erode more easily, as do areas with highly fractured or weathered rock. Porosity and permeability of the sediment rock affect the speed with which the water can percolate into the ground. If the water moves underground, less run-offs is generated, reducing the amount of surface erosion. Sediment containing more

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clay tends to erode less than those with sand or silt [9,10].

The aim of this study is to assess the effect of Geotechnical engineering properties on the development of gully erosion in the study area. The objectives of the study include the acquisition of soil samples of the gully erosion site, analysis of the soil samples in the laboratory and evaluation of the geotechnical engineering properties which contribute to the development of gully erosion in the study area.

2.0 Theoretical Analysis

2.1 Gully Erosion in Nigeria

Gullying is one of the most important erosion processes which largely contribute to the sculpturing of the earth's surface. The development of gullies has many negative impacts as it normally involves the loss of lives and (in some cases) the deposition of a great amount of soil [11]. Gully erosion is responsible for the widespread destruction of transportation and communication systems, degradation of arable land, contamination of water supply, isolation of settlements and migration of communities.It has also led to famine as a result of unavailability of farming land or infertility of farming land due to the washing away of the nutritious top soil[8].

The three major environmental problems facing Nigeria especially in the eastern part of the country are soil degradation and loss, coastal erosion and gully erosion. Gully erosion has been long neglected because it is difficult to study and to predict[12]. Gully processes have a three-dimensional nature affected by a wide array of factors and processes. Although gully erosion is commonly triggered or accelerated by land use change and extreme climatic event, it often results also from a long antecedent history that cannot be overlooked when attempting to understand spatial erosion patterns[13]. In different parts of Nigeria, gully erosion has attained a larger and a devastating dimension which has attracted the World-Bank attention. Moreover, many gullies grow rapidly to large dimensions making effective control difficult or prohibitively expensive[7, 14].

2.2 Soil and its Effects on Gully Erosion Site

The geotechnical properties of soil, generally, is of utmost concern to engineers that are engaged in the design and construction of engineering structures such as highway pavement, foundations, buildings, embankments, bridge abutment, earth dams, etc[15].Several Researchers have reported that the type of soil has a significant effect on the erodibility of a particular site or location[9, 16].Simple geotechnical tests such as degradation analysis and soil dispersion rate provide an indication of the susceptibility of the earth materials to gully erosion as well as the direction of the gully enlargement[8].

Texture of a soil is the visual appearance of a soil based on the qualitative composition of grain sizes in a given soil mass. Grain size of a soil refers to the diameter of the soil particles making up the soil. Soil texture, especially of coarse-grained soils, has some relation to their engineering behaviour. For fine-grained soils, the presence of water generally affects their Engineering responses, much more than grain size or texture alone. Water affects the interaction between the mineral grains, which may affect the plasticity and their cohesiveness [16, 17].

The two types of vital information that are obtained from particle size distribution curve are the range of grain sizes in the soil and the gradation of the soil, i.e. the manner in which the size variationsoccur in the soil. The grain size distribution curve of a well-graded or non- uniform soil covers smoothly a wide range of the sizes, while that of a poorly graded or uniform soil contains only a few grain sizes. A skip or gap graded soil is that soil whose curve is completely lacking grains in intermediate sizes. The two numerical indices for the identification of the gradation of a soilare the coefficient of uniformity (C_u)and the coefficient of curvature ($C_{c)}$ [18]. These are mathematically expressed as:

$$C_U = \frac{D_{60}}{D_{10}} \quad (1)$$

where;

D_{60} - the soil diameter on particle size at which 60% weight of the soil weight is finer than,

D_{10} - the soil diameter on particle size at which 10% weight of the soil weight is finer than, sometimes termed "effective size".

$$C_c = \frac{D^2{}_{30}}{D_{60}D_{10}} \quad (2)$$

where;

D_{30} - the particle size at which 30% weight of the soil weight is finer

A soil is well graded if the C_c is close to unity (1.0). If the $C_c$is much less or much greater than unity, the soil is poorly graded. $C_c$must be between 1 and 3 in order to avoid gap grading [18].

2.3 Runoff and Soil Erodibility

Rainfall is the primary source of runoff. Run-off may be influenced by a number of factors including climatic and physiographic factors.The climatic factors include type of precipitation, rainfall intensity, duration and distribution and other climatic factors which include temperature, wind velocity, relative humidity, annual rainfall, etc.Physiographic factors include size, shape, slope and orientation of watershed, land use, soil moisture content and soil type, topographic characteristics and drainage density [19].

2.3.1 Surface Runoff

Runoff is the portion of rainfall or any other flow which makes its way toward river, stream or ocean.When the velocity of surface runoff exceeds the critical limit at which external forces of flow in terms of energy are greater than the internal forces expressed by the soil cohesion, the washing of soil particle by flow commences. The critical velocity of surface flow is defined as the highest water velocity at which washing of soil particles does not yet take place [20]. The equation for describing the intensity of gullyingis given in[21] as:

$$\mathbf{Ig} = \mathbf{0.2 \times 10^{-4} d.A}\sqrt{\frac{V_{O-1}}{V_e}} \quad (3)$$

where;
Ig = Intensity of gullying
d = Mean diameter of soil particles
A = Area of transverse section of water flow
V_o = Initial water velocity
V_e = Extreme velocity of water flow
The water velocity at the top of gully depends on the catchment area above this point and the length of gullying.
TheLength of gully = (L- X) (4)
where;
L – distance of the gully bottom
X- Point of beginning of the gully
The shorter the value of X, the smaller will be the area and growth intensity of the gully.
The depth of gully in time (t) can be predicted from the following equation:

$$\boldsymbol{h_t = h}\left(\frac{t}{T}\right) \quad (5)$$

where;
$h_t$is the depth of gully in time t
h is the expected depth of gully stabilization.
t is the time (period) of gullying
T is period of gully stabilization
T can be determined by using the equation:

$$T = \frac{10^4 h}{0.2d}\sqrt{\frac{V_O-1}{V_k}} \quad (6)$$

where;
The value of V_k is determined as thecritical water velocity for eroding the upper layer of soil.
The most commonly used equation for V_k is that given in[22]as:

$$V_k = 3.13\sqrt{\mathbf{14d + 0.006}} \quad (7)$$

The critical water velocity is associated with the resistance of earth and rocks to gullying.
Gully density is usually not greater than 10km^2 watershed area and the surface area covered by gullies does not exceed 15% of the total surface area of the watershed. When these values are exceeded, then linear erosion changes into polymorphous erosion, in which the land surface is substantially more divided and dissected; in such cases, intra-soil erosion and land landslides occur simultaneously[20].

2.4 Soil Erodibility

Erodibilityis the vulnerability of soil to erosion. It is a function of physical characteristics of soil and land management practices. The physical characteristics of soils include soil texture, structures, organic content, land use pattern, etc [7].With regards to the role of soil texture on erodibility, it is observed that larger particles are resistant to transport because greater force is required in transporting them. On the other hand, finer particles are resistant to detachment, because of their cohesiveness.
The least resistant soil particles are silts and fine sand. Soils composed of high silt content are easily erodible. Soil erodibility decreases linearly with increase in organic content, ranging from 0–10% [23]. The physical properties of soils play an important role on soil erosion. The effects of physical properties of the soils should therefore be precisely evaluated to determine their erodibility. Soil erodibility depends on mechanical composition of soils such as sand, silt, and clay[20, 24]. Erodibility (E) is expressed in [20, 24] as:

$$E = \frac{\%sand + \%silt}{\% clay} \quad (8)$$

The equation for the relationship between soil erodibility, non – erodible particles content, moisture content of soils and wind velocity of the soil surface is;

$$E = 22.02 - 0.72p - 1.69V + 2.64R \quad (9)$$

where;
E - Soil Erodibility
P - Non-erodible particles Content
V - Relative Moisture Content

$$\boldsymbol{V = V_m - V_n} \quad (10)$$

where,
V_m = Instantaneous Moisture Content
V_n = Bound Moisture Content

The index of soil erodibility for water erosion called surface aggregation ratio is developed in [25]as:

$$\mathbf{E_I} = \frac{\text{surfaceareaofparticles}>0.5\text{mmdiameter}}{\%\ \text{silt}+\%\text{clayindispersedsoil}-\%\ \text{silt4}\%\text{clayinundisturbedsoils}} \quad (11)$$

where;
E_I –Index of soil erodibility

3.0 Research Methodology

3.1 The Study Area and the Gully Erosion Site

The study area (Auchi) is located in Etsako West local government area of Edo State, Nigeria. It lies between latitude $7^0 04'$ 09'' – $7^0 04'$ 14''N and longitude 6^0 15' 26''- 6^0 15'31''E in Edo State. The terrain of the gully erosion site is relatively sloppy.It slopes from both the Warake road axis and the Hospital road axis of Auchi town. The satellite imagery showing Auchi gully erosion site is presented in Fig.1. The photographic images showing Auchi Gully erosion site of the study area is presented in Fig. 2.

Fig.1: Satellite Imagery showing Auchi Gully Erosion Site (Source: Google Map)

Fig. 2: Photographic images of Auchi Gully Erosion site

3.2 Materials and Methods

The soil samples were collected from the gully banks, the gully bed and around the gully in the study area using disturbed sampling method and carefully stored in cellophane bags.The soil samples were taken from boreholes in twenty four (24) different locations around the gully site. The soil samples were transported to Geotechnical Engineering Laboratory of Civil Engineering Department, University of Benin, Benin City for several tests.

The soil samples were spread to air dry for five days and the laboratory tests performed on them. The laboratory tests, which includedspecific gravity, particle size distribution, Atterberg limit, compaction, permeability, California Bearing Ratio (CBR), and Shear box test for bearing capacity of the soils, were carried in accordance with the specification of the British Standard (BS) method of testing for Soil for Civil Engineering Purposes, BS 1377 [26].

The particle size Analysis and hydrometer (Sedimentation) tests were carried out in order to determine the percentage quantity of individual grain sizes as they occur in a particular soil layer in the study area.The British Standard Sieves (BS - Sieves) were used on the mechanical sieve shaker to separate the grains into their various sizes. These were then weighed and their percentage weights calculated.The hydrometer, which measures the specific gravity of the soils suspensions at the centre of its bulbs, was used to determine the particle size distribution of the soils.The Consistency(Atteberg)limits test carried out in this study included: Liquid limit (LL), Plastic Limit (PL), Plastic Index (PI).The Compaction test, which was performed to ascertain the optimum moisture content of the soil samples and their maximum dry densities, were carried out in accordance with the laid out procedures in BS 1377[26]. The Permeability test, whichwas conducted by constant head permeameter to determine the rate of flow through attached cross-sectional area under a unit hydraulic gradient, was also carried out in accordance with laid out procedures in BS 1377 [26]. The Coefficient of Uniformity (C_u) and Coefficient of Curvature (C_c)for the study areawere computed using equations (1) and (2) respectively.

4.0 Results and Discussion

The summary of the analyses of some of the Geotechnical Properties of the soils at the Gully erosion site of the study area is presented in Table 1. The Atterberg limits for Borehole 2 (BH_2)and Borehole 4 (BH_4)are shown in Figs.3and 4 respectively.

Table 1: Summary of the Analyses of some Geotechnical Engineering Properties of the Soils at Auchi Gully Erosion Site

Description of Properties	Minimum	Maximum	Mean
Sieve analysis			
% passing sieve 1.18	95.56	99.84	97.70
%passing sieve 0.075	5.18	26.57	15.87
Specific Gravity	2.56	2.72	2.64
Atterberg Limit:			
Liquid Limit (%)	18.56	23.52	21.04
Compaction			
MDD (g/cm^3)	1.58	1.99	1.78
OMC (%)	9.60	14.0	11.80
Permeability			
K (m/sec)	1.59×10^{-6}	2.19×10^{-6}	1.89×10^{-6}

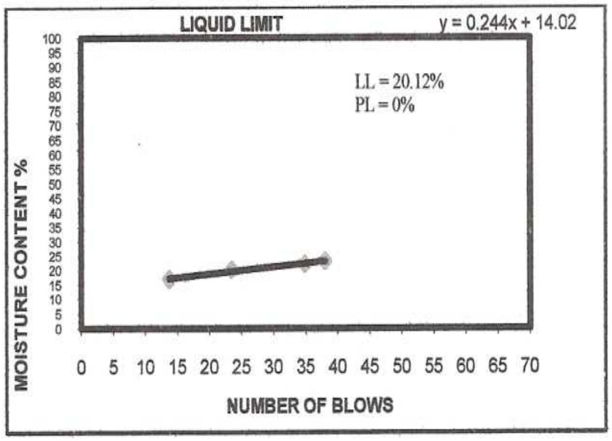

Fig. 3: Atterberg limit for Borehole 2 (BH_2)

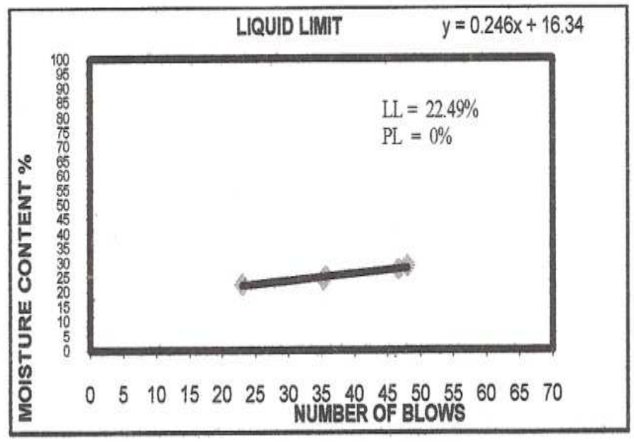

Fig. 4: Atterberg limit for Borehole 4 (BH_4)

a) The specific gravity and the sieve analysis of the soil

The results of the **specific gravity** of the soils in the different boreholes at the gully erosion site, which are shown in Table 1, range from 2.56 to 2.72 and with a mean of 2.56. This indicates the abundance of coarse particles in the study area. The results for percentage sieve sizes of 0.075mm and 1.18mm, presented in Table 1, range from 5.18% to 26.58% and 95% to 99.84% respectively. Based on the Unified Soil Classification System (USCS) [27], the soil is classified as coarse –grained material. The results of the **sieve analysis** have shown that the soil is predominantly sandy with a mixture of coarse to fine grains. This indicates that the soils in the study area are not well graded and are very susceptible to soil erosion. There is a strong correlation between gully growth rate and dispersion. Once the gully has been formed, its growth is controlled by the grain size.

From the soil tests results, the coefficient of Uniformity (C_u) and Coefficient of Curvature (C_c), the two numerical indices that aid in better understanding of the gradation of the soil for the study area, were 2.83 and 0.039 respectively. For a well graded soil, Cu should exceed 6 while Cc is between 1 and 3 [18, 28]. The Coefficient of Curvature is less than 1.0, and the coefficient of uniformity is less than 6. The obtained results of Cu and Cc for the study area indicate that the soils within the gully erosion area are poorly graded.

b) Compaction: The Optimum Moisture Content(OMC) of the study area ranges from 9.60% to 14%, and these results gave a further indication that the soils are sandy with traces of silt. Such soils are therefore highly erodible by water erosion. The values of Maximum Dry Density (MDD) were between 1.58% to 1.99%, and an average of 1.78%. This indicates very loose sand. Sandy soils are less pervious, less stable and mostly affected by water. Dry sand does not exhibit cohesion (does not hold together). The results have shown that the soils in the study area are characterized by high sand content and low fines; low to moderate dry density; high porosity and erodibility. These results are in conformity with the results of some researchers on related subject matter that sediment containing sand or silt tends to erode more than those with clay [9, 10,16]. Steep slopes with high sandy or silty soils are more susceptible to high erodility[9].

c) Atterberg limit test: The Consistency limit test, a measure of the index properties of the soil and its resistance to flow at the gully site, shows that the Liquid Limit (LL) and the Plastic index (PI) for Borehole 2 and Borehole 4 are 20.12% and 22.49% respectively(Table 1, Fig.3 and Fig.4). The results of the Atterberg limit test have shown that the soils at the gully erosion siteare non plastic or have low plasticity.

d) Permeability test: The results of the Permeability test for the soils in the study area(shown in Table 1), range from 1.59×10^{-6} m/sec to 2.19×10^{-6} m/sec and the mean is 1.89×10^{-6} m/sec.The sandy soil in the study area will experience a decrease in permeability [a soil property that indicates the ease with which water will flow through the soils [29], and affects the speed with which the water can percolate into the ground] as it become finer and more uniform. Besides, its stability will reduce in the presence of water. These results also confirm the report of other researchers[9, 10, 16].

5.0 Conclusion

In this study,the effects of soil and its geotechnical properties on the development of gully erosionin a gully site have been evaluated. It has shown the significance of appropriate investigation of the gully erosion site for a better understanding of the soil properties and its strength stability which varies from one location to another. As regards the study area (Auchi), whose terrain is relatively sloppy, the results of the tests show that the soils in the study area (Auchi) are cohesionless, not compacted, and non-plastic, hence the menace of gully erosion is influenced by geo-pedologic and hydrologic factors. Furthermore, the soils are characterized by high sand content and low fines; low to moderate dry density and high porosity and erodibility.Consequently, the rate of development(enlargement of width and depth,etc) of the gully erosion in the study area is rapid thereby claiming more lands, infrastructure inter alia.

6.0 References

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