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Reliability Analysis of Gully Wall Slope Stability and Gully Bed Erosion of Ekhaguere Gully in Benin City, Nigeria

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Abstract

Reliability analysis presents a logical way to quantitatively estimate the factor of safety (FoS) of geotechnical structures from a probabilistic viewpoint. However, due to the extensive computational requirements and poor efficiency of reliability analysis, its application in estimating the FoS of gully wall slopes is often hindered. In this study, slope stability reliability analysis was carried out for the Ekhaguere gully in Benin City, Edo State. In doing so, ten thousand (10,000) random numbers were generated for the different soil properties based on the probability distribution parameters to obtain 10,000 random samples of slope stability results of FoS for the gully walls (left and right walls of the gully). Knowing the mean value and the coefficient of variation, it was possible to define their standard deviations and shapes of the probability density functions. The probability density functions (pdf) of three different probability distributions (Normal, Lognormal and Weibull distributions) were fitted to the histogram of the FoS values of the gully wall. The pdf describes the relative likelihood that the variables will have a certain value within the range of potential values. The results of the reliability analysis showed that the gully wall slope stability reliability index value of 0.84 is less than the target reliability index value of 3.8 recommended in BS EN 1990, suggesting that the gully slope is unsafe. Reliability analysis for the gully bed erosion showed that the probability of getting moderate to severe annual rate of soil loss is very low and that the likely soil erosion rate will be in the region of very low to the lower bound of moderate soil loss (0 – 7 tonnes/hectare/year). The results suggest that the predicted erosion rates for the gully are unsatisfactory.

1. Introduction

Soil erosion occurs naturally under all climatic conditions in all the continents, but it is significantly increased and accelerated by unsustainable human activities (up to 1000 times) through intensive agriculture, deforestation, overgrazing and improper land use changes. Soil erosion rates are much higher than soil formation rates. Soil is a finite resource, meaning its loss and degradation is not recoverable within a human lifespan. Soil erosion can be a serious problem, resulting in catastrophic damage to water sources, landscaping, and wildlife. Repairing damage caused by soil erosion can be difficult, time consuming, and expensive [1-3].

Gully erosion, which is a form of soil erosion, occurs as linear features cut by channelized runoff and as large, complex mass-movement–fluvial-erosion features that are typically amphitheater-shaped [4,5]. It is most common in the soft rock hill Island. An additional form is tunnel gully erosion, where water moves down through the soil until it reaches a less permeable layer where it concentrates to form an underground channel [6,7]. As this widens, the roof can collapse forming a surface gully [8]. Gullies are relatively steep-sided watercourses which experience ephemeral flows during heavy or extended rainfall. Consequently, gully erosion is a serious form of soil degradation often involving an initial incision into the subsurface, by concentrated runoff along lines or zones of weakness such as tension and desiccation fractures [9,10].

One of the major issues associated with gullies is the stability of the gully walls, which is measured in terms of the factor of safety (FoS) of the gully wall slope or the index of stability. In the broadest terms, FoS may be defined as the ratio of the potential resisting forces to the forces tending to cause movement. In stability analysis, FoS is defined more specifically as the ratio of the moment of the available shearing forces on the trial failure surface to the net moment of the driving forces [11-13]. In recent times, critical slope stability analysis has proven to be a reliable technique which could be used in gully erosion risk assessments, and many studies are beginning to look into this, e.g. Nebeokike [14] and Egbueri [15].

Reliability analysis approach presents a logical way to quantitatively estimate the factor of safety of geotechnical structures from a probabilistic viewpoint. However, it suffers from a known criticism of extensive computational requirements and poor efficiency, which hinders its use in the reliability analysis of slope stability of geotechnical structures like earth dam walls, embankment walls and gully walls [16]. Despite this, it is still widely used in the evaluation of factor of safety of slopes, especially when combined with other numerical and geostatistical tools that can improve its efficiency. For example, Wang [16] developed an efficient extreme gradient boosting (XGBoost)-based reliability analysis approach that was used in evaluating the probability of failure of an earth dam slope. Response surface methodology was also used in combination with first order reliability method (FORM) and numerical analysis to estimate the factor of safety of an earth dam wall [17,18]. Liu [19] were able to efficiently perform the reliability analysis of soil slopes using multivariate adaptive regression splines-based Monte Carlo simulation (MCS). Wang [20] developed MCS-based reliability analysis approach for slope stability problems and utilized an advanced MCS method called "subset simulation" for improving efficiency and resolution of the MCS at relatively small probability levels.

MCS is one of the most popular methods in probabilistic analysis. It relies on repeated random sampling to address risk and uncertainty in quantitative analysis and decision making. MCS method calculates the probability of failure of a slope based on the assumption of the probability density function of input random variables [21,22]. In a Monte-Carlo simulation, random variables values are sampled randomly from the input probability distributions, and the resulting outcome from that sample is recorded. The probability distribution of the possible outcomes it provides thus gives a much more comprehensive view of what may happen. Due to its robustness and conceptual simplicity, MCS has been widely used in reliability analysis and design of geotechnical problems [19,20,23].

Reliability analysis studies usually require large amount of data from laboratory geotechnical experiments. These experiments usually take time and most times may not be feasible to be carried out. Also, the properties of the soil are usually not constant but vary from one point to another even within the same location, and can therefore affect the outcome of the reliability analysis [18,24,25]. Hence, it becomes imperative to be able to integrate experimental data with stability models in carrying out stability analysis for gully wall slopes. In this study, ten thousand (10,000) random numbers were generated for the different soil properties based on the probability distribution parameters to obtain 10,000 random samples of slope stability results of FoS for the gully walls. Thereafter, reliability analysis was carried out on the generated FoS values.

2. Materials & Methods

2.1 Study Area

The Ekhaguere gully is located within the confines of Benin City at Latitude 6.364314° and Longitude 5.651673°. It lies in between Temboga Road and Lucky Igbenedion Road in Benin City, Edo State. The geology is generally marked by top reddish earth, composed of ferruginized or literalized clay sand. Figure 1 shows the satellite imagery of the Ekhaguere gully.

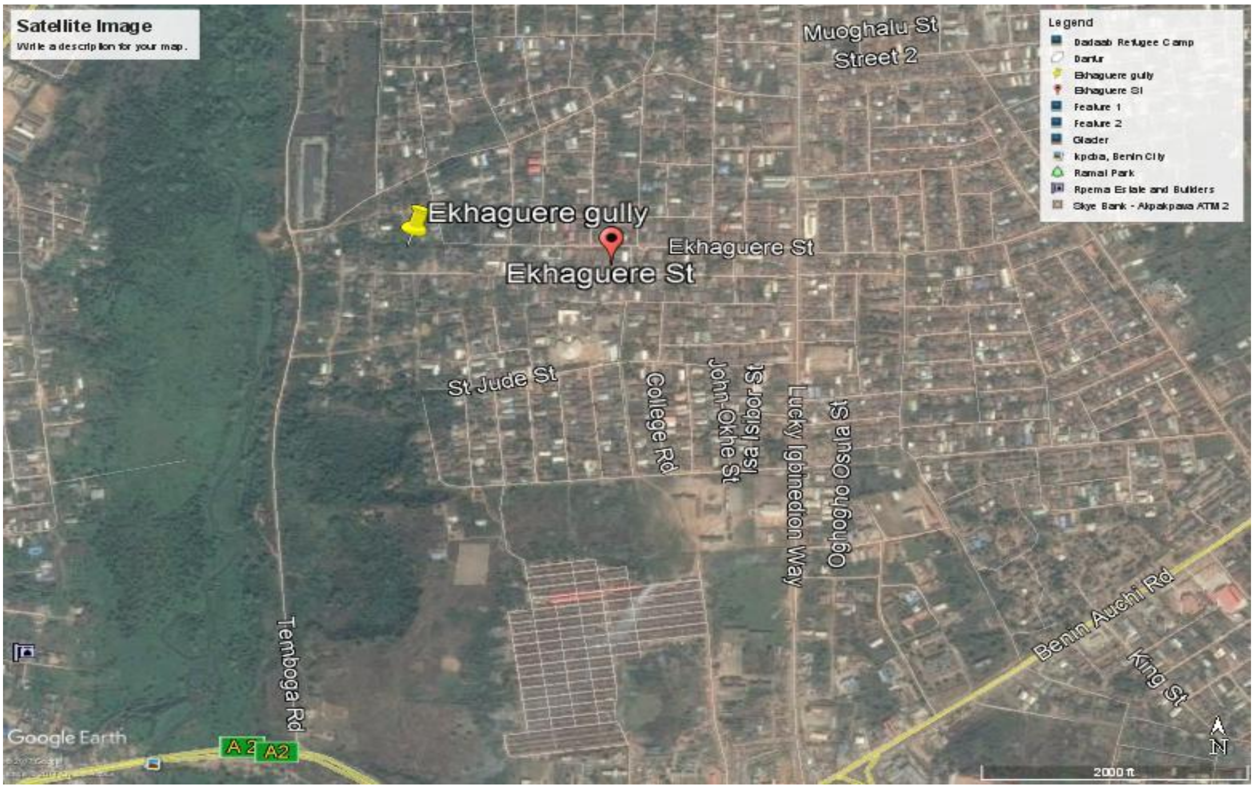

Figure 1: Satellite imagery of Ekhaguere gully

2.2 Reliability Analysis of Gully Wall Slope Stability

The procedure followed for the reliability analysis is listed as follows:

i. Specification of gully slope geometry

ii. Specification of probability distribution of relevant soil properties

iii. Determination of critical slip surface and its associated factor of safety using limit equilibrium methods

iv. Generation of *N* number of variables for each of the relevant soil properties using Monte Carlo simulation

v. Calculation of the FoS for each set of generated random variable of the soil properties

vi. Determination of the mean, standard deviation and probability distribution of the FoS

vii. Calculation of probability of failure and associated reliability index. Failure will be defined by the number of times a FoS of less than or equal to 1 is obtained.

2.3 Reliability Analysis of Rate of Soil Erosion of the Gully Bed

Monte Carlo Simulation (MCS) was used for the reliability analysis. A range of possible outcomes is provided and consequently the probabilities that they will occur for any choice of action is estimated. Models of possible results are built into the MCS by substituting a range of values (a probability distribution) for any variable with inherent uncertainty. The result is then calculated several times, each time using a different set of random values from the probability functions. Depending on the extent of uncertainty and the ranges specified for the variables, a significant number of simulation runs would be needed to produce distributions of possible outcome values.

Different permissible values of soil erosion rate ($SE_{permissible}$) ranging from 0.5 $t.ha^{-1}.yr^{-1}$ to 50 $t.ha^{-1}.yr^{-1}$ were used and the associated probability of exceedance was determined. The rate of soil erosion was evaluated using the formula below [26]:

$$A = R \times K \times LS \times C \times P \tag{1}$$

where:

A	Average annual rate of soil loss in t ha^{-1} $year^{-1}$
R	Rainfall erosivity factor in MJ mm ha^{-1} h^{-1} $year^{-1}$
K	Soil erodibility factor in t h MJ^{-1} mm^{-1}
LS	Slope length-gradient factor
C	Cover management factor
P	Conservation practice factor

The R-factor was calculated using Equation 2, using monthly and annual rainfall data in the absence of hourly rainfall intensity data.

$$R = \sum_{i=1}^{12} 1.735 \times 10^{\left(1.5 \log_{10}\left(\frac{P_i^2}{P}\right) - 0.08188\right)} \tag{2}$$

Where:

R	Rainfall erosivity factor in MJ mm ha^{-1} h^{-1} $year^{-1}$
P_i	Monthly rainfall (mm)

P Annual rainfall (mm)

The process employed in the reliability analysis is summarized in the following steps:

i. Specification of probability distribution of relevant soil properties
ii. Generation of *N* number of variables for each of the relevant soil properties using Monte Carlo simulation
iii. Calculation of soil erosion rate (SE) for each set of generated random variable of the soil properties
iv. Determination of the mean, standard deviation and probability distribution of the SE
v. Calculation of probability of obtaining a value of SE greater than $SE_{permissible}$
vi. Sensitivity analysis to determine the effect of different properties on the probability of exceedance of permissible soil erosion rate values.

3.0 Results and Discussions

3.1 Results of Reliability Analysis for Gully Slope Stability

For the slope stability reliability analysis, ten thousand (10,000) random numbers were generated for the different soil properties based on the probability distribution parameters shown in Table 1 to obtain 10,000 random samples of slope stability results of FoS for the gull wall (left and right walls of the gully). Knowing the mean value and the coefficient of variation of 10,000 generated FoS values, it is possible to define their standard deviations and shapes of the probability density functions. The probability density functions (pdf) of three different probability distributions (Normal, Lognormal and Weibull distributions) were fitted to the histogram of the FoS values of the gully walls as seen in Figures 2 and 3. The pdf describes the relative likelihood that the variables will have a certain value within the range of potential values.

Table 1: Probability distribution parameters of soil properties needed for reliability analysis of slope stability

Wall side	Property	Best fit probability distribution	Distribution Parameters
Left-hand-side (LHS)	AMC	Weibull	$\alpha = 2.8558$, $b = 12.767$
	AGs	Weibull	$\alpha = 40.071$, $b = 2.5937$
	Internal Friction	Lognormal	$\sigma = 0.4626$, $\mu = 2.5871$
	Co	Weibull	$\alpha = 1.5595$, $b = 15.817$
Right-hand-side (RHS)	AMC	Normal	$\sigma = 4.2401$, $\mu = 11.744$
	Ags	Weibull	$\alpha = 45.901$, $b = 2.5810$
	Internal Friction	Normal	$\sigma = 0.35613$, $\mu = 2.5022$
	Co	Lognormal	$\sigma = 0.69337$, $\mu = 2.4722$

***Note**: For Weibull distribution α is the scale parameter and b is the shape parameter; for Lognormal distribution σ is the standard deviation of logarithmic values and μ is the mean of logarithmic values; and for Normal distribution σ is the standard deviation of actual values and μ is the mean of actual values*

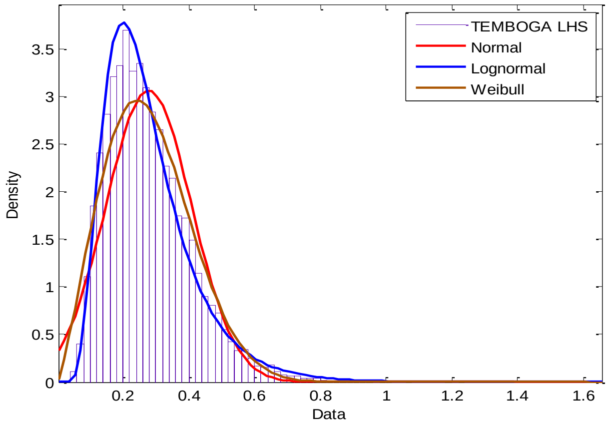

Figure 2: Probability Density Frequency of FoS of the gully wall LHS slope stability

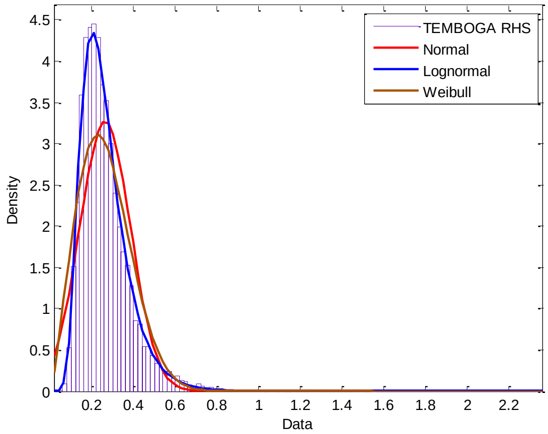

Figure 3: Probability Density Frequency of FoS of the gully wall RHS slope stability

The K-S goodness of fit test was applied to test for the probability distributions that best fits the generated FoS values. Results of the test as presented in Table 2 showed that the FoS of the slope stability for the Ekhaguere gully walls (LHS and RHS), were best fitted by lognormal distribution model. Using the best fit probability distribution, the probability of failure i.e., probability of obtaining a FoS of less than 1 were obtained as, 0.9991 and 0.9990 for the LHS and RHS respectively of Ekhaguere gully walls. These show a very high probability of failure indicating that the walls of the gully are very unstable and likely to fail, as was also observed by Egbueri [15] in their study on gully slope distribution characteristics and stability analysis for soil erosion risk ranking in parts of south-eastern Nigeria. This suggests that the gully in its present state has a high probability to continue to expand and therefore calls for immediate remedial action to be taken. The associated reliability index is approximately 0.84 for both walls of the gully.

Table 2: Reliability analysis results of slope stability analysis

Gully wall Side	**N**	**Probability Distribution**	**K-S Test**		**Decision at 5% significance level**	**Best Fit Distribution**	**Property**	**Pf = P(FoS< 1)**	**Reliability Index (β)**
			Statistics	**Rank**					
LHS	10,000	Normal	0.0679	3	Accept Normal	Lognormal	$\sigma = 0.4740$ $\mu = -1.3853$	0.9991	0.8411
		Lognormal	0.0265	1	Accept Lognormal				
		Weibull	0.0518	2	Accept Weibull				
RHS	10,000	Normal	0.1012	3	Accept Normal	Lognormal	$\sigma = 0.4183$ $\mu = -1.4233$	0.9990	0.8411
		Lognormal	0.0159	1	Accept Lognormal				
		Weibull	0.0817	2	Accept Weibull				
		Weibull	0.0518	2	Accept Weibull				

It should be noted whether a probability of failure (Pf) value is acceptable or not depends on its associated reliability index compared with the target reliability index. A high value of reliability index with reference to the target reliability index of 3.8 given in BS EN 1990 [27] implies an acceptable value of probability of failure while a lower value implies that the probability of failure value is unacceptable and not safe enough. For this study, the reliability index value was 0.84 which is less than the target reliability value of 3.8 suggesting that the probability of failure of slope of the gully wall is unacceptable and therefore unsafe.

3.2 Results of Reliability Analysis for Gully Bed Soil Erodibility

The reliability analysis was performed using the soil data for the gully bed. The Universal Soil Loss Equation (USLE) predicts the long-term average annual rate of erosion on a field slope based on rainfall pattern, soil type, topography, crop system and management practices. USLE only predicts the amount of soil loss that results from sheet or rill erosion on a single slope and does not account for additional soil losses that might occur from gully, wind or tillage erosion. This erosion model was created for use in selected cropping and management systems but is also applicable to non-agricultural conditions such as construction sites.

Five major factors were used to calculate the soil loss for the gully under study. Each factor is the numerical estimate of a specific condition that affects the severity of soil erosion at a location. The erosion values reflected by these factors vary considerably due to varying weather conditions. Therefore, the values obtained from the USLE more accurately represent long-term averages.

The R-factors calculated using Equation 2 is shown in Table 3.

Table 3: Rainfall Erosivity Factor (R) using monthly rainfall data from CBN and daily rainfall data from Nigerian Meteorological Agency, Oshodi, Lagos State NIMET for 30 years (1982 – 2011)

Year	**R-factor**	
	From CBN Rainfall Data	**From NIMET Rainfall Data**
1982	22.03773924	19.7773453
1983	22.3252068	22.4311232
1984	21.37108727	21.3115881
1985	21.06631697	20.8284971
1986	20.63013034	20.175075
1987	23.10650911	22.6932337
1988	20.77249646	20.7455282
1989	22.57785972	22.2826216
1990	21.81448815	21.1939312
1991	21.88133598	21.6869654
1992	23.19093636	23.1866521
1993	20.7752294	20.5384015
1994	21.57578291	21.3703177
1995	20.84755327	20.6685555
1996	21.97140427	20.8812473
1997	19.19432433	18.6324797
1998	21.87284076	21.1832634
1999	21.03782386	20.4252772
2000	20.73268185	20.7515766
2001	21.29435838	21.240807
2002	20.46805437	20.3632955
2003	20.53832961	20.4630563
2004	21.19537809	21.1554493
2005	22.78850597	22.5989945
2006	21.44965971	21.1606629
2007	20.93564754	19.9926305
2008	21.36243645	16.9430029
2009	19.76632934	19.5849092
2010	21.88240586	20.9128756
2011	21.09378255	23.8148824

Histogram of the data in Table 3 was plotted. It was observed that for CBN monthly rainfall data, R-factor for Benin-City follows Normal Distribution with $\mu = 21.385$, $\sigma = 0.9057$ (see Figure 4). Also, R-factor for Benin-City using daily rainfall data obtained from NIMET follows Normal Distribution with $\mu = 20.966$, $\sigma = 1.332$ (see Figure 5).

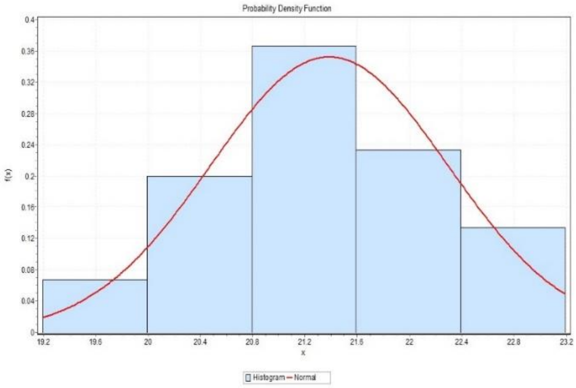

Figure 4: Probability Distribution Function for R-factor using CBN data

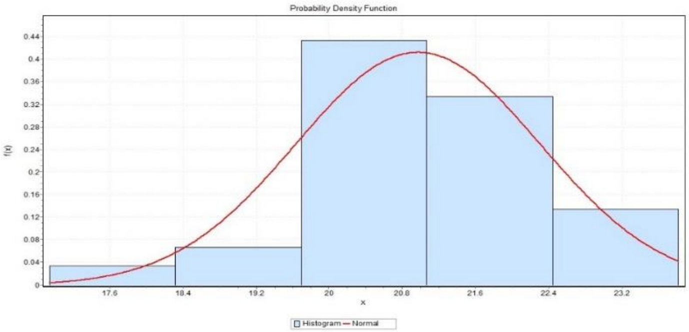

Figure 5: Probability Distribution Function for R-factor using NIMET data

The erodibility factor *K* was estimated using Universal Soil Loss Equation (USLE) as presented in Table 4.

Table 4: K-factor data

Textural Class	K-factor tonnes/hectare (tons/acre)		
	Average OMC*	**Less than 2% OMC**	**More than 2% OMC**
Clay	0.49 (0.22)	0.54 (0.24)	0.47 (0.21)
Clay loam	0.67 (0.30)	0.74 (0.33)	0.63 (0.28)
Coarse sandy loam	0.16 (0.07)	–	0.16 (0.07)
Fine sand	0.18 (0.08)	0.20 (0.09)	0.13 (0.06)
Fine sandy loam	0.40 (0.18)	0.49 (0.22)	0.38 (0.17)
Heavy clay	0.38 (0.17)	0.43 (0.19)	0.34 (0.15)
Loam	0.67 (0.30)	0.76 (0.34)	0.58 (0.26)
Loamy fine sand	0.25 (0.11)	0.34 (0.15)	0.20 (0.09)
Loamy sand	0.09 (0.04)	0.11 (0.05)	0.09 (0.04)
Loamy very fine sand	0.87 (0.39)	0.99 (0.44)	0.56 (0.25)
Sand	0.04 (0.02)	0.07 (0.03)	0.02 (0.01)
Sandy clay loam	0.45 (0.20)	–	0.45 (0.20)
Sandy loam	0.29 (0.13)	0.31 (0.14)	0.27 (0.12)
Silt loam	0.85 (0.38)	0.92 (0.41)	0.83 (0.37)
Silty clay	0.58 (0.26)	0.61 (0.27)	0.58 (0.26)
Silty clay loam	0.72 (0.32)	0.79 (0.35)	0.67 (0.30)
Very fine sand	0.96 (0.43)	1.03 (0.46)	0.83 (0.37)
Very fine sandy loam	0.79 (0.35)	0.92 (0.41)	0.74 (0.33)

Table 5 shows tolerable rates of annual soil loss. The probability of obtaining values of annual rate of soil loss (*A*) greater than these tolerable rates was estimated as the probability of failure (Pf). This was done by determining the number of times out of the 10,000 simulated values of annual rate of soil loss gives value higher than a given tolerable rate. The results are presented in Tables 6 and Table 7. The results are also presented in the form of cumulative probability plots in Figures 6 and 7.

Table 5: Soil loss tolerance rates

Soil Erosion Class	Potential Soil Loss tonnes/hectare/year (tons/acre/year)
Very low (tolerable)	<6.7 (3)
Low	6.7 (3)–11.2 (5)
Moderate	11.2 (5)–22.4 (10)
High	22.4 (10)–33.6 (15)
Severe	>33.6 (15)

Table 6: Probability of rate of annual soil loss exceeding the tolerable or permissible rate for Ekhaguere gully using daily rainfall data from NIMET (1982 – 2011)

$A_{Tolerance}$	$Pf = P(A > A_{Tolerance})$	Reliability Index (β)
0.5	0.99999	-7.94144
5	0.99999	-7.94144
10	0.9998	-3.54008
11	0.989	-2.29037
12	0.8656	-1.10583
13	0.4521	0.120357
14	0.0913	1.332792
15	0.0056	2.536396
16	0.0002	3.540084
17	0.000000000000001	7.941444
18	0.000000000000001	7.941444
19	0.000000000000001	7.941444
20	0.000000000000001	7.941444

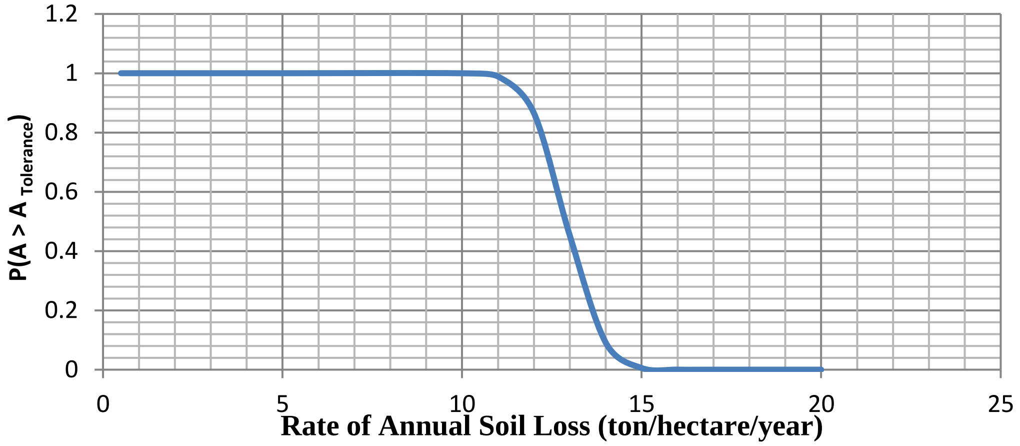

Figure 6: Graph of probability of rate of annual soil loss exceeding the tolerable or permissible rate against rate of annual soil loss for Ekhaguere gully using daily rainfall data from NIMET (1982 – 2011)

Table 7: Probability of rate of annual soil loss exceeding the tolerable or permissible rate for Ekhaguere gully using monthly rainfall data from CBN (1982 – 2011)

$A_{Tolerance}$	$Pf = P(A > A_{Tolerance})$	Reliability Index (β)
0.5	0.999999	-7.94144
5	0.99999	-7.94144
10	0.999999	-7.94144
11	0.999999	-7.94144
12	0.9795	-2.04353
13	0.6122	-0.28506
14	0.0601	1.553935
15	0.0003	3.431614
16	0.000000000000001	7.941444
17	0.000000000000001	7.941444
18	0.000000000000001	7.941444
19	0.000000000000001	7.941444
20	0.000000000000001	7.941444

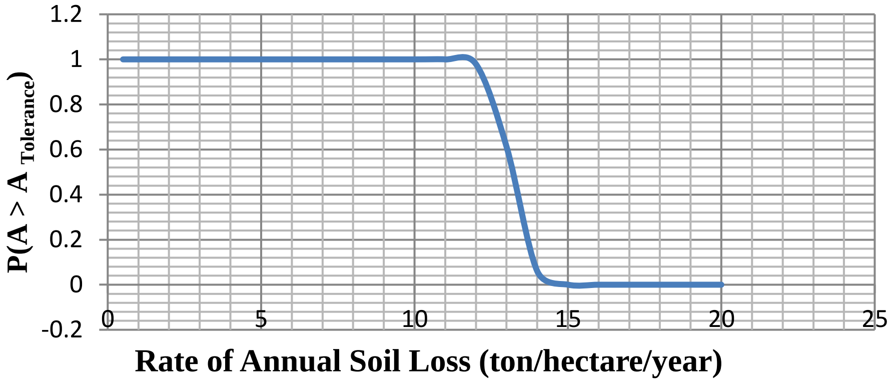

Figure 7: Graph of probability of rate of annual soil loss exceeding the tolerable or permissible rate against rate of annual soil loss for Ekhaguere gully using monthly rainfall data from CBN

The results of the reliability analysis show that the probability of getting moderate to severe annual rate of soil loss in Ekhaguere gully is very low and the likely soil erosion rate will be in the region of very low to the lower bound of moderate soil loss (i.e., *A* of 0 – 14 tonnes/hectare/year) with probability of exceedance of higher than 0.0601.

To obtain a reliability index greater than the target value of 3.8 specified in BS EN 1990 [27], the probability of obtaining or exceeding the very low to low soil loss rate has to be reduced by putting in place serious control measures to limit the influence of agents of soil loss and erosion.

4.0 Conclusion

From the results obtained from the study, the following conclusions are drawn:

i. The results of the reliability analysis showed that the gully wall slope stability reliability index value of 0.84 is less than the target reliability index value of 3.8 recommended in BS EN 1990, suggesting that the gully slope is unsafe.
ii. From the reliability analysis for slope stability, Ekhaguere gully (LHS and RHS) were best fitted by lognormal distribution model. Their reliability index value and probability of failure value were 0.9991 and 0.8411 respectively.
iii. Reliability analysis for the gully bed erosion showed that the probability of getting moderate to severe annual rate of soil loss is very low and that the likely soil erosion rate will be in the region of very low to the lower bound of moderate soil loss (0 – 7 tonnes/hectare/year). This suggests that the predicted erosion rates for both gully is unsatisfactory.
iv. The effect and impact of soil variability on the erosion and slope stability parameters were evaluated. From the reliability analysis for slope stability, Ekhaguere gully (LHS and RHS), were best fitted by lognormal distribution model. Their reliability index values, and probability of failure values were, 0.9991 and 0.8411. The reliability index value was 0.8413. The target reliability index value was one and from the analysis, the value obtained was less than one suggesting that the gully is unsafe.
v. The reliability analysis results for gully slope stability showed that the gully slope is unsafe after obtaining a reliability index value of 0.84 which is less than the recommended value of 3.8 in the Eurocode.
vi. Reliability analysis for soil erodibility was done using rainfall data for a period of 30 years obtained from CBN and NIMET. The R- factors from both rainfall data was evaluated and it was observed that the R-factors followed a normal distribution having

distribution parameters (μ and σ) as 21.385 and 0.9057 for CBN data and 20.966 and 1.332 for NIMET data.

Based on the findings of the study, the following recommendations are made:

i. Urgent attention by government should be given to the Ekhaguere gully to avert danger that might cause by this gully due to the unstable gully slopes with high probability of collapse and gully bed erosion rates.
ii. It is also recommended that farming activities on the slope around the gully areas should be reduced to prevent the already unstable slope from collapsing further and minimize the risk of environmental hazards.

Nomenclature

A	Annual rate of soil loss
AGs	Average specific gravity
AMC	Average moisture content
b	Shape parameter
BS	British Standard
C	Cover management factor
CBN	Central Bank of Nigeria
Co	Cohesion
EN	European Norm
FORM	First order reliability method
FoS	Factor of safety
K	Soil erodibility factor
LHS	Left-hand side
LS	Slope length factor
MCS	Monte Carlo Simulation
NIMET	Nigerian Meteorological Agency
OMC	Optimum moisture content
P	Annual rainfall
pdf	Probability density function
Pf	Probability of failure
Pi	Monthly rainfall
R	Rainfall erosivity factor
RHS	Right-hand side
SE	Soil erosion rate
USLE	Universal soil loss equation
XGBoost	Extreme gradient boosting

Greek letters

α	Scale parameter
β	Reliability index
μ	Mean
σ	Standard deviation

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