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Uncertainty and Reliability Analysis in Gully Slope Stability Prediction: A Case Study of Iguosa Gully, Benin City

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Abstract

Slope stability analysis is an essential tool in gully erosion risk assessment and modelling. The reliability of a gully wall slope stability analysis depends on many factors. These factors are: the uncertainties due to the varying geotechnical parameters within the site, uncertainties due to the slope stability modelling methods and soil sampling procedures. In this study, various properties of the soil and slope were analyzed in order to depict the risk associated with the gullying process at the Iguosa gully in Benin City. Based on the samples obtained from the gully walls, a large number of random slope stability parameters were generated by combining various geotechnical properties obtained from collected samples. The slope stability parameters – i.e. factors of safety (FOS) against slope failure – were analyzed statistically to obtain standard deviations, distributions, and probability density functions (PDF). Based on the statistical distribution of the numerous slope stability parameters, a probable and conservative slope stability index was calculated for the gully. The results of the analysis gave an average reliability index (RI) of 0.84 for the stability of the gully wall slope. The RI, which indicates the stability of the slope, can also be related to the likelihood of slope failure. The results obtained from this investigation implies that the likelihood of slope failure of the Iguosa gully is relatively high and that the current wall formation could lead to a major slope failure.

1. Introduction

Gullies are generally near-vertical watercourses that encounter transitory flows during torrential or prolonged rainfalls. In view of the above, gully erosion can be viewed as any erosion process that involves the accumulation of runoff water in narrow channels, which in turn results in the removal of large amount of the soil within a short period of time. The major factors that lead to the development of gullies are mostly man-made in nature, and they include: ploughing of uncultivated lands, opening up of natural woodlands, and other related hydrological changes that may impact on the rainfall and runoff systems [1,2]. Gully erosion is also a severe type of soil deterioration usually comprising of an early cut into the subsurface, by accumulated runoff flowing along fault lines or weak zones such as tension and parched fissures [3,4]. Gully erosions have a significant impact on the social-economic well-being of areas where they occur [5].

Soil erosion and gullying are major land ecological issues affecting various facets of human lives [5,6]. Therefore, controlling of soil erosion requires an understanding of the natural irregularity of soil properties and how they affect soil erosion [1]. Geotechnical parameters employed in obtaining the stability of soil systems are varying in nature. Variability in the soil can be ascribed to its intrinsic uncertainty, and traces of error that may arise when determining the size or measure of its properties. Native soils usually show large variability in their engineering properties. It is therefore pertinent to distinguish the variations of the usual design soil properties that will be encountered in a typical soil element and to examine the influence of sample size on the variations of these soil properties [7,8]. Modelling of these inherent variabilities will lead to the generation of more significant results when assessing stability. This is particularly significant when calculating the likelihood and risk related with an uncommon failure event. The soil properties that are used to compute the stability of soil systems vary in nature. According to [9], the most significant source of uncertainty in geotechnical reliability-based design is the spatial variability of the soil properties. Hence, it is essential to allow for variations in soil properties when carrying out geotechnical designs, so as to get a more accurate representation of the soil's *in situ* state. These variations can be modelled as a random field, using a specified probability density function (PDF) and scale of variation. It may even be more appropriate to constrain the modelled random field at the exact locations of where the field measurements were taken [10].

The unpredictability and uncertainty in the geotechnical properties of the soil are the most significant factors that can influence the reliability of the Factor of Safety (FOS) derived from the analysis. Variability in the soil properties can arise from inbuilt spatial variability in the soil properties and arbitrary errors in their testing and measurements. Uncertainties may also arise from regular errors that are as a result of sampling processes and predisposition in the process of measurement.

Soil variability plays an important part in erosion modelling. Erosion models are usually generalizations of reality that best illustrates the processes of erosion and the contributing factors that will lead to an output, reliant on the purpose of the model. Hence, the beginning point for erosion modelling must be a precise assertion of the purpose or objective, since this would determine the kind of output to be obtained [11]. Other experimental phenomena can be integrated in models such as, the effect of a near vertical (steep) slope, high elevation, and the geotechnical properties of the soils, which were the original conditions that started the landslides and gully formation in the study area. This can also be affected by inadequate vegetation, heavy rainfall, poor drainage systems, and human as well as socio-cultural activities [12].

This work complements recent works in gully slope stability which studied the effects of seasons on gully wall stability [13]. It has been established that geotechnical properties, groundwater, movement of sediments, water infiltration, and conduction affect the stability of gully walls [14]. It should be noted that the conventional factor of safety method cannot fully reflect the uncertainty in a gully wall slope. Thus, applying reliability theory using probability and statistics, will lead to a more objective way of evaluating the degree of influence on the slope. Research has shown through stochastic that the cohesion of the soil, c, has a major influence on the reliability index (RI), β. Though, the angle of internal friction, φ, is more sensitive in the computation process and therefore has a larger influence on the computation of the FOS and RI [15].

2. Geology and Physiology of Study Area

The Iguosa gully is located within the Federal Housing Estate, Oluku, Ovia- North East L.G.A, Edo State, Nigeria. Figure 1 shows a satellite image of the gully area and Figure 2 shows a topographical survey of a section of the gully. A site photograph from the gully site is shown in Figure 3. The geology and topographical characteristics of the Benin formation have their interdependence on weathering. Underneath the Benin formation is the South Sedimentary Basin. The geology of the

Benin formation is mostly comprised of top reddish soil made up of ferruginized clay sand. The Benin sand can be described as reddish soil, and under it lie sands, sandy clays, and ferruginized sandstone that indicate the Paleo-Coastal Environment of Paleocene-Pleistocene Age. These sediments span through the southern bounds of the Anambra Basin and indicating the upper fancies off-flaps of the Niger Delta.

Figure 1: Satellite Imagery of Iguosa Gully, Benin City

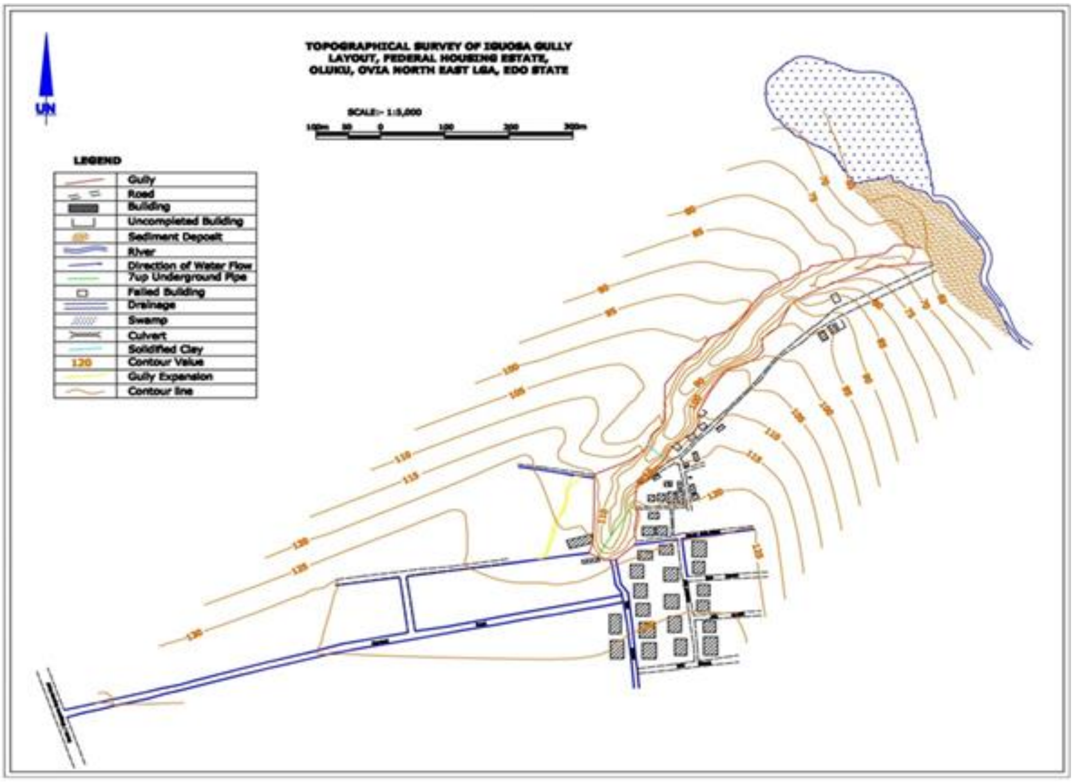

Figure 2: Topographical survey of Iguosa Gully, Benin City

Figure 3: Pictorial view of Iguosa gully

2.1 Method of Data Collection

The sampling methods adopted in this research are as follows:

a) Gully Survey: The gullies investigated were surveyed using a Global Positioning System to determine the edge and bottom points of the gully. Elevation and point coordinates were collected, which were transformed into polylines through Arc GIS 10 in the post-procedure stage.
b) Soil samples (disturbed and undisturbed) were extracted from the gully site at 10m intervals along the gully on both sides i.e. left and right-hand sides and 50m intervals along the gully invert (bed). Both horizontal and vertical soil sampling was done to ascertain variations in the properties of the soil.
c) The total number of samples extracted from the Iguosa gully site was 150. Each of these samples was extracted from a 50m x 50m grid on the gully bed and a 10m x 10m grid on the gully walls. Samples were extracted at depths ranging from 0m to 3m depth.
d) A combination of field and laboratory testing were carried out. For laboratory analysis, the samples were extracted using a shovel, core-cutter, and U- tubes at various specific depths.

2.2 Laboratory Tests

The laboratory tests carried out on the samples extracted from the gully site include:

a) Specific gravity
b) Moisture content
c) Atterberg limit/ consistency tests
d) Particle size distribution analysis/ hydrometer tests
e) Undrained triaxial tests
f) Organic carbon content tests
g) Organic matter content tests

These tests were selected as they constitute parameters required for the classification of the kinds of soil in the gully area and the determination of the erosion stability and the reliability analysis.

2.3 Slope Stability Analysis

Classical geo-technical deterministic methods were used to determine the stability of slopes of walls of the gully studied in this research. The Culmann equilibrium limit procedure was used to determine the factor of safety (FOS) against sliding failure. Equation (1) shows the general philosophy for obtaining FOS.

$$\text{FOS} = \frac{\text{Maximum forces tending to resist sliding down the plane QS}}{\text{Forces tending to cause sliding down selected failure plane}} = \frac{C + Ntan\theta}{T} \quad (1)$$

Where C = cohesion force acting on failure; N = resolve part of W (weight) acting normal to failure plane = $W\cos\vartheta$; T = resolved part of W acting down the plane QS.
Based on numerous computations of FOS a reliability index is determined based on Figure 4, where failure probability is represented by P_f, and reliability index by β. Standard deviation and mean are represented by σ and μ, respectively.

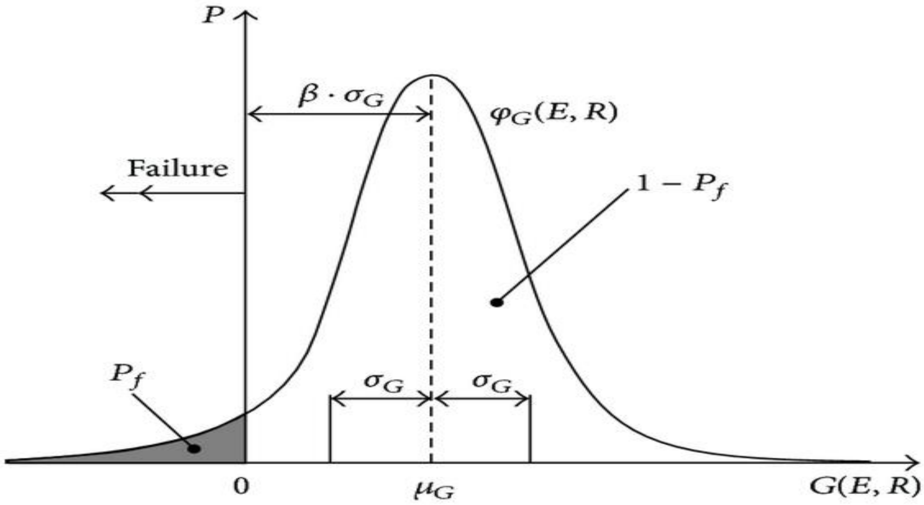

Figure 4: Estimation of reliability index

3. Results and Discussion

3.1 Reliability Analysis for Stability of Gully Wall Slope

Due to the inconsistency in the geotechnical properties of the soil, ten thousand (10,000) random values of FOS were generated for the various soil properties using the probability distribution parameters presented in Table 1. These generated properties were used to obtain random values of FOS for the gully wall (left and right walls of the gully respectively). Having the mean value as well as the coefficient of variation (COV) of the generated FOS values, it is possible to specify their standard deviations and shapes of the probability density functions (PDF) shown in Figures 1 and 2. The PDF generated depicts the relative probability that the variables will have a definite value within the range of potential values.

Table 1: Probability Distribution Parameters of Soil Properties needed for Reliability Analysis of Slope Stability

Location	Property	Best fit probability distribution	Distribution Parameters
Iguosa (LHS)	AMC	Normal	σ = 3.8515, μ = 10.952
	Ags	Weibull	α = 46.705, *b* = 2.5912
	Internal Friction	Lognormal	σ = 0.4347, μ = 2.4390
	CO	Weibull	α = 1.4287, *b* = 18.154
Iguosa (RHS)	AMC	Weibull	α = 2.6479, *b* = 13.447
	Ags	Weibull	α = 24.687, *b* = 2.5721
	Internal Friction	Lognormal	σ = 0.38248, μ = 2.2772
	CO	Lognormal	σ = 0.64167, μ = 2.8946

A semi-variogram was used to present the variability amongst the data points as a function of distance, as shown in Figures 5 to 9. The *y*-axis shows variability, while the *x*-axis shows distance. It is observed that at some points the distance between data points are no longer auto-correlated. Thus, a closely-spaced data point shows a low level of variability while widely-spaced points show a higher level of variability.

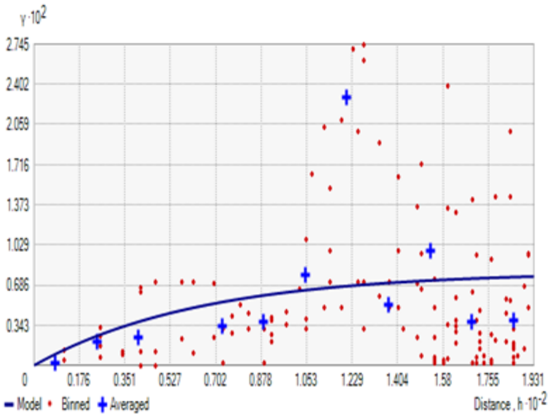

Figure 5: Maximum density semi-variogram

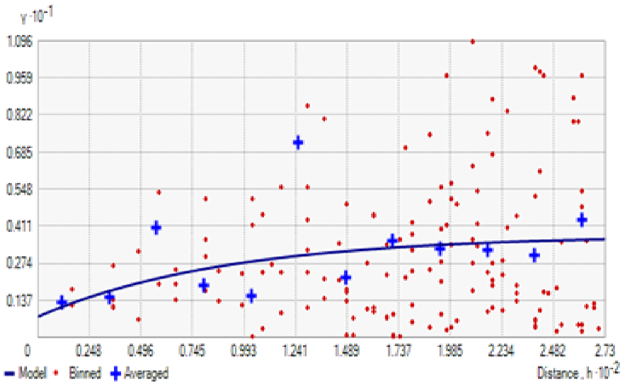

Figure 6: Optimum moisture content semi-variogram

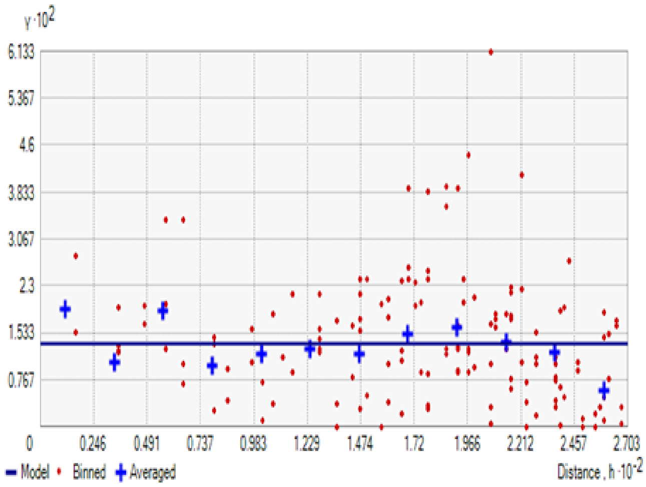

Figure 7: Specific gravity semi-variogram

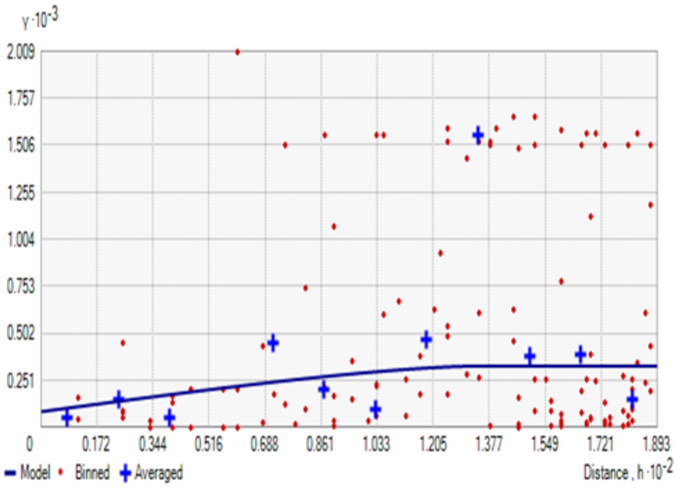

Figure 8: Cohesion semi-variogram

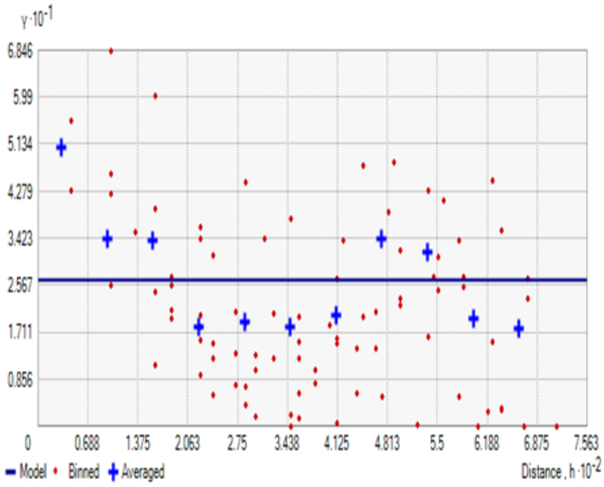

Figure 9: Internal friction semi-variogram

The intervals for the computed FOS can be seen in Figures 10 and 11 for normal, lognormal and Weibull distribution. The values in the horizontal axis are normalized values. The K-S goodness of fit test was applied to test for the probability distributions that bests fit the generated FOS values. Results of the test are presented in Table 2 for the walls of the Iguosa gully. Results obtained show a low probability of failure implying that the walls of the gully are currently stable and unlikely to fail. 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 RI derived from the PDF is approximately 0.84 for both walls of the studied gully with respect to the mean and standard deviation of the FOS obtained. It should be noted that whether a probability of failure value is acceptable or not depends on its associated RI compared with the target RI. Thus, a high value of RI with reference to the target RI shows a low probability of failure [16]. The RI value of 0.84 when compared to acceptable performances of slopes in literature (see Table 3), suggests a high probability of slope failure in the studied gully.

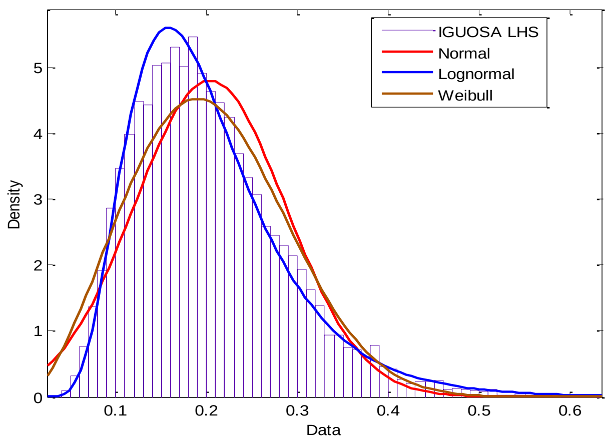

Figure 10: Probability Density Frequency of FOS of Iguosa Gully (LHS)

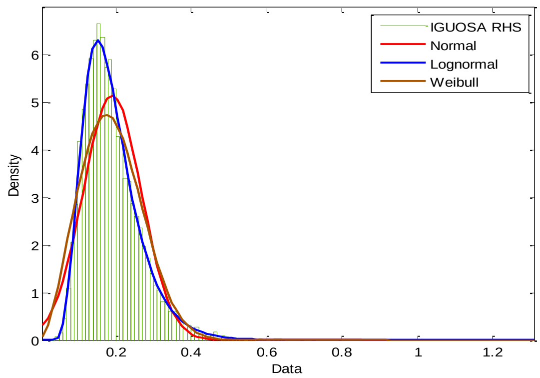

Figure 11: Probability Density Frequency of FOS of Iguosa Gully (RHS)

Table 2: Reliability analysis

Location of Gully	Gully Side	N	Probability Distribution	K-S Test		Decision at 5% significance level	Best Fit Distribution	Property	Pf = P(FS <1)	Reliability Index (β)
				Statistics	Rank					
Iguosa	LHS	10,000	Normal	0.0591	3	Accept Normal	Lognormal	σ = 0.4122 μ = -1.6725	1.0000	0.8413
			Lognormal	0.0262	1	Accept Lognormal				
			Weibull	0.0487	2	Accept Weibull				
	RHS	10,000	Normal	0.0679	3	Accept Normal	Lognormal	σ = 0.4740 μ = -1.3853	1.0000	0.8413
			Lognormal	0.0265	1	Accept Lognormal				
			Weibull	0.0518	2	Accept Weibull				

Table 3: Reliability Index and Probability of Failure [17]

Expected performance	Reliability index	Probability of failure (%)
High	5	3 x 10-5
Good	4	3 x 10-3
Above the average	3	10-1
Below the average	2.5	6 x 10-1
Poor	2	2.3
Unsatisfactory	1.5	7
Dangerous	1	16

4. Conclusion

From this research, the following conclusion can be drawn:

a) A simple statistical distribution function can be employed to predict the probability of slope failure for earth structures with varying geotechnical properties. Reliabilities of these structures can be obtained based on the PDF's of the FOS's

b) Geometric properties of soils with varying properties can be represented with a distribution function, i.e. a PDF. Such distribution functions give a bird's eye view of standard deviations and means which can be applied in conservative estimation of factors of safety (FOS).

c) Semi-variogram presents an important tool for analyzing the variability of geotechnical properties of soils. These variations could create uncertainties in measuring FOS which are inherently related to varying soil properties.

d) For the gully studied, reliability analysis showed that the gully wall slope stability reliability index value is 0.84. This suggests that probability of slope failure of Iguosa gully is relatively high and that the current wall formation could result to significant slope failure. Also, increase restructuring of the steepness of the gully wall by runoff could increase the instability of the slope.

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