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Research Paper

Evaluating the Stability of Gully Walls in Agulu-Nanka-Oko gully erosion complex area of Anambra State, Nigeria, using empirical approach

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Abstract. This paper describes the application of empirical model in evaluating the stability of gully wall profiles in parts of Anambra State. A theoretical model of gully wall profile, based on the principle of shear strength was used to determine the predicted gully wall profile of the Agulu-Nanka-Oko gully complex area. The coefficient of shearing resistance indicating the maximum sustainable inclination by the soil was obtained from the derived model. The process was repeated for each identifiable soil horizon to generate theoretical equilibrium profile for the gully wall. The theoretical profiles are compared with field observations of the gully wall geometry using linear regression. The coefficient of correlation (r) and coefficient of determination (R^2) were then obtained. The results show that the observed profiles are consistently steeper (especially at the bottom) than the predicted profiles. This is probably due to undercutting of the bottom and toppling which is one of the causes of gully erosion. Furthermore, apparent cohesion can increase the soils shearing resistance, and hence results in steeper gully wall. The model validation test indicated that the model provided an effective tool for predicting gully walls profile.

Keywords: Gully, erosion, stability, empirical, model, profile.

INTRODUCTION

Gully erosion is one of the most conspicuous forms of accelerated erosion which occurs in widely different climate, geologic and land use conditions (Bocco et al., 1990). Gully erosion accelerates the loss of soil and decreases the productivity of agricultural land. Eroded sediments are often transported into the receiving streams causing water quality problems and negatively impacting on geological process. They constitute threat to lives and property.

The government of Anambra State (1994) estimated that over 70% of the land of the state were being ravaged or threatened by erosion at various levels of development and stages of maturity.

Over the years, several efforts have been made towards solving or at least containing the soil erosion menace in Anambra State (Udo, 1971; Eze -Uzoamaka et al., 1979). Despite these efforts, the menace has continued to increase in spatial distribution and severity. The Agulu – Nanka – Oko gully erosion complex is selected for this study due to its devastating nature that has attracted wide attention over the years. The gully complex has a large concentration of gully systems within the same drainage basin and geologic Formation and accounts for large loss of agricultural land in southeastern Nigeria (Chukwueze, 1988). The catchment covers an area of 35.75 km^2.

Empirical equations have been used to predict gully growth by the Soil Conservation Services (1977). These equations consisted of linear measurement of gully-head retreat, by means of sequential aerial photographs at 1:20,000 scales. However, there was inadequate knowledge about the relative importance of the various causative factors and that precise quantitative values could not be given to variables used in the equation. The

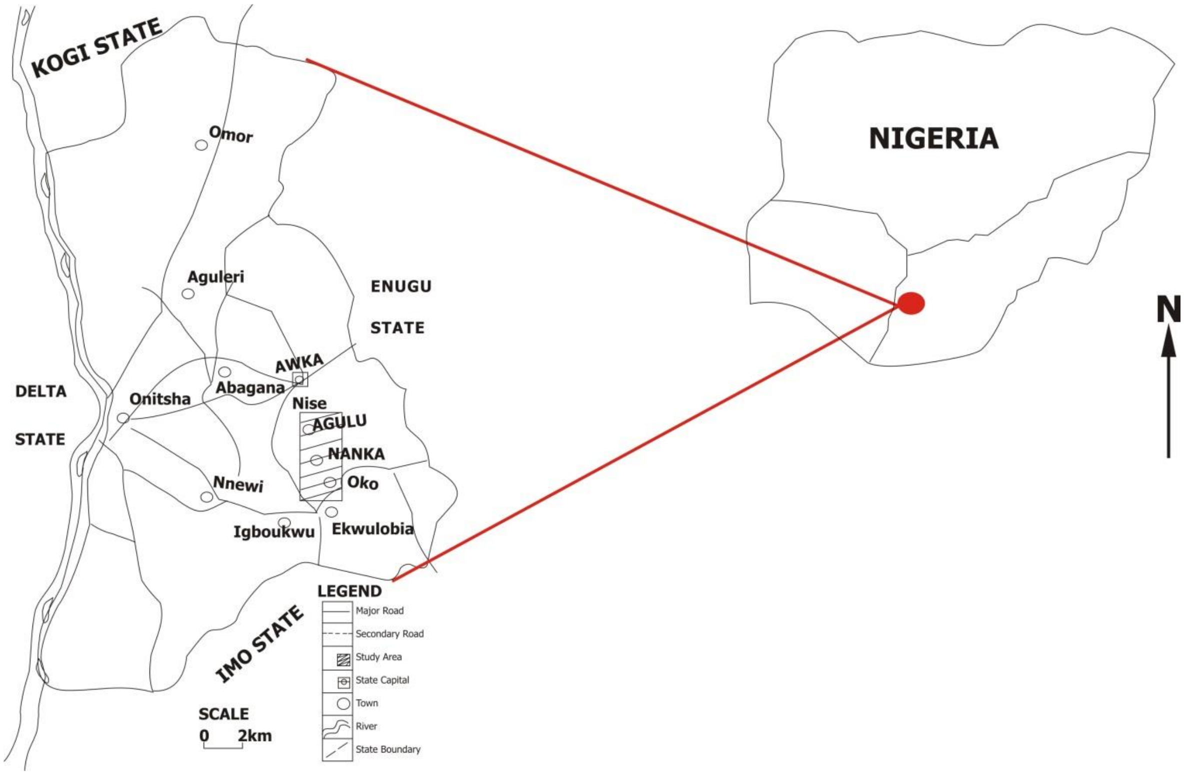

Figure 1. Map of Anambra State showing the study area.

stability of gully-heads and gully-walls is strongly dependent on factors, such as angle and height of gully wall (Bull and Kirkby, 2002; Poesen et al., 2002), structural instability of the materials (Collison, 2001). Generally, temporary stability of dry materials is achieved at angle of internal friction that is almost equal to repose angle (Shit and Maiti, 2012). Stocking (1980) used multiple regression analysis to predict gully-head retreat (in terms of volume of gully growth). Although these empirical models are useful in predicting gully growth, they, however suffer from regional bias, which restricts their extrapolation. Remote sensing techniques and geographic information systems (GIS) have been widely used in mapping and monitoring, simulation and hazard prediction modeling of gullies (Bocco et al., 1990; Zinck et al., 2001; Shrestha and Zinck, 2001; Vestappen, 1985).

Objectives

The main objective of the study was to develop an empirical model in evaluating the stability of gully wall profiles in Agulu-Nanka-Oko gully sites of Anambra State. A theoretical model of gully wall profile, based on the principle of shear strength was used to determine the predicted gully wall profile of the Agulu-Nanka-Oko gully complex area. The theoretical profiles was then compared with field observations of the gully wall geometry using linear regression and the coefficient of correlation (r) and coefficient of determination (R^2) would be obtained.

General description of the study area

The study area, (Agulu – Nanka – Oko gully complex) is located in the Southeastern part of Anambra state and about 30 km southeast of Onitsha, the commercial nerve centre of the state and about 16 km south of Awka, the state capital (Figure 1). It is situated between longitudes 7° 05′ and 7°10′ East of the Greenwich meridian and between latitudes 6° 10′ and 6° 05′ North of the Equator. The yearly rainfall regime encompasses dry and rainy seasons. The rainy season is from March to October and the dry season is from November to February. The average annual total rainfall ranges from 1510 to 2253 mm (Akintola, 1986). The total annual rainfall experienced mostly during rainy season in the area leads to high soil saturation over long period of time within the year.

The study area lies within the Anambra sedimentary basin, which is widely covered by Nanka Formation. Nanka Formation is an unconsolidated sand deposit forming part of the Eocene deposits of Southeastern Nigeria; it is underlain by the marine Imo shale of Paleocene age and overlain by the paralic Ogwashi- Asaba Formation of Oligocene (Figure 2).

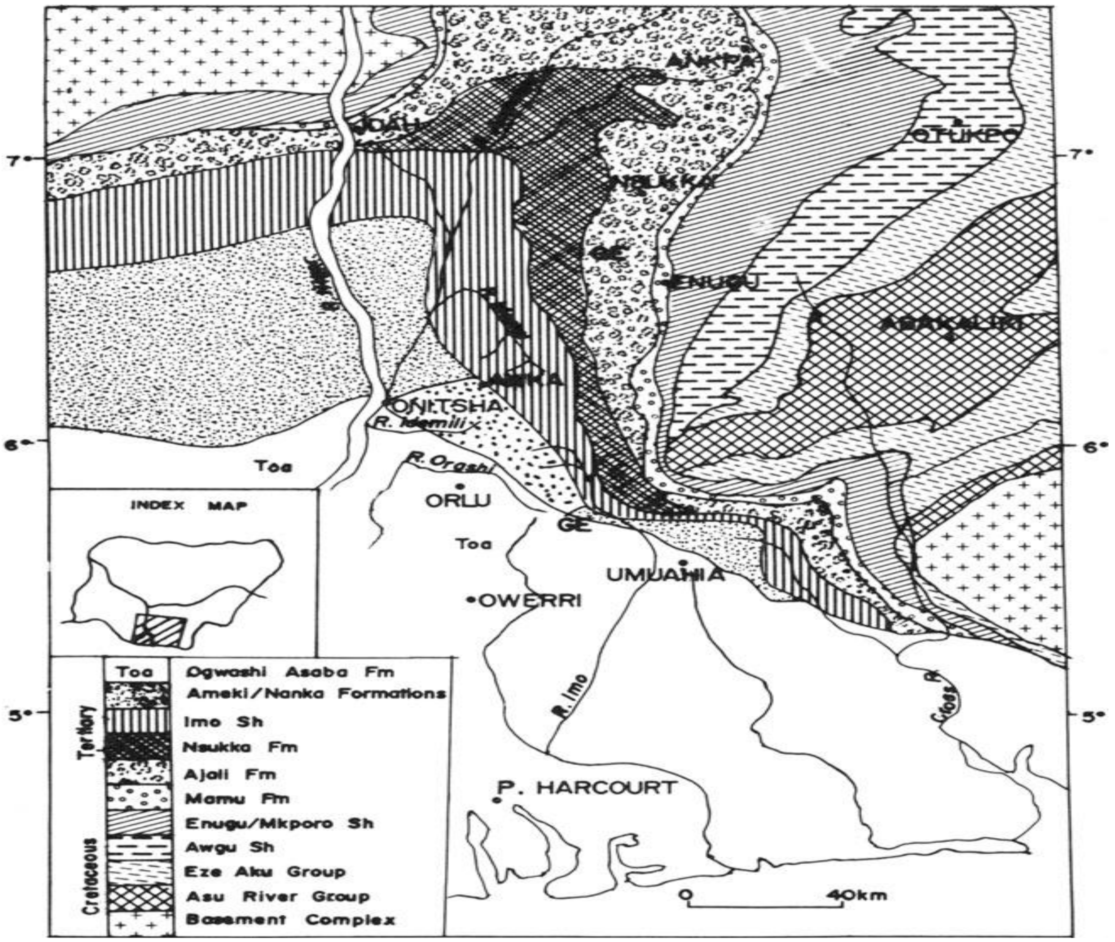

Figure 2. Geological map of part of southeastern Nigeria (Adapted from Nwajide, 1992).

Gully initiation and development

Gully erosion is initiated by overland flow or surface runoff taking advantage of minor irregularities on the surface to collect increasingly distinct but shallow channels called rills (Ologe, 1988). Similarly, it could be initiated by increased runoff due to land use and climate changes. Okagbue and Ezechi (1988) concluded that once a gully is initiated the soil properties become responsible for their rapid propagation. This accounts for the no response of most gullies to afforestation control measure. Most gullies are quite broad and have vertical walls. Increased pore pressure from groundwater moving towards the gully, coupled with some undercutting of the sidewalls by water causes deep rotational slumps along the sidewall. Widening of the gully wall also occurs when the upper portions of the gully walls separate and topple into the gully.

In the investigation of soil (Terzaghi and Peek, 1967), cohesion and angle of internal friction have been lumped together and are represented by shear strength. However, the more significant shear parameter of the soil in the context of soil erodibility is cohesion. The degree of erosion is widely related to soil strength. Shear strength is considered the most important in the detachment process.

Characteristics of gully wall profiles

Following shear stress based model concepts, Wirtz et al. (2013) showed that shear stress of the flowing water controls the detachment process of soil. Wirtz et al. (2013) therefore considered the transport rate up to the transport capacity as shear stress dependent uptake. The transport rate exceeding the transport capacity is considered as shear stress independent erosion caused by processes such as bank failure and head-cut retreat. However, a common feature of gullies irrespective of their geographical location is their steep angles which are generally above 45° (Nwajide, 1992). A typical gully wall profile of the study area is shown in Figure 3. The slopes of the nearly vertical wall of the gullies vary from 45° to 88° (Figures 3 and 4). The gully floor slopes vary from 5° to 27° (Figure 5). The upper part of the profiles of the gully walls are nearly always 90°. Change in sedimentary sequence is often reflected in the gully wall profile.

Whereas the granular and more erodible strata tend to

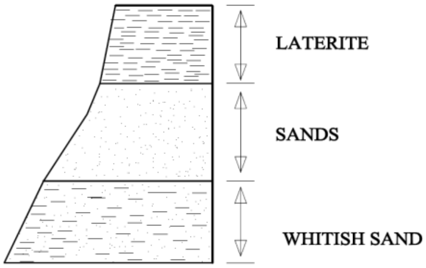

Figure 3. Typical gully wall profile of study area.

Figure 4. Gully side wall profile at Agulu Gully site.

Figure 5. U-shaped gully showing unconsolidated sediments and gully floor slope at Oko gully site.

Figure 6. Devastated landscape showing intercalation of red earth and unconsolidated whitish sand at Nanka and Oko gully sites.

Figure 7. Rotational slump at Nanka gully site.

be gently inclined, the erosion resistant layers tend to be steeply inclined (Figure 6).

The translational slides are plane features which occur when a discontinuity strikes parallel to the slope face and dips into the gully at an angle exceeding the angle of friction of the un consolidated sand (Nwajide, 1992). The recent rotational slumps generally occur on the steepest slopes and are characterized by single slump block (Figure 7).

MATERIALS AND METHODS

Sampling

Field soil sampling involved the examination and collection of soil samples. Nine (9) gully wall profiles in four (4) gully locations were examined and a total of twenty (20) soil samples were collected for laboratory analysis. These soil samples were collected using shovel, core-cutter and U-4 tubes at various depths ranging from 1.0 to 60 m. The vertical soil sampling on the gully walls was to ascertain changes in soil properties and spatial variability of soil properties. The soils were characterized and labeled. Slope angle (SA) and depth of sample collection were measured using clinometers and measuring tape respectively.

Laboratory tests

The laboratory tests were conducted in Soil Laboratory of Department of Geology, University of Port Harcourt, Rivers State, Nigeria. The testing procedures were in accordance with ASTM D 2166 and BS 1377: Part 8:1990. Bulk Density, cohesion(c) and angle of internal friction (θ) were estimated by Triaxial Compression Test.

Modeling of gully wall profiles

Soil detachment can be described by shear stress τ, unit

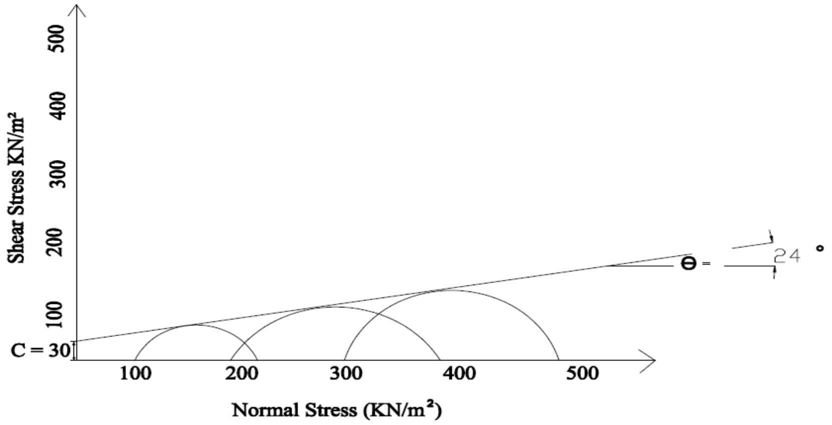

Figure 8. Total stress Mohr circle and failure envelope of 3 m depth in Oko.

length shear force, stream power ϖ, unit stream power ϖ_U and effective stream power ϖ_{eff} (Wirtz et al., 2013). However, the shear strength of slope materials is typically expressed as friction angle and cohesion. Similarly, bulk densities and the distribution of pore water pressure within the soil mass contribute mainly to the shear resistance to slope failure. However, it is a widely accepted principle (Terzaghi and Peck, 1969) that a soil fails when the shear stress exceeds the shearing resistance offered by the soil. It follows from this that a gully wall would fail at any point where induced shear stress can not be sustained by the shear strength of most of the soil. The shear strengths of most of the soils in the study area have both cohesive and frictional components and may be expressed as:

$$\tau = c + \gamma z tan\theta \tag{1}$$

where γ = unit weight of soil (kN/m^3)
c = cohesion (kN/m^2)
θ = angle of internal friction
z = depth (m)
Equation 1 may be re-expressed as:

$$\frac{\tau}{\gamma z} = \frac{c}{\gamma z} + tan\theta \tag{2}$$

the ratio $\tau / \gamma z$ is also called the coefficient of shearing resistance (Maslov, 1987) and is related to a hypothetical angle of shearing resistance (ψ_z) such that:

$$tan\Psi_z = \frac{\tau}{\gamma z} \tag{3}$$

By implication, ψ_z may be defined as the maximum sustainable inclination by the soil. The limiting angle at a given horizon (z) can thus be obtained as:

$$\Psi_z = tan^{-1}\left(\frac{\tau}{\gamma z}\right) \tag{4}$$

This expression can also be written in terms of the shear strength components and may be used as a numerical model for the description of gully wall profiles.

Substituting $\frac{\tau}{\gamma z}$ in Equation 2:

$$\Psi_z = tan^{-1}\left(\frac{c}{\gamma z} + tan\theta\right) \tag{5}$$

For dry cohesionless soils, where c = 0; Equation 5 can be simplified such that $tan\Psi_z = tan\theta$

RESULTS AND DISCUSSIONS

The stress-strain curves for a few of the samples are shown in Figures 8 to 11 along with the Mohr-Coulomb failure envelopes. Table 1 summarizes the test results.

The result indicate that for all the sites, the top stratum (laterite soil) possesses some cohesion, though little whereas the substratum made of predominantly whitish grey sands possesses no cohesion. The angle of shearing resistance increases with depth for all the sites, due perhaps to the downward increase in percentage of sand and decrease in the silt/clay content. The shearing resistance angles are quite reasonable for sand but their effects are probably subdued by the loose nature of the grains. Flowage is a characteristics pattern within the sands after saturation.

A requirement for the development of descriptive equations is that they should be generally applicable so that they can be used for predictive purposes (Abam, 1994). In order to establish the accuracy of the description model equations, field measurement of gully wall profile at the studied sites were compared with

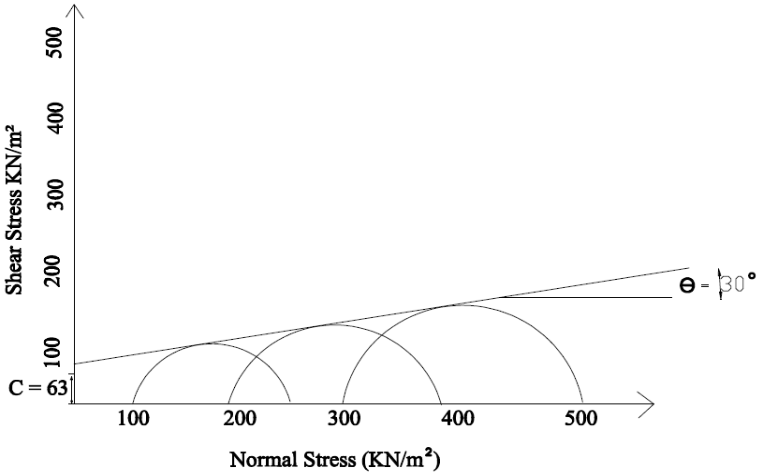

Figure 9. Total stress Mohr circle and failure envelope of 42 m depth in Nanka (Ubahu).

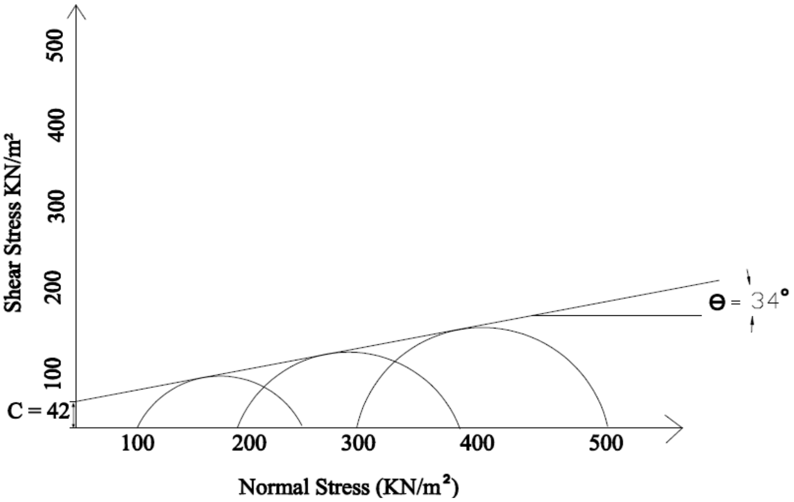

Figure 10. Total stress Mohr circle and failure envelope of 40 m depth in Agulu.

profiles determined from the model.

The geotechnical properties of the soils at the studied sites were substituted into Equation 5 to obtain the predicted gully wall profile. The result shows that the equilibrium inclination of the top gully walls varies from 60° to 81° while the second layer varies from 53° to 62°. Furthermore, the equilibrium inclination of the gully wall at the bottom layer varies from 35° to 40°. The observed and predicted gully wall profiles for the Agulu, Nanka, Oko and Oraukwu gully sites are compared in Figures 11 to 15. The graphs show that the observed profiles are consistently steeper (especially at the bottom) than the predicted profiles. This is probably due to undercutting of the bottom and toppling which is one of the causes of gully erosion. Furthermore, apparent cohesion can increase the soils shearing resistance, and hence results in steeper gully wall. This factor was not considered in the development of the model. Statistical analysis of the observed and the theoretical profiles in Figures 12 to 15 using linear regression gives a coefficient of determination of between $R^2 = 0.8983$ and 0.9921; and correlation coefficient of between $r = 0.95$ and 1.0. These values are generally high indicating good relationship. This also suggests that the model is comparable to the observed profile. In practical terms, this implies that the model is applicable.

CONCLUSION

The study reveals the following conclusions:

1. The predicted equilibrium inclination of the gully wall profiles in the studied area was derived from the

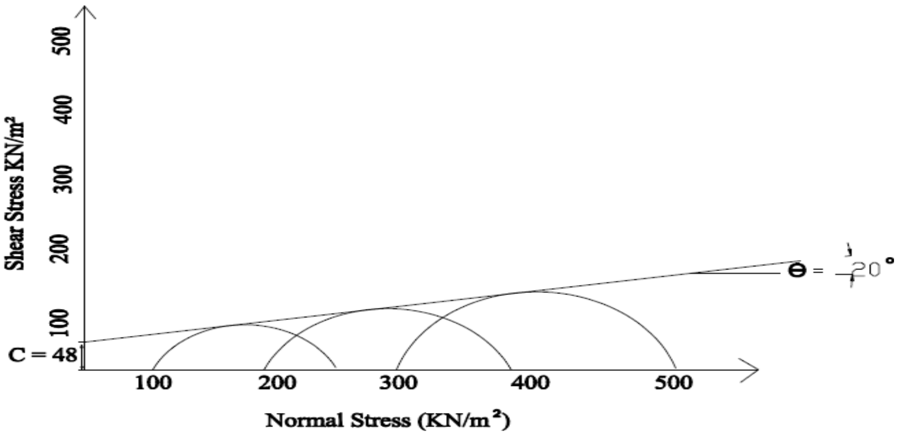

Figure 11. Total stress Mohr circle and failure envelope of 3 m depth in Oraukwu.

Table 1. Summary of field and laboratory results.

S/N	Location	Depth (m)	Gully wall slope	Bulk density (kg/m^3)	Cohesion (kN/m^2)	Angle of shearing resistance (degrees)	ψ_z (degrees)
1.	Oko (latitude 6º 15′ longitude 6° 03′)	3	88	1.68	30	24	81
		20	71	1.71	42	27	60
		35	65	1.70	56	31	57
		44	56	1.76	35	33	48
		60	42	1.81	5	35	37
2.	Nanka (Ubahu) (latitude 6° 06′ longitude 7° 08′)	4	88	1.70	68	22	85
		25	72	1.69	53	26	60
		38	65	1.78	55	28	53
		42	68	1.81	63	30	55
		60	43	1.83	4	34	35
3.	Agulu (latitude 6°10′ longitude 7° 05′)	3	82	1,51	81	24	87
		20	76	1.56	72	28	71
		30	68	1.55	58	32	62
		40	58	1.56	42	34	53
		60	46	1.86	6	38	40
4.	Oraukwu (latitude 6° 10′ longitude 6° 98′)	2	88	1.58	48	20	86
		15	76	1.54	57	25	71
		22	71	1.63	62	28	66
		42	64	1.68	65	36	59

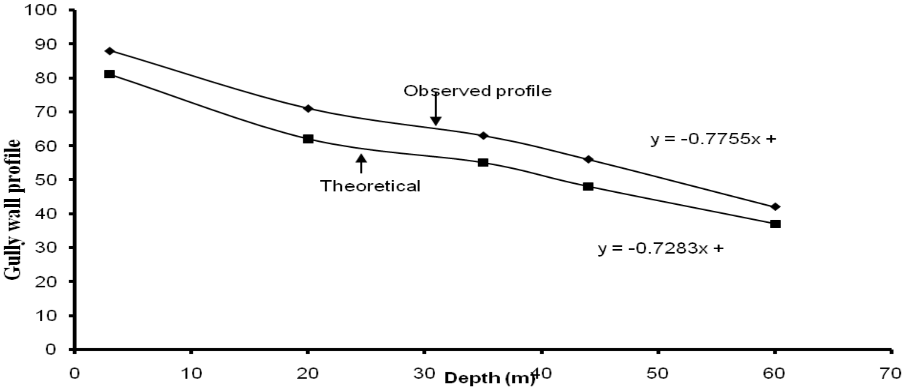

Figure 12. Graph showing the observed and predicted wall profile of Oko gully site.

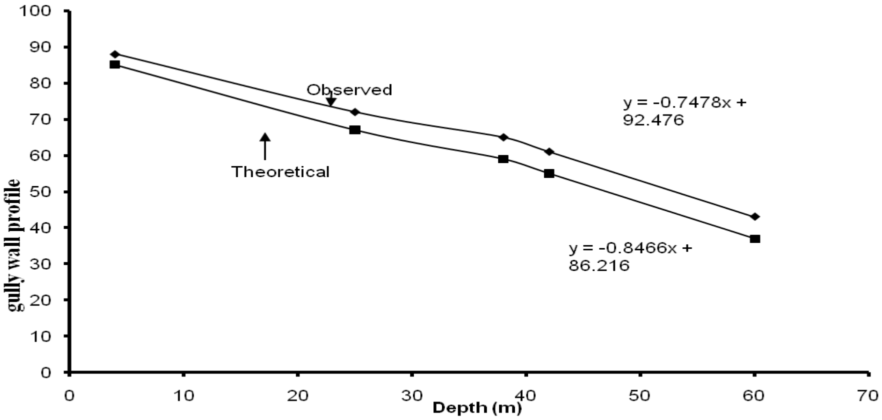

Figure 13. Graph showing the observed and predicted gully wall profile of Nanka site.

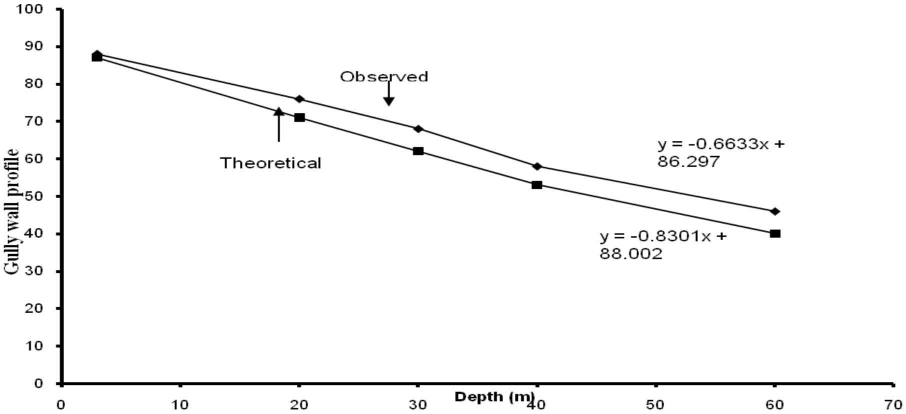

Figure 14. Graph showing the observed and predicted gully wall profile of Agulu gully site.

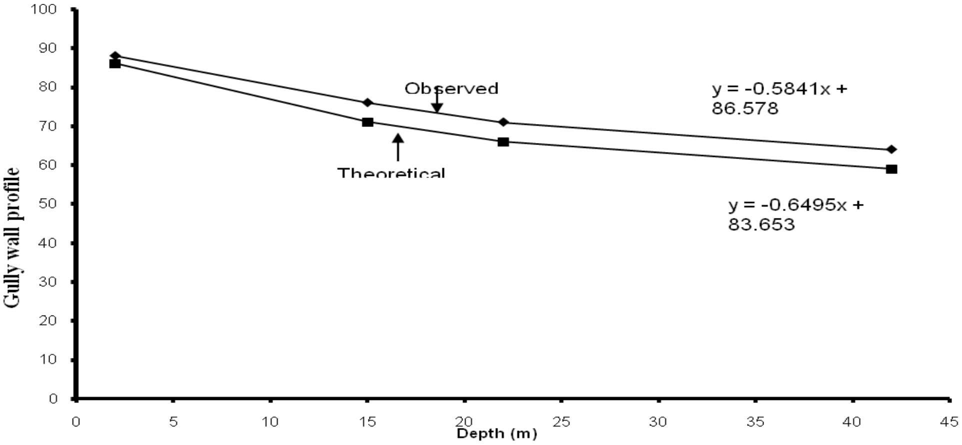

Figure 15. Graph showing the observed and predicted gully wall profile of Oraukwu gully site.

empirical model using the geotechnical properties of the soil.

2. The bottom layer of the observed gully wall profile is steeper than the predicted gully wall profile.

3. Coefficient of determination and coefficient of correlation indicate that the model described the gully wall profile in Agulu, Nanka, Oko and Oraukwu gully sites.

4. The model validation test indicates that the model predictions responded closely to field data, thus provided an effective tool for predicting gully wall profile.

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