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Structural stability of exposed gully wall in Central Eastern Nigeria as affected by soil properties

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A b s t r a c t. We studied the soil stability of a gully wall in a gully erosion prone area of Central Eastern Nigeria. The objective was to investigate the physico-chemical properties of the gully wall soils and to relate them to the collapsing and stability of the gullies. Ten soil layers were sampled for analysis. The bulk density was high while the saturated hydraulic conductivity (*Ks*) was moderately high resulting in rapid permeability for the soil layers. The liquid limits (LL) and plastic limits (PL) were low. The water-stable aggregates (WSA) were mostly aggregates of <0.50 mm. Such soils with fine aggregate sizes erode more than those with bigger aggregate sizes. Mean-weight diameter (MWD) positively correlated significantly with plasticity index but negatively correlated with soil organic matter. Soil properties that related well with the dispersion indices were water-dispersible clay (WDC), moisture at field capacity (FC), permanent wilting point (PWP), available water capacity (AWC), LL and plastic index (PI). The PI, K^+, and Ca^{2+} were the properties which increased aggregation while soil organic matter (SOM) which was low in the soil played little or no role in the aggregation of the studied soils.

K e y w o r d s: gully wall, soil properties, aggregate stability, slumping, permeability, moisture content

INTRODUCTION

Gully erosion is very common in the landscape of Central Eastern Nigeria and often becomes a constraint in agricultural and other infrastructural land use. A lot of studies have been conducted on the causes of these catastrophic gullies (Ofomata 1975; Obi and Asiegbu 1980; Ofomata 1985; Akamigbo and Igwe, 1990). The reasons attributed to the gully development include high rainfall intensity and distribution, deforestation, and the nature of the soils. Until recently, previous works on the erosion problem centered on the erosivity of rainfall and vegetation cover index (Obi and Salako, 1995). Studies on soil erodibility, however, have been done on the area but mainly on the prediction of the severity and erodibility potential (Igwe *et al*., 1995; Igwe, 1999; Igwe, 2000).

Rienks *et al*. (2000) observed that there are relationships between soils found on gully walls in South Africa and the physico-chemical properties of the soils. They showed that variation in sodium adsorption ratio (SAR) levels of gully walls might contribute to the slaking processes of the soil and to the eventual slumping of the soils. Yaalon (1987) suggested that sodicity might not be important in gully formation but the abrupt change in structure and texture typical of duplex soils may accelerate gullying. During high intensity rainstorms, a strong lateral flux over the less permeable B-horizon could develop, followed by convergence of drainage lines into percolines, thus causing piping. According to Rienks *et al*. (2000), collapse of the soil pipes and breaching of the B-horizon will eventually result in deep gully formation.

Apart from wrong land use, deforestation and very high rainfall, it is postulated that the erodibility component of soil erosion prone areas is not properly studied, as most of the gullies are observed on soils of similar characteristics and origin (Akamigbo and Igwe 1990). The objectives of the present study are (i) to characterize the soils of an exposed gully wall in Central Eastern Nigeria for their physico-chemical properties, (ii) to investigate the structural stability of soil layers of the gully wall, and (iii) to relate the soil properties to the structural stability of the gully wall with regards to slumping.

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MATERIALS AND METHODS

Field study

The erosion gully sampled for this study is located within the popular and famous Agulu/Nanka gully complex in Anambra state of Nigeria. It is situated between longitudes 6°52' and 7°30' E; latitudes 5°55' and 6°42' N (Fig. 1). The gully is popular among environmental scientists in Nigeria (Ofomata, 1975; Obi and Asiegbu, 1980; Ofomata, 1985). The gully complex chosen for the study was cleaned by scraping the weathered faces off, so that the inner part of the soil materials was exposed. These gullies have existed for more than 30 years and have become a regular feature of the landscape architecture of the area. The vegetation is derived savanna while the geological materials are weathered sandstone formations. The rainfall is 1700 mm per annum with annual average temperature of between 25 and 30°C. The difference between the average winter and average summer temperature is below 5°C.

Soil samples used for the study were collected from the sedimentary layers of the exposed gully wall at the Agulu/Nanka gully site. They were collected from 0-0.3, 0.3-0.9, 0.9-1.8, 1.8-2.5, 2.5-3, 3-3.8, 3.8-4, 4-4.5, 4.5-5 m and more than 5 m. On the whole, 10 samples were collected from the gully complex, representing different sedimentary layering. Soil samples were air-dried and sieved through a 2 mm sieve, while undisturbed samples were also collected for hydraulic conductivity, bulk density and water-stable aggregates (WSA) measurements. The soil analysis was carried out using the procedures described below.

Laboratory analysis

Particle size distribution of the less than 2 mm fine earth fractions was measured by the hydrometer method as described by Gee and Bauder (1986). The clay obtained from particle size analysis with chemical dispersant is regarded as total clay (TC), while clay and silt obtained after particle size analysis using deionized water only are the

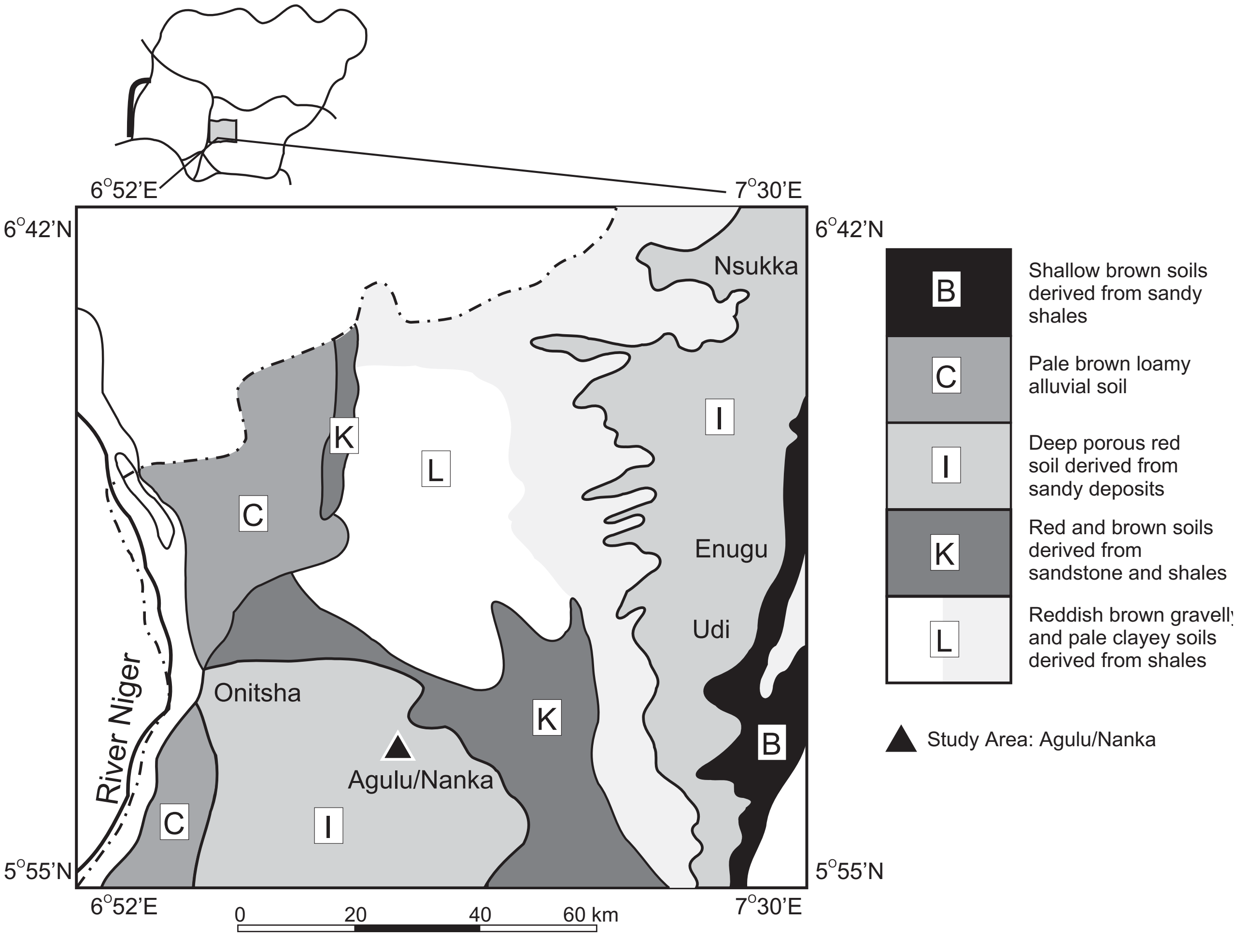

Fig. 1. Soil map of the study location showing sampling point.

water-dispersible clay (WDC). Soil pH was measured in a 1:2.5 soil/0.1 M KCl suspensions. The soil organic carbon was determined by the Walkley and Black method described by Nelson and Sommers (1982). Exchangeable cations were determined by the method of Thomas (1982). Electrical conductivity (Ec) was measured by means of a conductimeter. Exchangeable sodium percentage (ESP) was calculated using the following equation:

$$\text{ESP} = (\text{Exchangeable Na}^{+} / \text{CEC}) \times 100. \quad (1)$$

The microaggregate stability indices were calculated as follows:

$$\text{Dispersion ratio (DR)} = [(\%\text{WDSi} + \%\text{WDC}) / (\%\text{TSilt} + \%\text{TC})], \quad (2)$$

$$\text{Clay dispersion ratio (CDR)} = \%\text{WDC} / \%\text{TC}, \quad (3)$$

$$\text{Aggregated silt + clay (ASC)} = [\%\text{TC} + \%\text{Tsilt}] - [\%\text{WDC} + \%\text{WDSi}]. \quad (4)$$

In the equations above, WDSi and WDC are the silt and clay, respectively, obtained by water dispersion alone without a chemical dispersant. The higher the CDR and DR the stronger the ability of the soil to disperse, while the higher the ASC the better aggregated the soil. The soil saturated hydraulic conductivity (*Ks*) was measured using the Klute and Dirksen method (1986). Soil bulk density was determined by the core method (Blake and Hartge, 1986). The soil moisture contents at different retention levels were obtained by the Klute (1986) method, while the available water capacity (AWC) was calculated as the difference between moisture retention at 0.1 and 1.5 MPa *ie* field capacity (FC) and permanent wilting point (PWP), respectively. Permeability was derived using the system adopted by O'Neal (1952). Atterberg limits were determined by the Sowers method. The slaking index (SI) was calculated by the De Boodt method (1967):

$$\text{LL} / \text{FC}, \quad (5)$$

where: LL – liquid limits and FC – moisture content at field capacity (0.1 MPa).

The method of Kemper and Rosenau (1986) was used to separate the water-stable aggregates (WSA). In this method 40 g of <4.75 mm air-dried soils were put in the topmost of a nest of four sieves of 2, 1, 0.5, and 0.25 mm mesh size and pre-soaked for 30 min in deionized water. Thereafter, the nest of sieves and its contents were oscillated vertically in water 20 times, using 4 cm amplitude, at the rate of one oscillation per second. After wet-sieving, the resistant soil materials on each sieve and the unstable (<0.25 mm) aggregates were quantitatively transferred into beakers, then dried in the oven until steady weight was achieved. The percentage ratio of the aggregates in each sieve without sand particles represents the water-stable aggregates (WSA) of size classes; <2, 2-1, 1-0.5, 0.5-0.25 and <0.25 mm. Aggregate stability was calculated as the mean-weight diameter (MWD) of stable aggregates (Kemper and Rosenau, 1986):

$$\text{MWD} = \sum X_i W_i, \quad (6)$$

where: X_i is the mean diameter of the *i*th sieve size and W_i is the proportion of the total aggregates in the *I*th fraction. The higher the MWD values, the higher proportion of macroaggregates in the sample and therefore better stability.

Data analysis was performed by correlation analysis of aggregate stability indices and soil properties using the SPSS.10 on Windows computer package. The significant levels of relationships are shown on a matrix.

RESULTS AND DISCUSSION

Soil characteristics

The physical properties of the soil layers are presented in Table 1. The soils are Haplic Acrisol (FAO/UNESCO 1988). They were mainly sandy loam to sandy clay loam with sand dominating the particle sizes. Silt content was very low while the clay content of the materials ranged from 15 to 20%. The soil matrix colour as recorded with Munsell colour chart indicates that these soil materials from gully face were reddish brown to dusky red. The Hue colours were mainly 7.5 R, 2.5 YR and 10 R indicating the intensity of the reddish colour of the soil materials (Table 1). Table 2 shows the values of the chemical properties of the soil. The soil pH was acidic in reaction while the soils were low in soil organic matter content, exchangeable cations (Na^{+}, K^{+}, $Ca^{2+}$and Mg^{2+}) and the cation exchange capacity (CEC). The values of exchangeable sodium percentage (ESP) for the soil materials were between 2 and 19 % while the electrical conductivity Ec was from 10 to 67 μS m^{-1} (Table 2).

Atterberg limits, bulk density, saturated hydraulic conductivity and moisture content

The liquid limits were from 6.97 to 13.4% with a coefficient of variation (CV) of 21%. The plasticity limits (PL) were between 3.2 and 6.2 and 17% CV. Also the plasticity index (PI) ranged from 1.52 to 9.03 and 50% coefficient of variation (Table 3). Some researchers (Bell and Maud, 1994; Rienks *et al.*, 2000) have argued that the Atterberg limits do not provide means of identifying potentially dispersive soils, but they observed that the higher the values of PL, LL and PI, the higher is the resistance to disperse. In the soil materials studied these indices gave very low values, hence explaining their contributions towards the weakness of these gullies and frequent slumping and sliding of the gully surfaces. Low PL and LL in these soils made the soil to be loose, non-coherent and to slide upon getting in contact with water or even to disintegrate under dry conditions. This

T a b l e 1. Some physical characteristics of the gully wall layers

Sample depth (m)	Particle size distribution (%)			TC	Munsell colour (moist)
	Clay <0.002 mm	Silt 0.2-0.002 mm	Sand 2.0-0.2 mm		
0-0.3	15	1	84	SL	7.5R 3/6 Reddish brown
0.3-0.9	20	1	79	SCL	7.5R 3/6 Reddish brown
0.9-1.8	20	1	79	SCL	7.5R 3/6 Reddish brown
1.8-2.5	18	1	81	SL	7.5R 3/6 Reddish brown
2.5-3	18	1	81	SL	7.5R 3/6 Reddish brown
3-3.8	18	1	81	SL	7.5R 3/6 Reddish brown
3.8-4	20	1	79	SCL	2.5 YR 3/6 Dark red
4-4.5	20	1	79	SCL	7.5R 3/4 Reddish brown
4.5-5	20	1	79	SCL	10 R 3/4 Dusky red
More than 5	17	1	82	SL	7.5 R 4/6 Reddish brown
Mean	18.60	1	80.40		
CV (%)	9	-	2		

SL – sandy loam, SCL – sandy clay loam, TC – textural class, CV – coefficient of variation.

T a b l e 2. Some chemical characteristics of the gully wall layers

Sample depth (m)	pH_{H_2O}	SOM (g kg^{-1})	Na^+	K^+	Ca^{2+}	Mg^{2+}	CEC	ESP (%)	Ec μS m^{-1}
			cmol$_c$ kg^{-1}						
0-0.3	5.1	4.81	0.09	0.02	1.2	1.6	3.0	3.0	20
0.3-0.9	5.0	3.44	0.09	0.01	0.8	0.8	1.9	5.0	13
0.9-1.8	5.1	1.37	0.08	0.01	1.2	1.4	2.8	4.0	10
1.8-2.5	5.0	1.37	0.08	0.02	0.8	1.4	2.5	3.2	67
2.5-3	5.1	0.70	0.08	0.01	1.0	1.8	2.7	3.0	11
3-3.8	5.2	1.44	0.09	0.02	0.8	1.8	1.9	19.0	20
3.8-4	5.1	1.37	0.09	0.02	0.8	1.2	1.5	6.0	16
4-4.5	5.2	0.70	0.10	0.03	1.6	1.8	1.6	6.3	26
4.5-5	5.2	0.60	0.11	0.03	1.0	2.2	4.0	11.0	23
More than 5	5.5	0.14	0.09	0.04	1.4	2.0	4.5	2.0	27
Mean	5.2	1.79	0.09	0.02	1.06	1.60	2.64	6.25	23.30
CV (%)	3	86	10	47	27	26	38	83	71

is also a function of the particle size distribution. Soils with high clay contents may have higher values of Atterberg limits. In our study the values of clay and silt were low, thus conferring on the soils the low Atterberg limits recorded for the soils.

The soil bulk density values were between 1.4 and 1.6 Mg m^{-3} with 5% CV. These values are within the range obtained for similar soils (Obi and Asiegbu, 1980; Igwe *et al*., 1995; Igwe 2001). Igwe (2001) attributed the medium to higher bulk density to soil compaction and soil structural degradation. Again the alternate increases of the bulk density within the gully depth with the associated compaction may lead to overburdening of the soil materials on the top which may slide upon horizontal pressure. The high bulk density was reflected in the saturated hydraulic conductivity which was between 8.4 and 16.2 cm h^{-1} (Table 3). The permeability ratings according to O'Neal (1952) indicated that all the layers were rapid except for the lowest layer (more than 5 m) that was moderately rapid. This shows the loose and porous nature of these soils, which explains the ease of collapse of the soils with water saturation. Actually, when the bulk density is high the total porosity is also decreasing, creating problems for hydraulic transmission within the soils.

The amount of water retained by the soil at field capacity and the permanent wilting point were very low, reflecting also on the available water capacity (Table 4). The indirect effect of the low water content results in localized aridity which also affects the vegetation status of the area. At 0.1 MPa, the topsoil can only hold 8.73% moisture, while 1% was retained at 1.5 MPa. The reason for this can be linked to the low clay and organic matter contents of these soils. This situation cannot support favourable biological activities aimed at conserving the soil and the gully environment.

T a b l e 3. Atterberg limits, bulk density, saturated hydraulic conductivity and permeability determined for the soils

Sample depth (m)	LL	PL	PI	BD (Mg m^{-3})	*Ks* (cm h^{-1})	Permeability class
	(%)					
0-0.3	6.97	5.45	1.52	1.50	13.8	Rapid
0.3-0.9	8.38	6.20	2.18	1.60	13.2	Rapid
0.9-1.8	9.04	4.75	4.44	1.40	13.8	Rapid
1.8-2.5	7.96	4.60	3.36	1.60	13.2	Rapid
2.5-3	8.16	4.38	3.80	1.50	13.2	Rapid
3-3.8	8.00	4.76	3.24	1.60	15.9	Rapid
3.8-4	8.91	5.30	3.61	1.50	12.6	Rapid
4-4.5	7.66	3.32	4.34	1.50	16.2	Rapid
4.5-5	13.40	4.37	9.03	1.40	14.4	Rapid
More than 5	10.47	5.86	4.61	1.60	8.4	Mod. rapid
Mean	8.90	4.90	4.01	1.52	13.47	
CV (%)	21	17	50	5	16	

T a b l e 4. Volumetric moisture content, and clay dispersible indices determined for the soils

Sample depth (m)	FC	PWP	AWC	WDC	DR	CDR	SI	ASC
	(%)							
0-0.3	8.73	1.00	7.73	9	0.51	0.44	0.80	10.72
0.3-0.9	4.90	0.56	4.34	5	0.59	0.25	1.71	8.71
0.9-1.8	8.52	0.87	7.65	7	0.57	0.32	1.06	9.26
1.8-2.5	6.88	0.42	6.46	5	0.51	0.25	1.16	10.73
2.5-3	7.60	0.27	7.33	5	0.46	0.27	1.07	10.70
3-3.8	6.55	0.24	6.31	5	0.46	0.27	1.22	10.71
3.8-4	6.70	0.14	6.56	5	0.56	0.27	1.33	8.73
4-4.5	9.03	1.20	7.83	7	0.42	0.34	0.85	12.72
4.5-5	6.44	0.31	6.13	5	0.51	0.25	2.08	10.72
More than 5	6.71	0.14	6.57	5	0.46	0.27	1.56	10.72
Mean	7.21	0.52	6.69	5.8	0.51	0.29	1.28	10.37
CV (%)	18	74	16	24	11	20	31	12

Soil dispersion indices

The water-dispersible clay (WDC) was low in the soil (5 to 9%), reflecting the total clay content (Table 4). The dispersion ratio (DR) and the clay-dispersion ratio (CDR) are also presented in Table 4. The DR ranged from 0.42 to 0.59 while the values of CDR were between 0.25 and 0.44. Igwe (2003) indicated that soils with relatively higher DR and very high DR have the potential to erode more easily than those with lower DR. In this study, all the layers have DR index of 0.42 or more. In the CDR index the values were relatively lower, perhaps because of the low clay content of the soil. This index, although it is a good index for predicting erodibility as suggested by Bajracharya *et al*. (1992), may not be used for these soils due to the reason already given. The slaking index (SI) was high, ranging from 0.80 to 2.08 (Table 4). The disparity in the SI values within the depth of the gully indicate a high slaking rate at some point of the gully depth. This may lead to slumping of weakened gully walls when saturated with water.

The aggregated silt + clay (ASC) indicate that the values range from 8.71 to 12.72 with a CV of 12% (Table 4). Higher ASC implies greater stability of aggregates, therefore the abrupt decrease of ASC in alternate fashion within the gully depth may result in weaker carrying base of the soils. This weaker base may give way under pressure resulting in slumping of gully wall.

Water-stable aggregates and mean-weight diameter

Table 5 presents the water-stable aggregates (WSA) for the different soil layers. WSA sizes >2 mm were between 0.28 and 3.48% while WSA sizes of 2-1 mm were from 6.7 to 10.72 %. In the WSA sizes between 1-0.5 mm, the values ranged from 23.6 to 29.68% with 7% CV. The values for the

WSA sizes between 0.5 and 0.25 mm were 26 to 31.8% while the WSA < 0.25 mm gave the highest values of between 29.96 and 43.3% (Table 5). The WSA <0.25 mm aggregates accounted in all cases for more than 25% of the soil structure. This is very undesirable as the aggregates are very unstable at this aggregate size.

The mean-weight diameter (MWD) of the soil layers was very low (Table 5). The calculated values of the MWD were from 0.45 to 0.59 mm. This is a reflection of the values of WSA sizes which were more in the <0.5 mm sizes. Igwe *et al*. (1999); Zobeck *et al*. (2003) and Igwe (2003) observed that soils with low MWD have the potential to erode faster than those of higher MWD. Soils with good structure and high MWD resist aggregate breakdown during rainstorms. The low MWD values of the soils were attributed to low clay and organic matter contents resulting in the weak aggregation of the soils.

Relationships between soil dispersion/ aggregating indices and soil properties

The interrelationships between the dispersion and aggregate stability indices and the soil properties are presented in Table 6. The dispersion indices in this study were assumed to be DR, SI, CDR and WSA< 0.25 mm. On the other hand, the aggregate stability indices are the WSA sizes >2, 2-1, 1-0.5 and 0.5-0.25 mm. The DR positively and significantly correlated with PL (r = 0.58), while it negatively, and significantly, correlated with K^+ and Mg^{2+}. This result confirmed our earlier statement on PL which could be used to predict dispersion. The K^+ and Mg^{2+} were low in the soil layers and showed that the low contents of these elements encourages dispersion and hence slumping of existing gullies. The soil properties that correlated negatively with the slaking index (SI) are WDC, FC, PWP and AWC, while LL and PI correlated positively with SI. WDC index has been shown to affect erodibility of soils positively (Igwe, 2003), while Zhang and Horn (2001) observed that clay contents of soils determine to a large extent the aggregate stability. Also CDR positively correlated with WDC, FC, PWP and AWC, thus confirming the significant role played by clay content in the aggregation of soils. The role of water content in the dispersion of these soils may be seen from the point of dispersion when moisture is higher than normal for these soils. This is because such a situation may lead to dispersion and dissolution in runoff. The soil organic matter correlated positively with WSA class <0.25 mm. Goldberg *et al.* (1990) indicated that SOM can act as an aggregating or disaggregating agent or have no noticeable influence on aggregate stability depending on its composition in the soil and/ or the relative contribution of other aggregating agents.

Water-stable aggregates (WSA) >2 mm significantly correlated positively with LL and PI (r = 0.58, 0.71), respectively (Table 6). WSA sizes between 0.5-0.25 mm positively correlated significantly with K^+ and Ca^{2+} just as ASC also correlated positively with Ca^{2+} and Mg^{2+}. However, WSA sizes of 0.5-0.25 mm negatively correlated significantly with SOM. The significant contributions of exchangeable Ca^{2+} and Mg^{2+} to the stability of tropical soils have been shown (Boix-Fayos *et al*., 2001; Igwe, 2004). Also low SOM content of these soils plays a negative role in their stability. These soil layers are low in exchangeable base cations and SOM, and hence the weak cohesion among the soil aggregates leading to collapse of soil structure and extensive gully formation. SOM is negatively correlated significantly with MWD. The MWD, which is often used to predict the erodibility and soil aggregate stability (Elwell, 1986; Diaz-Zorita *et al*., 2002; Igwe, 2003), shows in this study that the low values may be attributed to low SOM and low polyvalent cations. This is not desirable for the stability of the soil structure and of the gully walls. There was a significant positive correlation coefficient between MWD and PL (r = 0.71). Rienks *et al*., (2000) observed that Atterberg

T a b l e 5. Water-stable aggregate (WSA) content and mean-weight diameter of aggregates (MWD) for the sampled soil materials

Sample depth (m)	WSA (%) (dia in mm)					MWD (mm)
	>2	2-1	1-0.5	0.5-0.25	<0.25	
0-0.3	0.4	6.70	23.60	26.00	43.30	0.45
0.3-0.9	0.28	7.40	25.8	26.44	40.50	0.46
0.9-1.8	2.12	10.72	25.56	26.92	34.68	0.57
1.8-2.5	3.0	9.20	26.48	27.64	33.68	0.58
2.5-3	0.76	9.80	26.52	28.52	34.40	0.53
3-3.8	0.44	8.80	28.48	26.96	35.32	0.51
3.8-4	0.32	7.52	25.88	27.00	34.28	0.47
4-4.5	1.12	7.72	27.52	30.44	33.20	0.52
4.5-5	3.48	9.20	25.28	27.72	34.32	0.59
More than 5	0.80	7.76	29.68	31.80	29.96	0.52
Mean	1.27	8.48	26.56	27.94	35.36	0.52
CV (%)	92	15	7	7	11	10

T a b l e 6. Correlation coefficient matrix between soil aggregate stability indices and soil properties

	DR	SI	CDR	ASC	WSA1	WSA2	WSA3	WSA4	WSA5	MWD
WDC	-0.03	-0.65*	0.98*	0.26	-0.14	-0.26	-0.52	-0.21	0.55*	-0.29
Clay	0.33	0.39	-0.53	-0.26	0.28	0.33	0.03	-0.02	-0.31	0.30
LL	0.09	0.84*	-0.47	-0.08	0.58*	0.26	0.08	0.23	-0.42	0.53
PL	0.58*	0.34	-0.08	-0.71*	-0.43	-0.42	-0.06	-0.25	0.37	-0.55
PI	-0.15	0.62*	-0.40	0.21	0.71*	0.42	0.09	0.31	-0.54	0.71*
BD	-0.18	-0.02	-0.27	0.02	-0.43	-0.42	0.54	0.18	-0.01	-0.37
Ks	-0.14	-0.30	0.22	0.31	0.12	0.15	-0.31	-0.43	0.32	0.08
SOM	0.31	-0.26	0.50	-0.24	-0.46	-0.44	-0.45	-0.72*	0.90*	-0.64*
Na^+	-0.21	0.51	0.01	0.34	0.22	-0.34	-0.03	0.18	-0.03	0.05
K^+	-0.55*	0.26	-0.01	0.54	0.17	-0.35	0.51	0.72*	-0.52	0.16
Ca^{2+}	-0.53	-0.34	0.53	0.63*	-0.03	-0.14	0.23	0.68*	-0.26	0.06
Mg^{2+}	-0.71*	0.11	0.05	0.70*	0.34	0.21	0.34	0.54	-0.47	0.48
CEC	-0.14	0.43	-0.03	0.13	0.40	0.16	0.11	0.39	-0.26	0.41
ESP	-0.20	0.24	-0.24	0.11	0.01	0.11	0.23	-0.23	-0.03	0.08
Ec	-0.20	-0.05	-0.19	0.34	0.52	0.02	0.16	0.17	-0.27	0.42
FC	-0.41	-0.79*	0.78*	0.54	0.05	0.12	-0.19	0.16	-0.01	0.11
PWP	-0.06	-0.58*	0.75*	0.37	0.01	-0.15	-0.40	-0.09	0.42	-0.12
AWC	-0.47	-0.74*	0.65*	0.52	0.05	0.20	-0.09	0.23	-0.16	0.17

*Significant $p<0.05$; WSA1 – water stable aggregates >2 mm; WSA2 – water stable aggregates 2-1 mm; WSA3 – water stable aggregates 1-0.5 mm; WSA4 – water stable aggregates 0.5-0.25 mm; WSA5 – water stable aggregates <0.25 mm.

limits have a direct relationship with clay contents and often affect the cohesiveness of the soils. In this study, the significant contribution of PI to MWD is noted, but the problem was that both the clay content, the PL and LL were low, hence diminishing the presupposed contribution of PI.

CONCLUSIONS

1. The soils were mainly sandy loam to sandy clay loam with coarse sand dominating the other fractions. The soil matrix colours were mainly reddish brown to dusky red with low SOM content.

2. The soils have low LL, PL and PI. This property may have affected the soil strength, causing it to be weak and to slump under pressure. In addition, soil bulk density was high, affecting the soil saturated hydraulic conductivity and causing a reduction in the total porosity. This may cause heavier overlying soils to slide or slump upon wetting.

3. The water-stable aggregate sizes were more on the <0.5 mm sizes. Aggregates within this range are very weak and can slake easily when submerged or under runoff.

4. The soil properties that correlated significantly with dispersion or slaking indices were WDC, FC, PWP, AWC, LL and PI. The WSA, however, were significantly correlated with PI, K^+ and Ca^{2+}. The low SOM content did not seem to exert enough influence on the soils, hence the frequent collapse and slumping of the soils.

5. The low nutrient cations, low WDC and quick release of moisture in the soil make the soil weak, non-coherent and thus leading to slumping and to the development of gullies.

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REFERENCES

Akamigbo F.O.R. and Igwe C.A., 1990. Physical and chemical characteristics of four gullied soils locations in Anambra State, Nigeria. Niger. Agric. J., 25, 29-48.

Bajracharya R.M., Elliot W.J., and Lal R., 1992. Interrill erodibility of some Ohio soils based on field rainfall simulation. Soil Sci. Soc. Am. J., 56, 267-272.

Bell F.G. and Maud R.R., 1994. Dispersive soils: a review from South African perspective. Quaterly J. Eng. Geology, 27, 195-210.

Blake G.R. and Hartge K.H., 1986. Bulk density. In: Methods of Soil Analysis, Part 1 (Ed. A. Klute). Am. Soc. Agron., 363-382, Madison, WI.

Boix-Fayos C., Calvo-Cases A., Imeson A.C., and Soriano-Soto M.D., 2001. Influence of soil properties on the aggregation of some Mediterranean soils and the use of aggregate sizes and stability as land degradation indicators. Catena, 44, 47-67.

De Boodt M., 1967. West European Methods for Soil Structutre Determinations. Int. Soc. Soil Sci. Com. I, West European Group, Part VI, 17-18, 36-38.

Diaz-Zorita M., Grove J.H., and Perfect E., 2002. Aggregation, Fragmentation, and Structural Stability Measurement. Encyclopedia of Soil Sci., Marcel Dekker Publ., 37-40.

Elwell H.A., 1986. Determination of erodibility of a subtropical soil clay soil: a laboratory rainfall simulator experiment. J. Soil Sci., 37, 345-350.

FAO-UNESCO, **1988**. Soil map of the world (1:5000000), Revised Legend. Food and Agriculture Organization, Rome.

Gee G.W. and Bauder J.W., 1986. Particle-size analysis. In: Methods of Soil Analysis, Part 1 (Ed. A. Klute). Am. Soc Agron., 9, 91-100, Madison, WI.

Goldberg S., Kapoor B.S., and Rhoades J.D., 1990. Effect of aluminium and iron oxides and organic matter on flocculation and dispersion of arid zone soils. Soil Sci., 150, 588-593.

Igwe C.A., 1999. Land use and soil conservation strategies for potentially highly erodible soils of Central Eastern Nigeria. Land Degradation & Development, 10, 425-434.

Igwe C.A., 2000. Runoff, sediment yield and erodibility characteristics of some soils of Central Eastern Nigeria under simulated rainfall. Int. Agrophysics, 14, 57-65.

Igwe C.A., 2001. Effects of land use on some structural properties of an Ultisol in SE Nigeria. Int. Agrophysics, 15, 237-241.

Igwe C.A., 2003. Erodibility of soils of the upper rainforest zone, southeastern Nigeria. Land Degradation & Development, 14, 323-334.

Igwe C.A., 2004. Soil properties influencing stability of structure of B-horizons of Ultisols in semiarid Nsukka, Eastern Nigeria. Arid Land Res. Manag., 18, 185-195.

Igwe C.A., Akamigbo F.O.R., and Mbagwu J.S.C., 1995. The use of some soil aggregate indices to assess potential soil loss in soils of southeastern Nigeria. Int. Agrophysics, 9, 95-100.

Igwe C.A., Akamigbo F.O.R., and Mbagwu J.S.C., 1999. Chemical and mineralogical properties of soils in southeastern Nigeria in relation to aggregate stability. Geoderma, 92, 111-123.

Kemper D.W. and Rosenau R.C., 1986. Aggregate stability and size distribution. In: Methods of Soil Analysis, Part 1, (Ed. A. Klute). Am. Soc. Agron., 9, 425-442, Madison, WI.

Klute A., 1986. Water retention: Laboratory methods analysis. In: Methods of Soil Analysis, Part 1, (Ed. A. Klute). Am. Soc. Agron., 9, 635-662, Madison, WI.

Klute A. and Dirksen C., 1986. Hydraulic conductivity and diffusivity. In: Methods of Soil Analysis, Part 1, (Ed. A. Klute). Am. Soc. Agron., 9, 694-783, Madison, WI.

Nelson D.W. and Sommers L.E., 1982. Total carbon, organic carbon and organic matter. In: Methods of Soil Analysis, Part 2, (Eds A.L. Page, R.H. Miller, D.R. Keeney). Am. Soc. Agron., 539-579, Madison, WI

O'Neal A.M., 1952. A key for evaluating soil permeability by means of certain field clues. Soil Sci. Soc. Amer. Proc., 16, 312-315.

Obi M.E. and Asiegbu B.O., 1980. The physical properties of some eroded soils of southeastern Nigeria. Soil Sci., 130, 39-48.

Obi M.E. and Salako F.K., 1995. Rainfall parameters influencing erosivity in southeastern Nigeria. Catena, 24, 275-287.

Ofomata G.E.K. 1975. Soil erosion. In: Nigeria in Maps. Eastern States, (Ed. G.E.K. Ofomata). Ethiope Publ. House, Benin, Nigeria, 43-45.

Ofomata G.E.K., 1985. Soil erosion in southeastern Nigeria: The view of a Geomorphologist. Inaugural lecture series, 7. Nigeria Press, University of Nigeria, Nsukka, 43.

Rienks S.M., Botha G.A., and Hughes J.C., 2000. Some physical and chemical properties of sediments exposed in a gully (donga) in Northern KwaZulu-Natal, South Africa and their relationship to the erodibility of the collovial layers. Catena, 39, 11-31.

Thomas G.W., 1982. Exchangeable cations. In: Methods of Soil Analysis, Part 2, (Eds A.L. Page, R.H. Miller, D.R. Keeney). Am. Soc. Agron., 159-165, Madison, WI.

Yaloon D.H., 1987. Is gullying associated with highly sodic colluvium? Further comments to the environmental interpretation of Southern African dongas. Palaeogeography, Palaeoclimatology, Palaeoecology, 58, 121-123.

Zhang B. and Horn R., 2001. Mechanisms of aggregate stabilization in Ultisols from subtropical China. Geoderma, 99, 123-145.

Zobeck T.M., Popham T.W., Skidmore E.L., Lamb J.A., Merrill S.D., Lindstrom M.J. Mokma D.L., and Yoder R.E., 2003. Aggregate-mean diameter and wind-erodible soil predictions using dry aggregate-size distributions. Soil Sci. Soc. Am. J., 67, 425-436.