



# Erodibility characteristics and slope stability analysis of geological units prone to erosion in Udi area, southeast Nigeria

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Received: 20 December 2019 / Accepted: 7 March 2020 / Published online: 14 March 2020  
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## Abstract

In Udi province, gully erosion has caused several environmental damages such as loss of agricultural lands and natural vegetation, loss of residential apartments, destruction of engineering structures, and disruption of wildlife ecosystem. In this paper, an attempt was made to assess the erodibility characteristics and slope stability of geological units prone to erosion in this area using integrated approach. Geotechnical analysis of soil samples revealed that they are susceptible to erosional processes. The soil samples were classified as poorly graded sands and silty sands based on Unified Soil Classification System. Grain size distribution analysis showed that the soils were almost devoid of clays, which could serve as binding materials. Atterberg limit test revealed that they were nonplastic. Compaction test indicated that the soils were loose and collapsible, with dry density ranging from 1.65 to 1.96 g/cm<sup>3</sup>. On the basis of permeability coefficients (which ranged from  $6.81 \times 10^{-5}$  to  $1.28 \times 10^{-4}$  m/s), the soils are moderately to highly permeable, indicating high infiltration capacity. Shear strength analysis revealed that the soils have low cohesive capacity (ranging from 0 to 5 kPa) and relatively low angle of shearing resistance (ranging from 22° to 30°). Multivariate statistical analyses aided the establishment of the interrelationships between the analyzed geotechnical parameters. The obtained factor of safety of the gully slopes (in both saturated and unsaturated conditions) ranged from 0.81 to 0.90 and 1.02 to 1.41, respectively. This indicates that the gully slopes are typically unstable in saturated conditions and critically stable in unsaturated conditions.

**Keywords** Erodibility characteristics · Gully · Slope stability analysis · Soil erosion · Statistical analysis · Udi province

## Introduction

Land degradation, as a result of soil erosion, is one of the major geologic hazards threatening many lives and properties in different parts of Nigeria (Igwe and Egbueri 2018; Egbueri and Igwe 2020). The most critical part of this menace is the formation of rills and gullies. Gullying has caused several environmental damages in this region. Such environmental problems caused by gullying in Udi include loss of agricultural lands and natural vegetation, loss of residential apartments, destruction of engineering structures like roads and drainage channels, and disruption of wildlife ecosystem (Figs. 1 and 2). Being geomorphic processes, rill and gully

erosions play a critical role in the continuous modification and reshaping of the topographical configurations of the study region. This has given the topography of the study region an undulating appearance.

Water erosion occurs when the shear stress of overland flowing water becomes greater than the shear strength of the soil material over which it flows (Horton 1945). By this definition, the shear stress represents the ability of the flowing water to entrain and detach soil materials, while the shear strength represents the properties of the soil enabling it to resist the shear stress of flowing water. However, numerous other factors play significant roles in the initiation, development, and expansion of erosion gullies. Such factors that influence gully erosion and gully slope movements include geological, meteorological, hydrogeological, geotechnical, topographical, geometrical, geochemical, biological, and anthropogenic factors (McCarthy 2007; Nwajide 2013; Emeh and Igwe 2017; Igwe 2018; Igwe and Egbueri 2018; Igwe and Una 2019; Egbueri and Igwe 2020). Among the listed factors, the geological, meteorological, geotechnical,

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**Fig. 1 a, b** Developing gully channels destroying and threatening engineering structures in Udi province



**Fig. 2** Engineering structures destroyed by gully erosion in Udi province



and anthropogenic components play the most important roles in the initiation, development, and expansion of gullies.

According to Igwe and Egbueri (2018), gullying processes are usually accompanied by landslides. By the sliding of gully walls and slopes, many gullies become massively expanded. This facilitates the activities of gully erosion in destroying numerous properties worth millions of dollars. As noted by Igwe (2015), climatic conditions, such as high precipitation, have particularly favored the prevalence of landslides in the tropics. Rainfall infiltration has been identified to reduce the shear strength of soils at slip surfaces, because of the incremental soil weight and positive pore-water pressure. In such scenario, many gully slopes are triggered and bound to fail. In order to determine the vulnerability of gully slopes to fail, different slope stability analytical criteria are employed. However, one of the most commonly used criteria

is the Morgenstern–Price liquid equilibrium method (Igwe and Chukwu 2018a, b; Igwe and Una 2019). Generally, the major goal of all slope stability analyses is the determination of factor of safety (FoS). The FoS is a vulnerability index used in predicting how far a slope is from failure (Liu et al. 2001; Moudabel 2013).

Although there have been numerous research works on gully erosion and landsliding in southeast Nigeria (Emeh and Igwe 2017; Igwe 2018; Igwe and Egbueri 2018; Igwe and Una 2019; Egbueri and Igwe 2020), little to none is known about the erosional processes in Udi province. Therefore, it became necessary that the gullies in this area be studied to obtain a firsthand scientific information regarding their influencing factors, with special emphasis on erodibility characteristics and gully slope stability. The specific objectives of this study are to (1) determine the gully distribution in the

study area; (2) determine the geotechnical properties of the gully materials; (3) investigate the interrelationships of the measured soil geotechnical parameters using multivariate statistical analyses; (4) develop deterministic gully slope failure models based on the geomechanical properties; and (5) produce a factor of safety map for erosion and landslide risk ranking in the study area. It is hoped that this study will provide an understanding of the mechanics of gully slope initiation and instability in the Udi province. Moreover, the information provided by this study would be very useful for mitigation plans by concerned citizens and policymakers.

## The study area description

### Location, climate, and vegetation

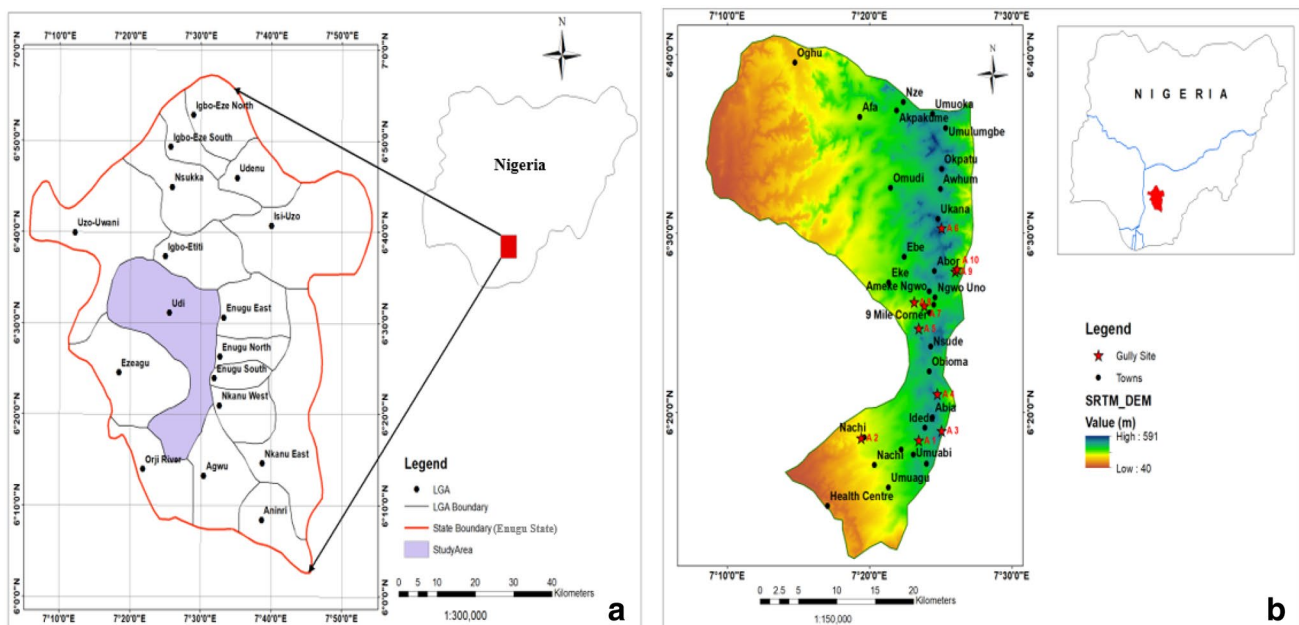
Udi province is a fast developing and thickly populated (with estimated population of over 400,000 people) suburb within Enugu State, southeastern Nigeria. Due to the rapid population growth, the erosion menace is seen as a very critical threat to the urbanization and development of this area. The study area, covering about 897 km<sup>2</sup>, is located within latitudes 6°15' to 6°40'N and longitudes 7°10' to 7°30'E (Fig. 3a), with elevations varying from 221 to 485 m above the sea level. The area is bordered in the north by Nsukka; to the south by Oji River; to the east by Enugu metropolis; and to the west by Ezeagu. Seventeen communities (Nachi, Ukana, Ebe, Eke, Ngwo, Nsude, Umudim, Umana, Amokwe,

Abia, Umuaga, Obinagu, Ama, Abor, Awhum, Okpatu, and Afa) within the Udi province were covered in this study.

The research area is characterized by a tropical climate with two distinct seasons, rainy and dry seasons (Nwajide 2013; Emeh and Igwe 2017). The rainy season usually spans from April to October, while the dry season spans from November to March. The mean annual temperature varies from 22 to 32 °C. Moreover, the mean annual rainfall of the study region ranges between 1750 and 2500 mm (Igwe 2018; Igwe and Egbueri 2018; Igwe and Una 2019). The intense rainfall pattern experienced in the area is believed to facilitate the gullying processes in the region. Furthermore, the study region is characterized by altered tropical rainforest belt (Nwajide 2013; Emeh and Igwe 2017; Igwe and Egbueri 2018). This vegetation is marked by short-tall trees, shrubs, and grasses. However, due to some anthropogenic activities (such as urbanization, construction, mining, and agriculture), the rainforest is being altered such that some areas in the region are marked by bare lands and low vegetation cover.

### Topography and geological setting

Flat hilltops that are at an altitude of about 480–500 m and v-shaped valleys are present in the study area. The landscape of the area is undulating (Fig. 3b). Generally, the topography controls the dendritic pattern of the natural drainage systems in the area. Specifically, the Ekulu River is the main drainage course in the area. All the surface water networks in the area jointly facilitate ease of transportation of the eroding soils



**Fig. 3** a Location map of the study area, b topographical and gully location map of the study area

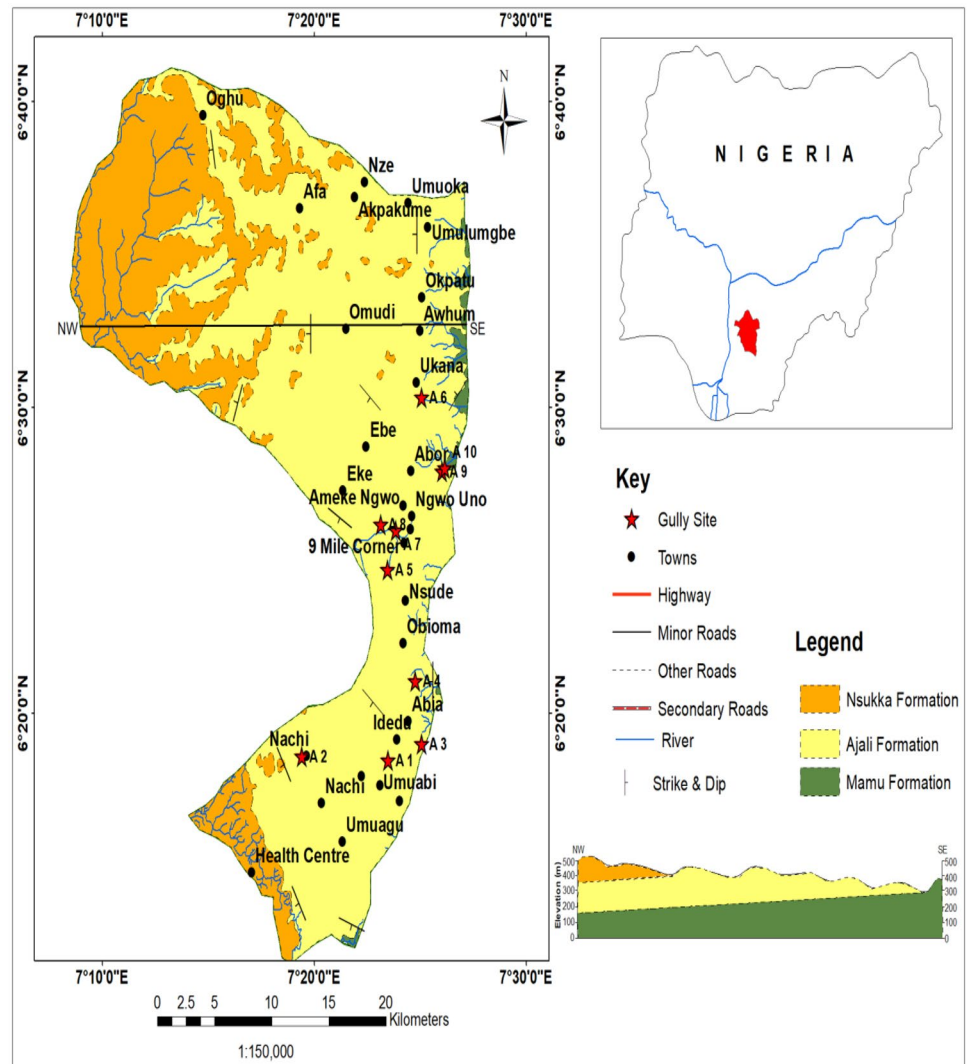
and sediments. The dominant geologic formation underlying the area under study is the Ajali Sandstone (Upper Maastrichtian) (Fig. 4) of the Anambra Basin (Table 1). The origin and structural features of the Anambra Basin have been well described by Nwajide (2013). The Ajali Sandstone is underlain by the consolidated Mamu Formation but is overlain by the Nsukka Formation (Fig. 4; Table 1).

The peculiar characteristics of the Ajali Formation include (1) the upper parts of the formation are lateritized due to weathering and ferruginization; (2) the formation is mostly comprised of moderately to poorly sorted thick sand units with very little mudstones and clays; (3) the formation is predominantly underlain by fine, medium-/coarse-grained subangular to subrounded quartzarenites; (4) the sand deposits are weakly consolidated and friable; (5) the sandstones are cross-bedded; and (6) the formation has a wide range of lithologic colors (Nwajide 2013; Emeh and Igwe 2017). These characteristics are similar to those of the eroding younger Eocene Nanka and Oligocene Ogwashi

**Table 1** Stratigraphy of the Anambra Basin (Murat 1972; Igwe and Chukwu 2018a)

Geologic age	Stratigraphic units
Eocene	Ameke Group (including Nanka Sands, Nsugbe Formation)
Paleocene	Imo Shale
Maastrichtian	Mamu Formation, <b>Ajali Sandstone</b> , Nsukka Formation
Campanian	Nkporo Group (including Nkporo Shale, Oweli Sandstone, Enugu Shale, Afikpo Sandstone, Otobi Sandstone)
Santonian	Nondeposition
Coniacian	Awgu Group (including Awgu Shale, Agbani Sandstone)
Turonian	Ezeaku Formation (including, Amasiri Sandstone)
Cenomanian	Odukpani Formation
Albian	Asu River Group
Precambrian	Basement Complex

**Fig. 4** A geologic map of the study area



Formations in the southeastern Nigeria (Igwe and Egbueri 2018; Egbueri and Igwe 2020). With the features highlighted about the geology of the study area, it becomes obvious why the sediments are vulnerable to erosion.

## Materials and methods

### Fieldwork and analysis of soil engineering properties

The fieldwork exercise involved onsite observations, identification of gully distribution and collection of soil samples. A total of 15 gully sites were identified in this study (Table 2). However, for an in-depth analysis, eight representative soil samples were collected from eight different gullies selected (on the basis of their large sizes) across the study area. The eight soil samples were collected randomly (with hand auger) from failed scarps in the eight gullies for geotechnical analysis. The samples were collected in such a way that distortion of grain properties was minimized. Additionally, the eight samples were labeled A1, A2, A3, A4, A5, A6, A7, and A8, respectively.

For erodibility characterization, the eight soil samples were tested for engineering properties such as natural moisture content (NMC), grain size distribution, Atterberg limits, specific gravity, permeability, porosity, compaction, and shear strength. These laboratory tests were carried out in accordance with the relevant American Standard of Testing Materials (ASTM) standards for soil testing. The particle size distribution analysis was done following ASTM D421

guideline. The NMC was carried out in accordance with ASTM D4959, whereas the Atterberg limits were performed with the ASTM D4318 recommendations. The compaction characteristics were determined at standard effort following the ASTM D698 guideline, while the shear strength parameters were analyzed with a direct shear box device following the procedures stated in ASTM D3080. The permeability of the soil samples was determined by falling head test. This was carried out in accordance with ASTM D5084 guideline. The specific gravity was done in accordance with ASTM D854. A laboratory manual describing in detail all these tests was also utilized during the geotechnical analysis (Kalinski 2011).

### Multivariate statistical analysis of geotechnical parameters

The obtained geotechnical parameters were subjected to both Pearson’s correlation and factor analyses, to determine their interrelationships (associations). The SPSS software (v. 22) was utilized for all the statistical analyses. Correlation coefficients ( $r$ )  $> 0.7$ ,  $0.5 < r < 0.7$ , and  $< 0.5$  were considered as strong, moderate, and weak correlations, respectively. Simply put, the larger the coefficient, the stronger the parameters’ association and vice versa. For the factor analysis, the Varimax rotation method was utilized to optimize the factor loadings at eigenvalue  $\geq 1$ . Similar to the considerations of Egbueri et al. (2019), factor loadings  $< 0.5$ ,  $0.5–0.75$ , and  $> 0.75$  were considered as low (insignificant), medium, and high, respectively.

**Table 2** The gully sites, their locations and acquired data

Gully site	Latitude (N)	Longitude (E)	Elevation (m)	Average depth (m)	Average width (m)	Average lateral extent (m)	Slope angle (°)	Soil texture
Obinagu	06°18'26"	07°23'27"	367	15	4	> 35	52	Loose laterite
Nachi (Umuike)	06°18'34"	07°19'24"	251	24	5	> 60	59	Loose laterite
Amagu Udi	06°18'58"	07°25'03"	414	24	6	> 50	55	Medium-grained sand
Abba (Obioma)	06°21'02"	07°24'45"	446	28	4	> 100	42	Fine-grained sand
Ameke (Nsude)	06°24'40"	07°25'03"	398	30	5	> 30	44	Medium-grained sand
Ukana	06°30'18"	07°25'03"	488	25	3	20	54	Fine sand
9th Mile (Ama)	06°25'18"	07°23'50"	313	28	4	35	39	Lateritic fine sand
Ajali Water Works	06°26'07"	07°28'23"	325	75	12	40	55	Fine sand
Iva Valley 1	06°27'53"	07°26'07"	330	> 80	> 15	> 150	60	Loose–medium sand
Iva Valley 2	06°28'00"	07°26'31"	310	30	> 7	> 100	58	Loose–medium-coarse sand
Nkwoida	06°29'04"	07°25'21"	380	8	3	35	40	Loose laterite
Ohum	06°31'39"	07°21'26"	370	10	4	50	40	Loose laterite
Abor (Umuavulu)	06°27'52"	07°24'33"	395	6	3	15	47	Lateritic fine sand
Akuma	06°26'28"	07°25'15"	325	5	2	40	41	Lateritic fine sand
Abia	06°20'39"	07°24'43"	392	14	3	10	47	Medium sand

## Gully slope stability analysis

Gully slope stability analysis aids in the determination of the factor of safety (FoS), which is generally defined as the ratio of available shear strength of the gully material to the shear resistance required to maintain equilibrium. Gully slope gradients were measured in the field using a Silva handheld compass-clinometer. In this study, the stability simulations were performed for eight critical gully slopes, using the Slope/W GeoStudio (v. 2012) software. The Morgenstern and Price (1965) limit equilibrium method available in the Slope/W GeoStudio software was adopted to compute the FoS for the selected gully slopes. This method was also described by Igwe and Una (2019). Geotechnical parameters such as slope angle, cohesion, internal friction angle, and unit weight were used for the stability analysis. The slope stability simulations were done for both saturated and unsaturated conditions. Arc-Map (ArcGIS) 10 and Surfer 11 softwares were used for the production of erosion vulnerability zonation based on the obtained FoS values.



**Fig. 5** A typical V-shape gully in the study area

**Table 3** Particle size distribution and soil classification of the studied gullies

Parameter	A1	A2	A3	A4	A5	A6	A7	A8	Max	Min	Mean
Gravel (%)	0.00	0.00	0.86	0.00	1.10	0.00	0.00	1.4	1.40	0.00	0.42
Sand (%)	82.7	74.8	94.8	94.1	92.2	75.5	83.9	91.6	94.2	74.8	86.2
Silt (%)	17.3	25.3	4.3	5.95	6.70	24.5	16.1	7.01	24.5	4.30	13.4
CU	3.00	1.00	2.00	3.00	3.00	1.67	2.00	2.00	3.00	1.00	2.20
CC	1.3.0	0.50	0.9	1.50	1.10	0.60	0.90	1.62	1.50	0.50	1.05
USCS	SM	SM	SP	SP	SP	SM	SM	SP	–	–	SP-SM

## Results and discussion

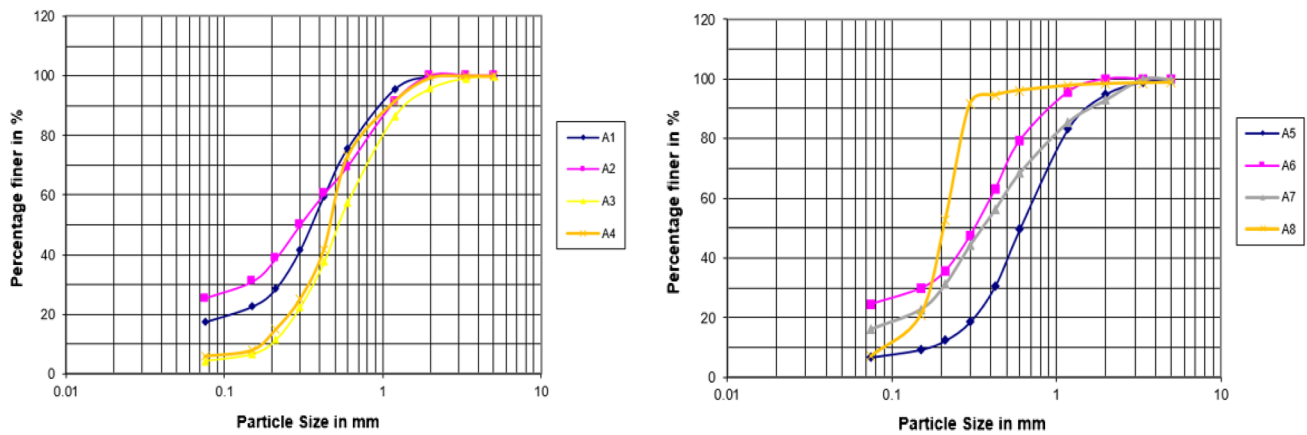
### Field observation and gully distribution

The acquired field data for the study area are summarized in Table 2. A total of 15 gully sites on the Ajali Formation were identified in this study. The gully depths, widths, and lateral extents ranged from 5 m to over 80 m, 2 m to over 15 m, and 10 m to over 100 m, respectively (Table 2). Most gully slopes were observed to be v-shaped and relatively continuous (Fig. 5). The steep v-shaped nature of the gullies relates to the inherent instability of the gullies. Horton (1945) found the optimal slope angle for erosion initiation to be approximately 40°. Based on the field measurements, slope angles of the gully slopes ranged from 40° to 60° (Table 2), indicating that they are critically vulnerable to failure. Evidences of collapsed slopes, failed drainage channels, and minor landslides were generally noted. It was observed during the fieldwork exercise that the mode of slope failure in the gullies was dominantly rotational. Based on the gross field observations, the erodibility of these soils is thought to be greatly influenced by their loose and sandy nature (Emeh and Igwe 2017; Igwe and Egbueri 2018).

### Erodibility characteristics of the soils

#### Grain size distribution analysis

The results obtained from the grain size analysis are presented in Table 3. Based on the particle size distribution, the percentage contents of gravels, sands, and silts are in the ranges of 0–14%, 74.3–94.8%, and 4.3–24.47%, respectively. The result reveals that there are high percentage of sands and low proportions of silts and gravels, and insignificant amount of clays. This observation corresponds with the observations made in the field and the work of Emeh and Igwe (2017). However, it was observed that the particle size distribution curves (Fig. 6) are of similar s-shapes for all the gully sites, confirming the predominance of sands in the gully slope materials. Traditionally, clays and silts constitute the fines content of a soil. The fines serve as natural binders that enhance the cohesion of a soil and its resistance to erosion (Igwe and Egbueri



**Fig. 6** Grain size distribution of the soils collected from failed slopes (samples A1–A8)

2018). In other words, the lower the percentages of the fines, the lower the cohesion, and the higher the erodibility of the soil and vice versa. According to a Unified Soil Classification System (USCS) presented in Arora (2008), the soils were classified into two major groups, silty sand (SM) and poorly graded sands (SP) (Table 3). Based on the results presented, the soils are adjudged to have high erodibility tendency (Igwe and Egbueri 2018), because the high amount of loose sands in the slope materials has strong implications for gully erosion occurrence. It is also suspected that some of the gully materials may be failing due to liquefaction during the rainy season.

**Soil porosity and permeability**

Porosity, permeability, and amount and duration of rainfall are such factors that influence the infiltration capacity of a soil (Todd 1980; Emeh and Igwe 2017; Igwe and Egbueri 2018). The soil porosity obtained in this study ranged from 36 to 52%, while the soil permeability values were found in the range of  $6.81 \times 10^{-5}$  to  $2.04 \times 10^{-4}$  m/s (Table 4). It has been reported that permeability coefficients ( $k$ ) in the range of  $10^{-7}$ – $10^{-5}$  m/s are characteristic of a moderately to highly permeable material (Igwe et al. 2013). The results of porosity and permeability for this study suggest that the soils are generally loose, porous, and moderately permeable. The moderate permeability of the soils could be indicating the predominance of fine-grained sands. With the high rainfall intensity in the study region and the porous and permeable nature of the analyzed soils, high water infiltration capacity is indicated (Egbueri and

Igwe 2020). Such a condition predisposes the soils to high erodibility (Rahimi et al. 2010; Igwe and Egbueri 2018). It has been noted that the infiltration of water into an unsaturated zone usually results in the formation of a wetted zone (usually near the gully slope surface), and this can cause shallow slope failures during the rainy season (Cho and Lee 2002).

**Compaction characteristics**

The compaction characteristics of the soils are presented in Table 5 and Fig. 7. According to Egbueri et al. (2017) and Igwe and Egbueri (2018), compaction tests can reveal (1) how loose or compacted a soil material is and (2) the relationship between compaction effort and the optimum water content. In this study, the compaction result showed that the soil optimum moisture content (OMC) ranges from 12.0 to 13.5%, while the maximum dry density (MDD) ranges from 1.65 to 1.96 g/cm<sup>3</sup> (Table 5). The result revealed that the soils have low OMC and poor MDD. These results suggest that the soils are loose materials and hence require very little force to detach and transport the particles (Igwe and Egbueri 2018). Additionally, the loose nature of the soils has more influence on their water holding capacity and hydraulic conductivity (Egbueri et al. 2017; Igwe and Egbueri 2018).

**Natural moisture content and Atterberg limits**

The materials’ NMC ranges from 3 to 15% (Table 5), signifying that the soils were in unsaturated state. The low

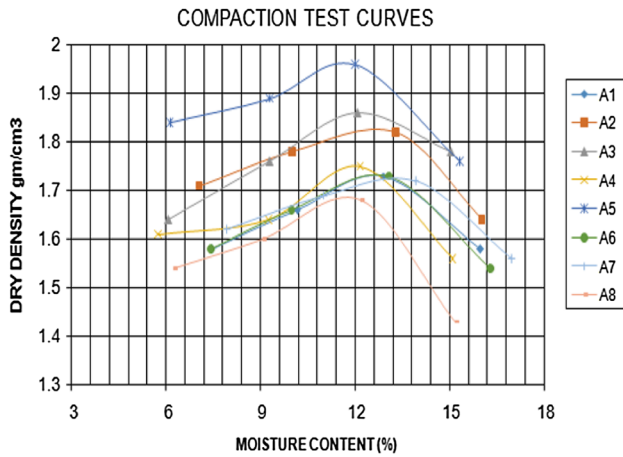
**Table 4** Permeability (m/sec) of the various soil samples

Parameter	A1	A2	A3	A4	A5	A6	A7	A8
$k$ (m/s)	$2.96 \times 10^{-5}$	$1.32 \times 10^{-4}$	$9.85 \times 10^{-5}$	$8.06 \times 10^{-5}$	$5.88 \times 10^{-5}$	$1.28 \times 10^{-4}$	$2.04 \times 10^{-4}$	$6.81 \times 10^{-5}$
Porosity (%)	36	44	40	52	38	39.2	39.2	48

**Table 5** Results of the compaction and Atterberg limits tests

Parameter	A1	A2	A3	A4	A5	A6	A7	A8
MDD	1.73	1.83	1.86	1.75	1.96	1.73	1.73	1.68
OMC	12.9	12.9	12.7	12	12.07	13	13.5	11.9
NMC	9	10	3	9	4	15	9	3
LL	29	28	18	22	19	30	29	20
PL	NP	NP	NP	NP	NP	NP	NP	NP
PI	NP	NP	NP	NP	NP	NP	NP	NP

NP nonplastic



**Fig. 7** Compaction curves for the soil samples

NMC suggests low moisture holding ability of the soils in the area (Egbueri et al. 2017). Research has shown that low moisture content reduces the cohesiveness of soil particles, hence making them easily dispersible (Isikwue et al. 2012). Nevertheless, high rainfall intensity increases the water content of soils, thereby increasing their detachment rate. The silty components of the soils were subjected to Atterberg limits test. The results of this investigation are also shown in Table 5. The liquid limit (LL) ranges from 18 to 29% (Table 5), indicating that the soils are clay-deficient. However, the plastic limit (PL) and plasticity index (PI) indicated that the soils are non-plastic (Table 5). This property predisposes the soils to high water erodibility tendency (Igwe and Egbueri 2018). In this study, the Atterberg limits validated the soils’ low-to-moderate moisture content because the plasticity index (PI) generally depends on the water content. The lower the NMC, the higher the PI.

**Table 6** Direct shear strength characteristics of the soils

Sample ID	A1	A2	A3	A4	A5	A6	A7	A8
Cohesion ( <i>C</i> , kPa)	3	5	0	0	0	5	4	1
Friction angle ( <i>φ</i> , °)	25	23	29	30	26	27	22	26
Unit weight ( <i>γ</i> , kN/m <sup>3</sup> )	16	17.8	16.4	15.1	16.2	17.5	17.2	15.5

### Shear strength parameters of the soils

The shear strength parameters also play a vital role in determining the erodibility and stability of gully materials. In establishing the strength and stability of the gully slopes, cohesion and friction angle are the major key inputs. The shear strength parameters of the analyzed soil samples are presented in Table 6. The results show that the soil materials generally have negligible cohesion and low angle of internal friction. Based on these properties, the soils are adjudged to be vulnerable to erosion. The low cohesion is attributed to the low proportion of fines content (Egbueri et al. 2017; Emeh and Igwe 2017). The shear resistance of a soil material to erosive forces decreases with a decrease in its cohesive strength (Chaulya 1993; Igwe and Egbueri 2018). The decrease in shear strength reduces the stability of gully slopes. Additionally, the shear strength of soil material also decreases with decreasing angle of internal friction. As such, the soil’s effective stress significantly depreciates (Egbueri and Igwe 2020), leading to gully slope instability.

### Multivariate statistical analysis of geotechnical parameters

#### Pearson’s correlation analysis

Results of the Pearson’s correlation analysis are presented in Table 7. It was observed that there is a strong negative relationship (−0.972) between sand percentage and cohesion. Again, cohesion has a relatively moderate negative relationship (−0.622) with gravel and silt. The observed negative correlations signify the indirect relationships between the parameters. An increase in silt, sand, and gravel contents depreciates the cohesion of a soil sample. In general, an increase in sand content of a soil has been reported to influence the instability



**Table 7** Pearson correlation matrix of soil geotechnical parameters

Parameter	Silt	Sand	Gravel	C	Ø	MDD	OMC	NMC	LL	φ
Silt	1									
Sand	<b>0.563</b>	1								
Gravel	<b>1.000</b>	<b>0.563</b>	1							
C	<b>-0.622</b>	<b>-0.972</b>	<b>-0.622</b>	1						
Ø	0.146	<b>0.603</b>	0.146	<b>-0.624</b>	1					
MDD	0.208	0.237	0.208	-0.250	0.097	1				
OMC	<b>-0.595</b>	<b>-0.789</b>	<b>-0.595</b>	<b>0.880</b>	<b>-0.731</b>	-0.291	1			
NMC	<b>-0.780</b>	<b>-0.799</b>	<b>-0.780</b>	<b>0.822</b>	-0.189	-0.369	<b>0.693</b>	1		
LL	<b>-0.715</b>	<b>-0.888</b>	<b>-0.715</b>	<b>0.912</b>	<b>-0.586</b>	-0.465	<b>0.913</b>	<b>0.866</b>	1	
φ	-0.132	0.313	-0.132	-0.311	0.425	-0.265	-0.479	-0.058	-0.301	1

Significant values are in bold

of slopes making soil particles detachable by erosive forces (Emeh and Igwe 2017; Igwe and Egbueri 2018).

The optimum moisture content (OMC), soil natural moisture content (NMC), and liquid limit (LL) were noted to correlate positively (0.880, 0.822, 0.912, respectively) with the soil cohesion (C). Therefore, since cohesion is a function of clay content, soil cohesive strength is known to increase with clay content. Increased clay content in the soil indicates its tendency to retain moisture, thus making the LL to increase. Also, Horton (1945) hypothesized that sandier soils are more likely to be eroded than clayey soils, because clays tend to have higher cohesion than sands. By definition, soil cohesion is the amount of shear strength working to hold its particles together. In this analysis, cohesion has a negative (-0.624) relationship with internal friction angle, illustrating an inverse proportionality between both. However, an increase in both strength parameters can increase the shear strength of soils and their resistance to erosion (Coulibaly et al. 2017).

The negative (-0.595, -0.780, -0.715) relationships between the NMC, OMC, and LL with the friction angle can be related to the fact that the presence of fluids decreases the friction (interlocking force) between the soil grains, thereby making the particles become loose and detachable. Moreover, the correlation matrix shows a significant relationship between the determined values of shear strength parameters (especially the soil cohesion) and moisture content as well as the optimum moisture content. These results further confirm that the soils are loose and susceptible to erosion. In all, water content has been reported to influence the stability of slopes (Emeh and Igwe 2017).

**Factor analysis**

Two main factor classes were obtained from the factor analysis. The extracted factor loadings and their percentages of variance are presented in Table 8. In the first factor class (which explains 44.241% of the total variance), significant

positive loadings on C, OMC, NMC, and LL were observed. These parameters were initially identified by the CA to have positive linearity. They are also the parameters that enhance the shearing resistance of the soils against erosion. Thus, the higher the fines content, the higher the cohesion and water retention capacity (i.e. NMC) of the soil which thereby reduces erosion.

The second factor class (with 35.144% of the total variance) has significant loadings on sand, silt, and porosity. Considering the friability of the sedimentary units in the study area, these parameters are those likely to accelerate the soil erosion processes. Based on the field observations, most of the sands are rounded to well-rounded grains. This property predisposes the soils to failure by shearing, especially when they become lubricated and saturated with water. Furthermore, soil erosion by water in southeast Nigeria has been reported to be fiercer in rainy seasons by different researchers (Igwe and Egbueri 2018). With increasing

**Table 8** The Varimax-rotated factor loadings

Parameter	Factor components	
	Factor 1	Factor 2
Silt	<b>-0.919</b>	0.099
sand	<b>-0.605</b>	<b>0.704</b>
gravel	<b>-0.919</b>	0.099
C	<b>0.646</b>	<b>-0.714</b>
Ø	-0.067	<b>0.841</b>
MDD	-0.492	-0.041
OMC	<b>0.540</b>	<b>-0.792</b>
NMC	<b>0.872</b>	-0.323
LL	<b>0.746</b>	<b>-0.640</b>
φ	0.308	<b>0.798</b>
Total	4.424	3.511
% of variance	44.241	35.114
Cumulative %	44.241	79.355

Significant values are in bold

rainfall intensity, the soils absorb more water and thus have their frictional angle (and effective stress) reduced (Acharya et al. 2016).

### Stability analysis of the gully slopes

Stability analysis of various gully slopes within the Udi province was evaluated, and their factor of safety (FoS) computed for the eight gully sites was analyzed for geotechnical properties. A stability classification chart is presented in Table 9. Based on this chart, a factor of safety (FoS) < 1 indicates an unstable slope, while that > 1 indicates a stable slope. Table 10 presents the summary of the stability analysis (for both saturated and unsaturated conditions) for the various gully sites. Results of the slope stability modeling for gullies A2 (Nachi), A4 (Obioma), and A7 (9th Mile) were broadly studied in both saturated and unsaturated conditions and are shown in Fig. 8. With respect to the saturated condition, the computed FoS values (in the range of 0.81–0.9) showed that all the gully sites have FoS < 1, predicting that all would basically be unstable during rainy season. This is because the gully slopes would be partially to fully saturated with water in this season.

However, for the dry condition, the obtained FoS values ranged from 1.02 to 1.41, indicating that they are stable in this season. This observation is supported by the fact that the gully materials usually have little or no water infiltration during the dry season. The results further illustrate that the FoS decreases with an increasing precipitation, under constant volumetric water content. When water starts to infiltrate into

the soil, the matric suction especially near the ground surface will slowly reduce but becomes zero as the soil reaches saturated condition. The significant reduction in matric suction is known to cause a decrease in the soil shear strength and slope failure (Li et al. 2005; Igwe and Una 2019).

The simulated FoS values for both dry and wet conditions indicate several disparities in this research. In the event of a possible gully erosion, model (Fig. 8) predicts that the slope failure would be relatively rotational slip surface passing slightly below the toe of the slope and having an average depth of about 6 m and a sliding mass of about 146.49–176 m<sup>3</sup> as water content increases within the slopes. A slide with this geometry can be considered to be a low-to-medium-magnitude soil movement, because it occurs regularly in saturated state. A drop in rainfall infiltration during the dry season improved the FoS of the gully slope, and as can be observed from Fig. 8, a significant drop of the FoS from 0.82 to 1.28 showed a reduction in the sliding mass from 146.49 to 124.17 m<sup>3</sup>.

To simulate both saturated and unsaturated pore-water pressure failure mechanisms in the slope mass, the material grain size was taken into account. Usually, a coarse-grained soil slope fails in saturated condition because its high permeability causes a rapid development of positive pore-water pressure. In fine-grained soils, however, there is no rapid development of positive pore-water pressure, owing to the relatively low permeability. In Fig. 9, pore-water pressure was simulated for both wet and dry conditions to understand the mode of pore-water buildup in both conditions. The variation in pore-water pressure in all the sites witnessed very rapid pore-water pressure response in the wet condition. Possibly, the infiltration through the soil decreases the matric suction.

The pore-water pressure regime was observed to be transient, due to soil type, porosity, permeability, and potential seepage face on the gully slopes. Initially, the pore-water pressure was negative. With continual rainfall over a long time, the pore-water pressure increases gradually. The pore-water pressure in the wet season for all the

**Table 9** Slope stability classification based on FoS (Hadmoko et al. 2010)

No	FoS value	Slope stability	Hazard level
1	FoS > 1.5	Stable slope	Low hazard
2	1.0 ≤ FoS ≤ 1.5	Critical slope	Medium hazard
3	FoS < 1.0	Unstable slope	High hazard

**Table 10** Stability analysis result for both wet and dry conditions

Sample ID	Gully location	FoS value (wet condition)	Remarks (wet condition)	FoS value (dry condition)	Remarks (dry condition)
A1	Obinagu	0.9	Unstable gully	1.35	Fairly stable
A2	Nachi	0.82*	Unstable gully	1.28*	Fairly stable
A3	Amagu Udi	0.86	Unstable gully	1.20	Fairly stable
A4	Abba (Obioma)	0.81*	Unstable gully	1.34*	Fairly stable
A5	Ameke (Nsude)	0.82	Unstable gully	1.25	Fairly stable
A6	Ukana	0.88	Unstable gully	1.41	Fairly stable
A7	9th Mile (Ama)	0.80*	Unstable gully	1.02*	Critically stable
A8	Iva Valley	0.81	Unstable gully	1.13	Critically stable

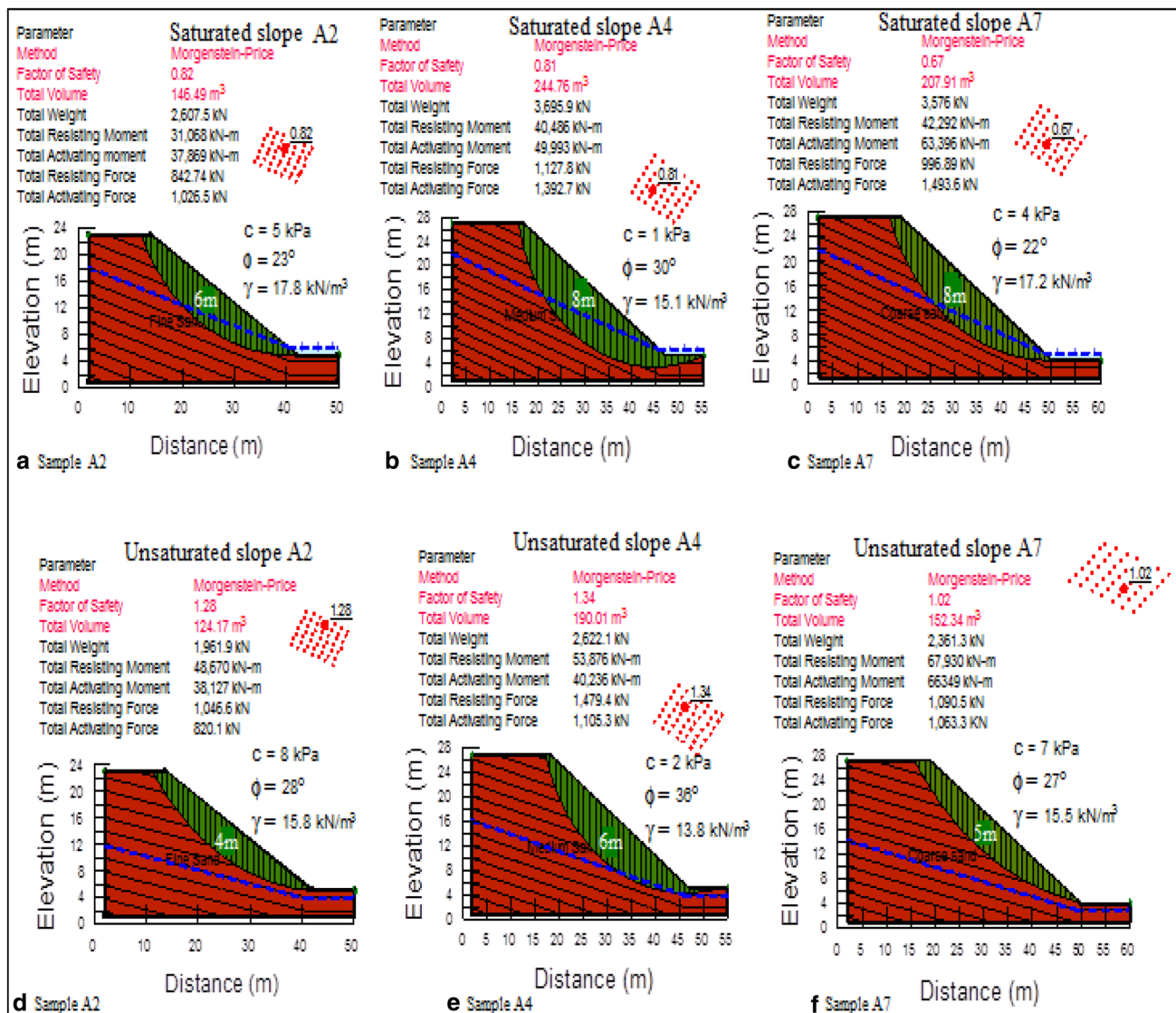
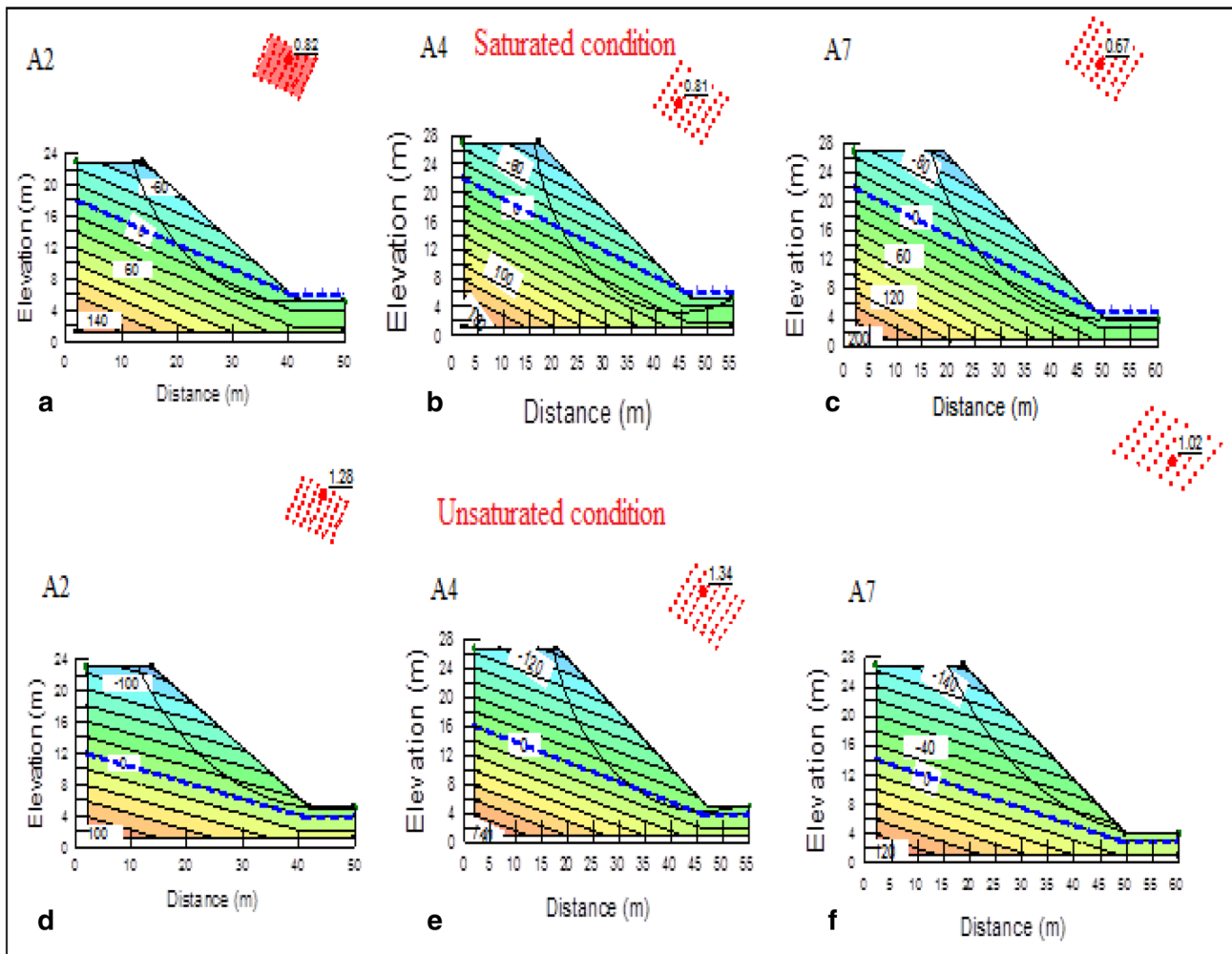


Fig. 8 Stability models for both saturated and unsaturated conditions

gully slopes ranged from  $-80$  to  $-60$  kPa, validating the fact that the soils are almost homogenous and tend to have relatively similar pore-water pressure condition (Fig. 9). The rainfall infiltration and residual soils' self-weight increase, while the wetted zones' matric suction decreases or even disappears. In the dry condition, there is little or no rainfall; thus, the pore-water pressure decreased from  $-100$  to  $-140$  kPa. The fundamental cause of negative pore-water pressure appears to be osmotic and adsorptive effects, hydrostatic stresses, and the surface tension of water. Negative pore-water pressure may exist in both saturated and partially saturated soils.

### Erosion susceptibility zonation

The FoS values were used in ArcMap (ArcGIS) environment to produce a landslide (erosion) susceptibility map (Fig. 10). Figure 10 shows the geospatial distribution of the areas of stability and instability, for both the wet and dry conditions in the study area. The result illustrates that during the rainy season (peak time of failure), all the gully slopes are practically unstable due to rapid buildup of pore-water pressure and total loss of soil matric suction. In this period, gullies receive huge volumes of water which facilitate slope failures and consequently lead to



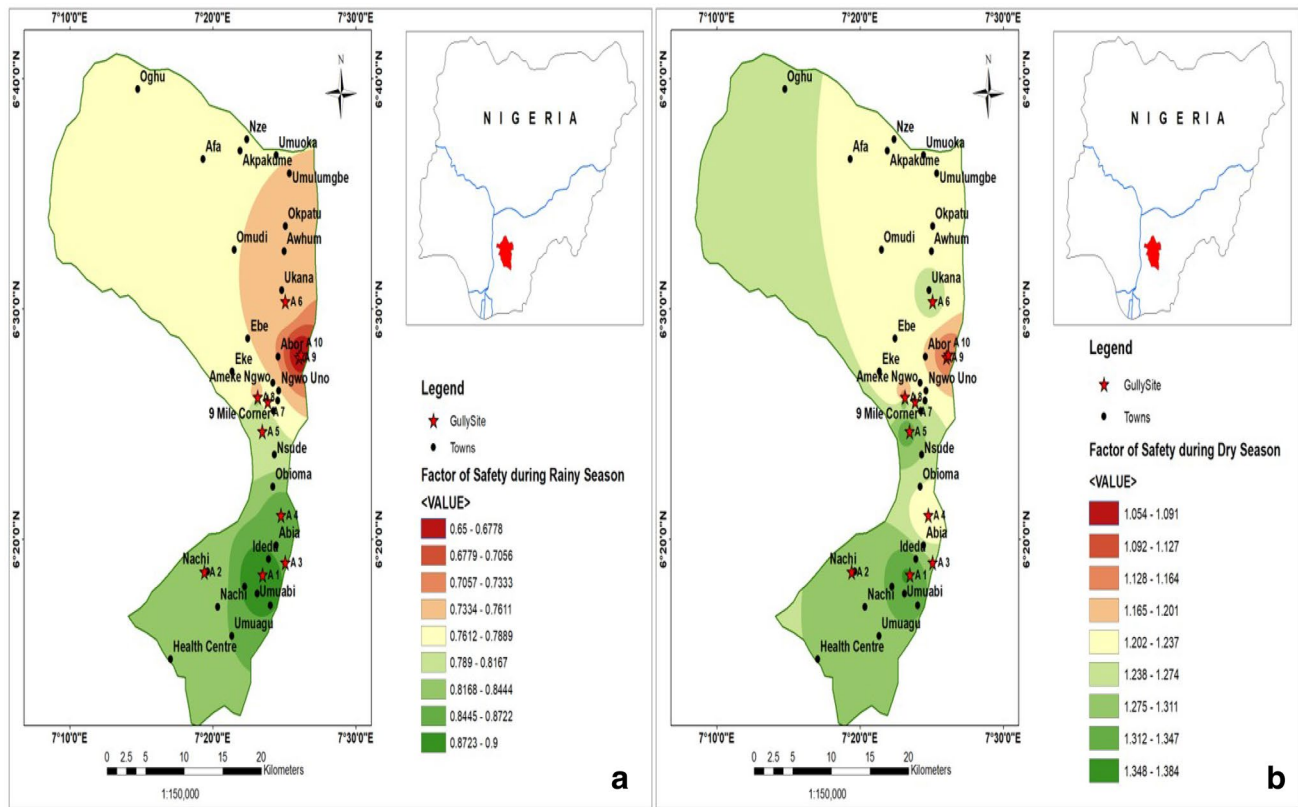
**Fig. 9** Soil pore-water pressure variations for both wet and dry conditions

gully expansion. Towns such as Abor, Ngwo Uno, and the Iva Valley area have the least FoS values, and thus they are said to be more vulnerable to erosion. These areas are relatively unstable to critically stable in both wet and dry conditions.

## Conclusions

This study has successfully evaluated the erodibility characteristics and gully slope stability of geological units prone to erosion in Udi area, southeastern Nigeria. Based on the results presented in this study, the following conclusions are drawn:

- The grain size distribution showed that the soils are devoid of clays and hence are loose and vulnerable to erosion.
- SM soils are the predominant soil type in the gully slopes. Therefore, an increment in pore-water pressure in such soil type may facilitate gully initiation and expansion.
- Compaction results confirmed that all the soils were loose and collapsible, with dry density ranging from 1.65 to 1.96 g/cm<sup>3</sup>.
- The gully lithologies are made up of nonplastic soils, with low water holding capacity that could reduce the shear strength of the gully slopes.
- Based on the permeability coefficients (which ranged from  $6.81 \times 10^{-5}$  to  $1.28 \times 10^{-4}$  m/s), the soils are moderately permeable, indicating moderate infiltration capacity.
- Shear strength analysis revealed that the soils have low cohesive capacity (with cohesion in the range of 0–5 kPa) and relatively low angle of shearing resistance (as the angle of internal friction ranges from 22° to



**Fig. 10** Factor of safety map illustrating areas of varying stability conditions

30°). This implies that the soils are weak to withstand shearing forces.

- Multivariate statistical analyses aided the identification of the interrelationships between the analyzed geotechnical parameters.
- The obtained factor of safety of the gully slopes (in both saturated and unsaturated conditions) ranged from 0.81 to 0.90 and 1.02 to 1.41, respectively. This predicts that the gully slopes will typically be unstable in saturated conditions and critically stable in unsaturated conditions.
- Factor of safety (FoS) spatial distribution map illustrated that some areas such as Abor, Ngwo-Uno, and Iva valley are characterized by severely unstable gully slopes (with  $FoS \geq 1$ ), for both dry and wet conditions. Therefore, these communities need urgent mitigation measures than others.
- Recent rise in annual rainfall in southeastern Nigeria would further facilitate the rapid initiation and expansion of more gullies in the study area. Hence, great care should be taken in proffering probable solutions to this menace. Moreover, strict soil conservation programs should be launched, encouraged, and enforced.

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