ORIGINAL ARTICLE

Gully slope distribution characteristics and stability analysis for soil erosion risk ranking in parts of southeastern Nigeria: a case study

Johnbosco C. Egbueri[1] · Ogbonnaya Igwe[2] · Chinanu O. Unigwe[3]

Abstract
Critical slope stability analysis has proven to be a reliable technique which could be used in gully erosion risk assessments. The integration of experimental and stability modelling has assisted extensively in the analysis of natural slopes. In the current paper, several geotechnical properties and slope parameters were studied in an attempt to characterize gullying processes and risk in southern Anambra State, Nigeria. Field mapping, geotechnical analyses, geostatistical analyses, and limit equilibrium simulations were integrated to achieve the research objectives. The field measurements showed that most of the gullies are characterized by high slope angles ranging between 18° and 85°. Based on the geotechnical analysis, the soil slopes were observed to be highly vulnerable to landsliding. Principal component and regression analyses efficiently captured the interrelationships between the analyzed erosion gully parameters. Several slope stability models were used to estimate the factor of safety (FS) of the slope materials. It was revealed that most of the slopes are unstable and vulnerable whereas others are critically to moderately stable. Furthermore, while the slopes recorded FS in the range of 0.82–1.72 in unsaturated condition, FS of 0.70–1.33 was observed for saturated condition. This result indicated that the gully slopes are more vulnerable to failure by erosive forces in wet season, due to rainwater infiltration and pore-water pressure buildup. Gully slopes within the Nanka Formation showed higher failure vulnerability than those in Ogwashi and Benin formations. The details of this study would be helpful towards the mitigation of landslide hazards in the study area.

Introduction

Soil erosion due to water is a serious and continuous environmental problem in many parts of the world. Soil erosional processes often result in the development of gullies of different sizes (Egboka and Nwankwor 1985; Okagbue 1992; Igwe 2012; Nebeokike et al. 2020; Egbueri and Igwe 2020). In southeast Nigeria, there are many deep active gullies which their development and expansion are continuously and strongly influenced by such factors as (1) head-ward linear progression by surface runoffs, (2) lateral expansion by different forms of mass wasting processes, and (3) downward deepening by abrasion and attrition forces. Due to persistent gully development and expansion, commonly associated with landsliding, in southeastern Nigeria, many lives and properties have been lost and many currently are posed with serious risks (Okagbue 1992; Igwe and Egbueri 2018; Egbueri and Igwe 2020). With respect to their angles of inclination, many of the slopes in deep gullies experience sheet erosion (Ilori et al. 2017) at varying scales; thus, accelerating the gullying processes. In the study region, the numerous deep gullies are usually associated with different forms of landslides, which further facilitate high rate of residual soil loss, siltation of available surface water bodies, destruction of natural habitats, destruction of roads, loss of arable lands, diminishing soil nutrients and crop yield, and loss of residential and commercial apartments, etc. (Egboka and Nwankwor 1985; Okagbue 1992; Igwe 2012; Nwajide 2013; Chikwelu and Ogbuagu 2014; Obiadi et al. 2014;

✉ Johnbosco C. Egbueri
johnboscoegbueri@gmail.com; jc.egbueri@coou.edu.ng

[1] Department of Geology, Chukwuemeka Odumegwu Ojukwu University, Uli, Nigeria

[2] Department of Geology, University of Nigeria, Nsukka, Nigeria

[3] Department of Physics/Geology/Geophysics, Alex Ekwueme Federal University, Ndufu-Alike, Ikwo, Nigeria

Okoyeh et al. 2014; Igwe and Egbueri 2018; Egbueri and Igwe 2020; Nebeokike et al. 2020). In several attempts to minimize the rate of soil loss due to gullying in the study region, sand bags, concrete bars, artificial drainages and run-off breakers are constructed inside some of the deep gullies (Fig. 1). Plantation of vegetation covers (such as bamboo trees) has also been adopted. Yet, with increasing annual rainfall intensity, the persistency of this menace keeps ravaging many more lands in the region.

The environmental problems due to gully erosion have become a subject of increasing interest for scholars in different parts of the world (Wang and Fan 2019). Similarly, analysis of the stability of gully slopes is a research subject that is currently attracting the attention of some researchers from various countries. Many mega-gullies enlarge by failure of gully walls and slopes. Thus, in mass movement studies, slope analysis measures the potential of slopes to withstand or yield to failure by sliding or collapsing. The potential of a soil slope to slide or slip is generally summarized as its factor of safety (FS), which is defined as the ratio of soil shear stress to soil shear strength along a possible slip surface (Igwe and Chukwu 2018). This analysis is very important in risk characterization of erosion gullies associated with landslides; as it helps in determining whether there is potential for slippage of soils and in the identification of endangered areas, potential failure mechanisms, and a slope's sensitivity to different failure mechanisms, etc. (Ilori et al. 2017; Igwe and Una 2019).

Any erosion hazard risk assessment based on slope stability analysis primarily considers soil texture and steepness of slope. These two parameters (soil characteristics and slope angle) determine the impact of surface runoffs and the potential soil erosion risk. The soil characteristics that often define the stability of soil slopes include geology, grain size distribution, soil moisture content, Atterberg limits, permeability, and shear strength parameters (especially the cohesion and friction angle), etc. (Ilori et al. 2017; Igwe and Chukwu 2018; Igwe and Una 2019). However, the factors that influence a slope's susceptibility to failure based on its geometric configuration include angle of inclination, surface runoff, height and gravitational force, hydrogeology and water seepage, changes in stress, removal of lateral support by either natural processes or indiscriminate anthropogenic activities (e.g. soil excavation during sand/laterite mining), etc. Nevertheless, Burman et al. (2015) noted that "slides may occur in almost every conceivable manner, slowly or suddenly, and with or without any apparent provocation." Additionally, the distribution of gullies based on slope is much dependent on the gully slope parameters and the density of terrains with different slope classes (Wang and Fan 2019).

The current study focuses on selected mega-gullies in southern Anambra State, southeast Nigeria. Because many of the gullies in the study region are associated with landsliding and mass wasting, it is important to study the stability of their slopes. In this area, most previous erosion studies did not consider critical gully slope analysis for soil erosion risk assessment. Various researchers (including Egboka and Nwankwor 1985; Igwe 2012; Nwajide 2013; Chikwelu and Ogbuagu 2014; Obiadi et al. 2014; Okoyeh et al. 2014; Igwe and Egbueri 2018; Emeh and Igwe 2018; Egbueri and Igwe 2020) have reported on gully erosion in some other parts of Anambra State, but their works did not integrate numerical slope stability analysis for erosion risk characterization in the study region. However, Okagbue (1992) attempted a slope stability analysis of a gully in Nanka town (within the current study area) based on three stability computations. Also, Igwe and Una (2019) recently used an approach integrating field mapping, laboratory analysis and limit equilibrium simulations to study erosion gullies associated with landslides in parts of Anambra State. Nevertheless, their research focused only on gully landslides within Nanka-Ekwulobia province (underlain by Nanka Formation) in the

Fig. 1 Different technical methods used in the study area to check erosion: **a** sand bags (Igwe and Una 2019), **b** runoff breakers

State. Although their work is very important, there is still an imperative need to cover more areas and geologic formations in the State using a more sophisticated approach.

Therefore, in the current study, gully slope distribution characteristics and stability analysis were used for the characterization of gully erosion risk in different geologic formations (Nanka, Ogwashi, and Benin formations) underlying the southern Anambra State. The research objectives were to (1) identify and analyze the spatial distribution of gully slopes within mega-gullies in the area; (2) identify and describe the mechanisms of gully slope failures within the gullies; (3) simulate the stability conditions of the gully slopes; and (4) characterize the soil erosion risks due to landsliding in the study area. Field mapping, geotechnical (geomechanical) analysis, multivariate statistics, and limit equilibrium simulations were integrated to accomplish the objectives of this paper. It is hoped that this research would provide a better (1) understanding of the geomechanical behaviours of the erodible soil slopes from the various mega-gullies; (2) identification of the stability statuses of the gullied areas; and (3) insight for the design and development of effective soil erosion and landsliding countermeasures.

Geology and physiography of the study area

Anambra State is one of those States in Nigeria with highest numbers of erosion gullies. In the current study, the southern part of Anambra State, situated within latitudes 05°10′ N–6°55′ N and longitudes 06°10′ E–07°40′ E (Fig. 2a), is considered. The increasingly high number of erosion gullies in this area is attributed to both natural and anthropogenic factors (Igwe and Egbueri 2018). In the study area, apart from the fact that rainfall pattern is responsible for most gullies and landslides, the excavation of soils (sands and laterites) from gully slopes contributes immensely in perpetuating these environmental hazards.

Based on the geology, Anambra is underlain by five different stratigraphic units: the Imo Shale, Nanka Formation, Ogwashi Formation, Benin Formation, and alluvium deposit (Nwajide 2013; Egbueri et al. 2017). The Imo Formation (Paleocene-Early Eocene) essentially comprises mudrock (shale and claystone) units, with admixtures of sandstone, ironstone and limestone intercalations. Sandstone members of the Imo Formation are the poorly consolidated Ebenebe Sand, the Igbaku and Umuna members. These geologic members of the Imo Formation occur as ridges flanked by marshy low grounds underlain by shales (Nwajide 2013).

The Nanka Formation (Eocene-Early Oligocene) is underlain by the Imo Formation and is majorly made up of unconsolidated and poorly consolidated sand units (Nwajide 2013; Egbueri et al. 2017; Igwe and Egbueri 2018; Igwe and Una 2019). This formation has thin claystone and siltstone bands, poorly-sorted medium- to coarse-grained sands, cross-beds (Igwe and Una 2019) and pebbly textured outlook. This formation underlies most of the gully sites in the study area. Most of the Nanka Formation sits on the Awka-Orlu Highland (Cuesta), which has a steep slope at the east reach. The intense velocity of running water down the slope is thought to account for most of the deep gullies concentrated in this portion of the highland. The ironstone bands, which form the hard ground in some areas underlain by the Nanka Formation, are intensely exploited for economic and construction purposes. This act leaves the friable sand units exposed to erosive agents and processes. Landslides reported in the Nanka Formation included shallow translational debris slides, slumps and debris topples types (Igwe and Una 2019). The Ogwashi Formation (Oligocene–Miocene) primarily comprises pebbly, poorly sorted and mildly consolidated sands (Nwajide 2013; Igwe and Egbueri 2018). The Benin Formation (Oligocene-Present) is known to be texturally and mineralogically mature and forms table land, with very gentle slopes. This formation is characterized by high percentage of sand (usually between 70 and 100%), most of which are yellowish and whitish in colour, and forms the top layer of the Niger Delta depositional sequence (Igwe and Egbueri 2018). However, the current study focuses on three formations — the Nanka, Ogwashi, and Benin formations. The typical lithostratigraphic columns of the formations are shown in Fig. 2b.

Collectively, the configuration of the study area is marked by uneven topography (Fig. 3), badlands, and tropical rainforest belt (although, this belt is now intensely altered by anthropogenic activities, such as agriculture, deforestation and urbanization) (Egbueri and Igwe 2020). However, areas within the Nanka Formation have the highest elevations. Annually, dry and rainy seasons are the two major seasons experienced in the area. The former spans from around November to March while the latter lasts longer, spanning from April to October. In this region, the outset of the rainy season is characterized by intense and short duration rainfalls (Igwe and Una 2019). However, rainfall intensity increases for longer durations within the months of May to early August. The intensity breaks around mid-August and resumes increasingly in late August to October (Igwe and Una 2019). Generally, the average annual rainfall is about 2100 mm (Igwe and Egbueri 2018). The average annual rainfall distribution pattern for the study region is about 1800 mm. Landslide occurrences are more in rainy season (April to October) than in dry season (November to March). According to Igwe and Una (2019), "the average monthly temperatures vary from 22 to 28 °C in the rainy season and between 28 and 32 °C in the dry season."

Fig. 2 **a** Maps showing the study location and geology. **b** Representative lithostratigraphic distribution of Nanka and Ogwashi formations in the study area. cl: clay, slt: silt, vfs: very fine sand, fs: fine sand, ms: medium sand, cs: coarse sand, cg: conglomerate)
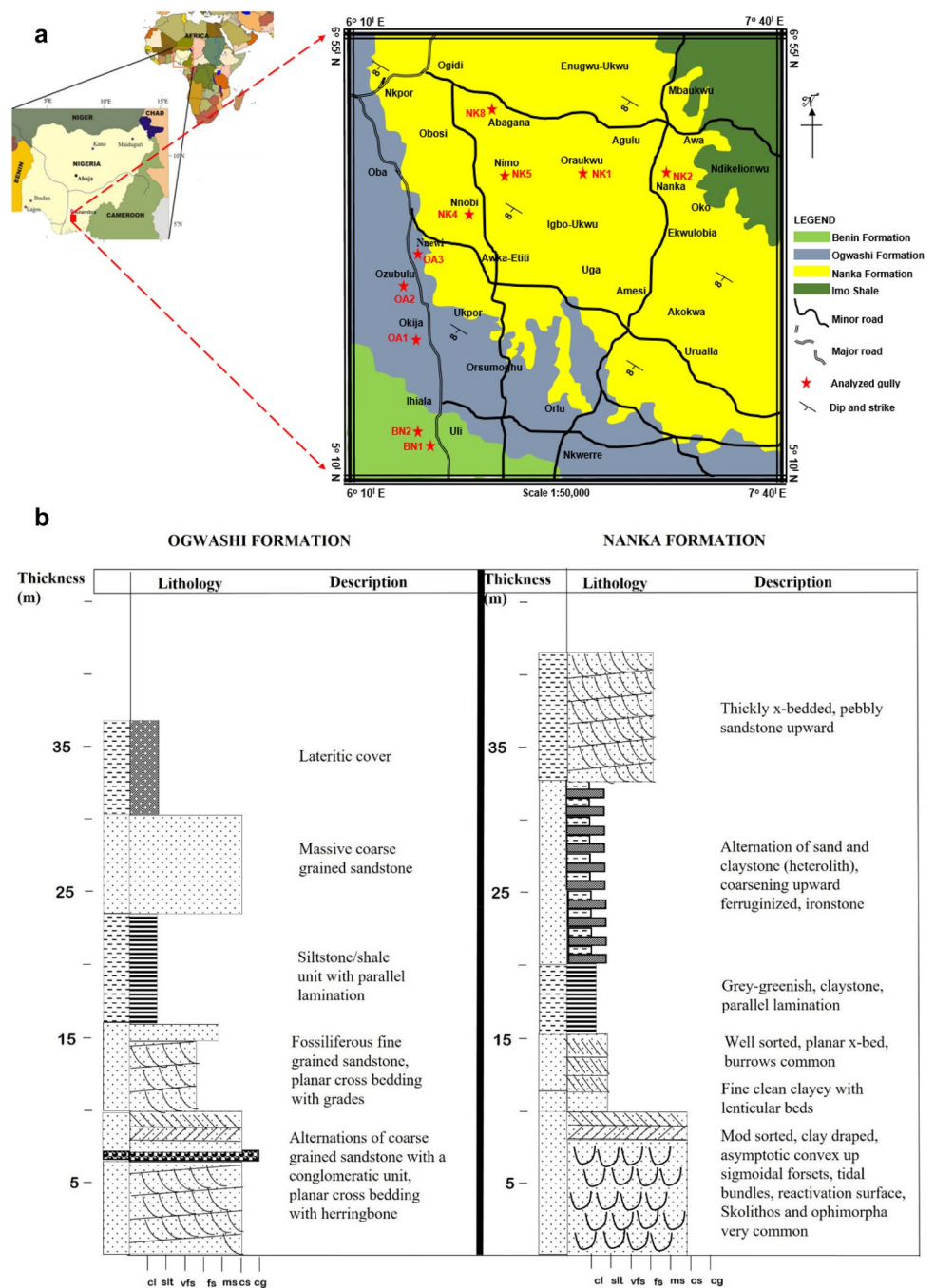

Research methodology

Field mapping, soil sampling and geomechanical analysis

The field mapping involved detailed field investigations preceded by reconnaissance survey. The field exercise was undertaken to carefully observe and investigate the various features of the study area, especially the gully slopes. The locations of the major gullies are shown in

Fig. 2a. Field measurements (such as coordinates obtained with global positioning system) essential for the preparation of geologic map and digital elevation model of the study area were taken at various gully locations during the field mapping. Additionally, during the detailed field mapping, slope geometries and soil samples (for geomechanical analysis) were taken. The slope geometries were determined using a portable Brunton handheld compass. Gully size (widths, depths (heights), and lateral extents (lengths)) distribution, slope movements, slope angles,

Fig. 3 3D digital elevation model showing the key topographic features of the study area (Egbueri and Igwe 2020)
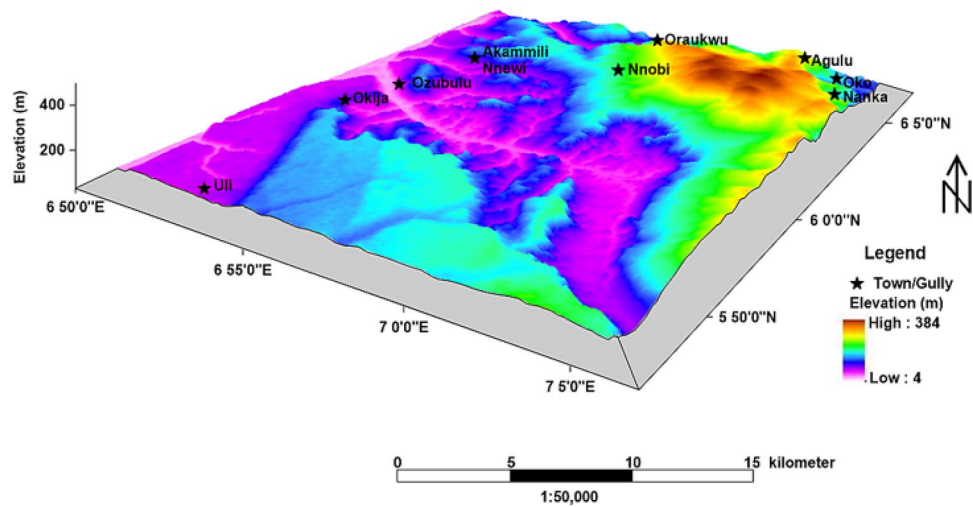
landslide features were carefully recorded during the detailed field mapping exercise.

Moreover, a total of one hundred and three (103) gully slopes were measured in this study (Table 1). Sixty-seven (67), twenty-two (22), and fourteen (14) slopes were, respectively, recorded for the Nanka, Ogwashi, and Benin formations (Table 1). Further, a total of 10 soil samples were collected across the gully slopes for geomechanical analysis. Five (5), three (3) and two (2) samples were analyzed for the Nanka, Ogwashi, and Benin formations, respectively. The fresh soil samples were collected from gully slope horizons at depth of about 30–50 cm.

The engineering properties of the gully slope materials investigated in the laboratory included the particle size distribution, Atterberg limits, soil moisture content, bulk density, specific gravity, coefficient of permeability, compaction and direct shear strength properties. The laboratory tests were performed following the guidelines and soil testing standards of the American Society for Testing and Materials (ASTM) which are well described in Kalinski (2011).

Geostatistics and limit equilibrium simulations

Multivariate statistical analysis (such as principal component analysis and linear regression analysis) was performed on the analyzed geomechanical parameters. Furthermore, the slope geometry (slope height and angle), unit weight, and the shear strength parameters (cohesion and frictional angle) were utilized in slope stability analysis and limit equilibrium simulations performed with GeoStudio® (v. 2012) software. The GeoStudio software aided in the 2D modelling of gully slope morphology for failure prediction (in terms of factor of safety, FS) (Igwe and Chukwu 2018; Igwe and Una 2019). This was based on the Morgenstern and Price (1965) limit equilibrium method.

Table 1 Gully dimensions and gully slope components

| Gully ID	Town/locality	Geologic formation	Average gully depth (m)	Average gully width (m)	Average lateral extent (m)	Slope angle (°) range	Slope aspect (direction)	Number of gully slopes measured	Erosion intensity based on field observation
NK1	Oraukwu	Nanka	63	75	> 1000	30–70	Various	12	High–very high
NK2	Nanka	Nanka	110	600	> 1200	33–85	Various	24	Very high
NK4	Nnobi	Nanka	5	5	350	22–50	Various	6	Moderate–high
NK5	Nimo	Nanka	7	15	> 800	25–56	Various	10	Moderate–high
NK8	Abagana	Nanka	35	40	> 1000	30–75	Various	15	High–very high
OA1	Okija	Ogwashi	5	7	430	20–33	Various	7	Moderate
OA2	Ozubulu	Ogwashi	18	65	> 800	20–50	Various	10	Moderate to high
OA3	Nnewi	Ogwashi	5	6	380	18–32	Various	5	Moderate
BN1	Uli	Benin	9	15	450	18–34	Various	8	Moderate
BN2	Uli	Benin	7	10	600	22–32	Various	6	Moderate

Results and discussion

Gully slope distribution, dimensions and geometric characteristics

Based on field and satellite imagery (i.e., Google Earth Map) observations, areas underlain by the Nanka Formation have more numbers of massive erosion gullies than those underlain by the Ogwashi and Benin formations (Table 1; Fig. 4). Hence, the gullies underlain by the Nanka Formation have more gully slopes than the others. On the basis of genetics as proposed by Ezechi and Okagbue (1989), most of the gullies are classified as incidental gullies, having been initiated by human concentration of runoff onto vulnerable ground. For instance, the graphics shown in Fig. 4 indicate that OA1 and NK1 could have originated from poor channeling of roadway runoff, as the gullies appear to have adjacent association with roadways.

Similar observations are true for other gullies in the studied areas.

The topographic and morphological configuration shows that the study area is undulating, with steep highlands and gently sloping lowlands (Fig. 3). However, over the years, it has been noticed that the gullies in this area are continuously evolving in size and morphology. Previous studies conducted in respect of soil erosion in different parts of the southeastern region of Nigeria have identified topography as one of the most important factors controlling the erodibility of the tropical soils (Okoyeh et al. 2014; Igwe and Egbueri 2018; Igwe and Una 2019; Egbueri and Igwe 2020; Nebeokike et al. 2020). In the current study, it was realized that areas underlain by the Nanka Sand appear to have higher topographic elevations above the sea level than those areas underlain by the Ogwashi and Benin formations (Fig. 3). The Benin Formation forms more of table lands in the study area.

Details of the gully sizes (dimensions) and slope angles for this study area are presented in Table 2. Based on the field estimations (Table 1), it was realized that gullies within
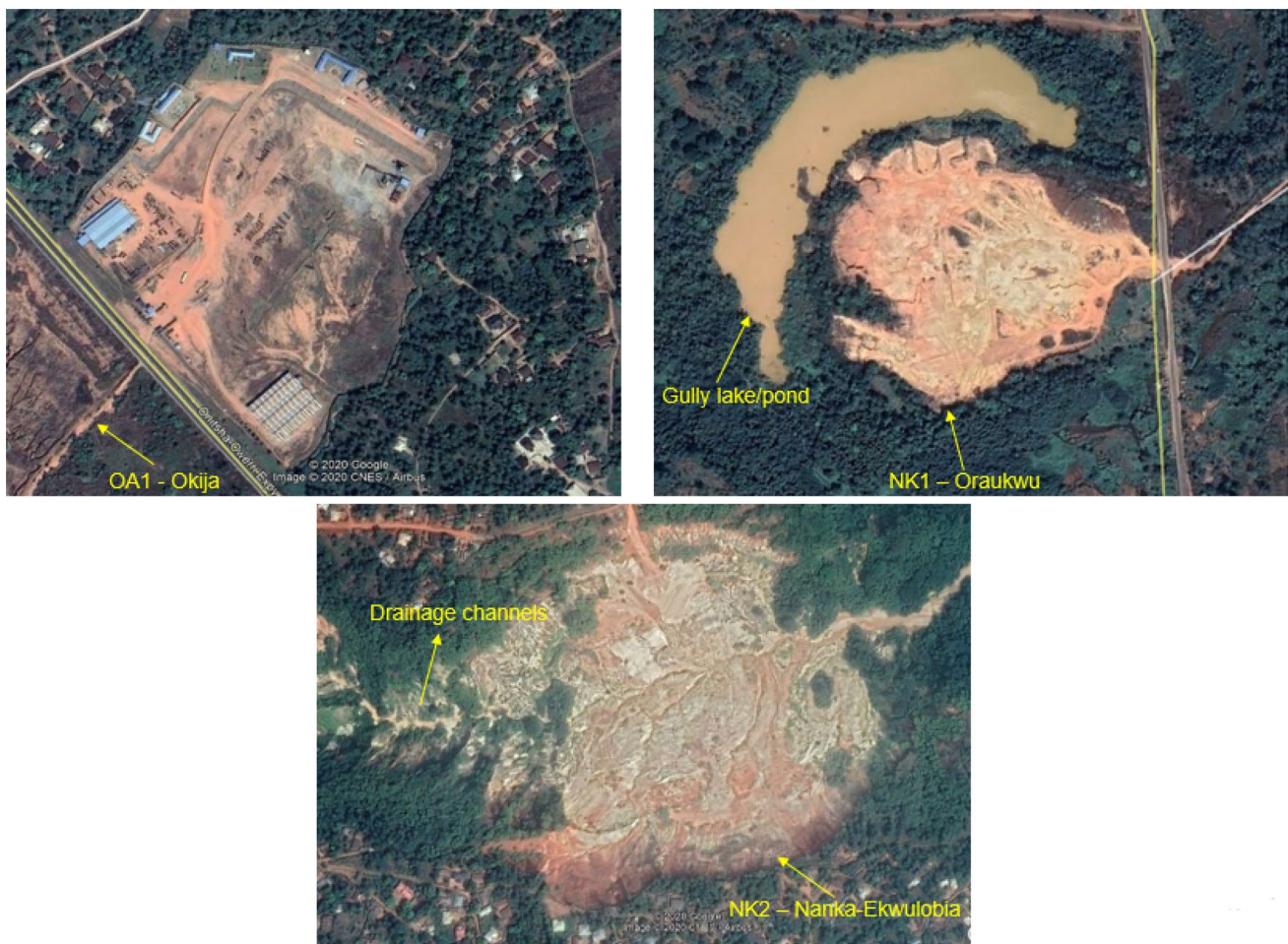
Fig. 4 Some of the gullies captured from Google Earth maps. Nanka Formation has more of massive gullies than other formations

Table 2 Correlation matrix for gully depths, widths and lengths

Parameter	Average gully depth (m)	Average gully width (m)	Average lateral extent (m)
Average gully depth (m)	1		
Average gully width (m)	0.899[a]	1	
Average lateral extent (m)	0.835[a]	0.666[b]	1

[a]Correlation is significant at the 0.01 level (two-tailed)

[b]Correlation is significant at the 0.05 level (two-tailed)

the Nanka Formation are larger in sizes, followed by those within the Ogwashi Formation and then those within the Benin. Pearson's correlation analysis was performed on the gully depths (heights), widths, and lateral extents (lengths). The results of this analysis are shown in Table 2. Significant positive correlation scores (r) scores were obtained in all, implying that there are significant agreements between these parameters. Similar agreements were observed from a regression analysis performed on these parameters (Fig. 5), as significant regression scores (r^2) were obtained too.

Figure 5 provides a useful insight into the mechanism of the gully expansion and evolution in the study area. It was revealed that a strong positive relationship ($r^2 = 0.8081$) exists between the gully depths and the gully widths (Fig. 5a). This result suggests that both the gully widths and depths expand simultaneously over the years. Similarly, it was learnt that as the gully depth deepens, the lateral extent also stretches. In other words, the deeper gullies in the area seem to have longer lateral extents. This assertion follows the observed moderate-strong relationship ($r^2 = 0.6976$) between the gully depths and the lateral extents (Fig. 5b). However, a fair positive association ($r^2 = 0.4434$) was noticed between the gully widths and the lateral extents (Fig. 5c). This result suggests that the rate of expansion of the gully widths does not strongly match with that for the extension of the gully length. This also indicates that forces inducing the sliding of gully slopes (which causes width expansion) in the area could be more prevalent than those forces inducing the lateral extension of the gullies.

In the current study, slope geometries were recorded for several gully slopes within the gullies situated on the three geological formations. Generally, the gully slopes are characterized by concave curvatures and varying slope aspects striking west, north, east and south. The concavity of the slopes seems to be responsible for the high slope angles (generally > 30°) recorded in the study area. Several researches have reported that most landslides and slope failures are due to the concavity of slopes, which usually have inclinations in the range of 36°–58° (Mugagga 2011; Mugagga et al. 2011; Igwe and Chukwu 2018). Only few slopes were observed to be convex in curvature. Moreover, numerous landslide scars were observed on the concave slopes than on the convex slopes. In some parts of the gullies, landsliding has reduced the slope angles to appear stable. This matches the reports of Schuster and Highland (2003) who opined that the reduction of slopes to angles at which they possess long-term stability is the net morphological effect of landslides.

The larger, complex gullies within the Nanka Formation were noticed to have wider range of slope angles (i.e. 22°–85°). This observation seems to be in agreement with the findings of previous researchers that worked within the Nanka Formation (Okagbue 1992; Igwe and Una 2019). However, the gully slopes within the Ogwashi Formation ranged between 18 and 50° while those within the Benin Formation ranged from 18° to 34° (Table 1). Given the steep nature of the gully slopes, it is thought that they are partly responsible for the continuous gully enlargement and evolution in the study area. Studies have shown that steep slopes are mainly affected with a decline in their factor of safety, when the shear strength drops against an increasing shear stress (Yang et al. 2007; Wati et al. 2010; Mugagga et al. 2011), probably due to rainfall loading and gravity pull.

In the study area, during the rainy season, concentrated overland flow induces landslides of varying extents (shallow and deep slides) along the gully slopes. However, slides have been noticed to be few during the dry season. Admittedly, the gravitational mass movements (landslides) in both seasons play parts in the continuous morphological modifications taking place in these gullies (Yalcin 2007).
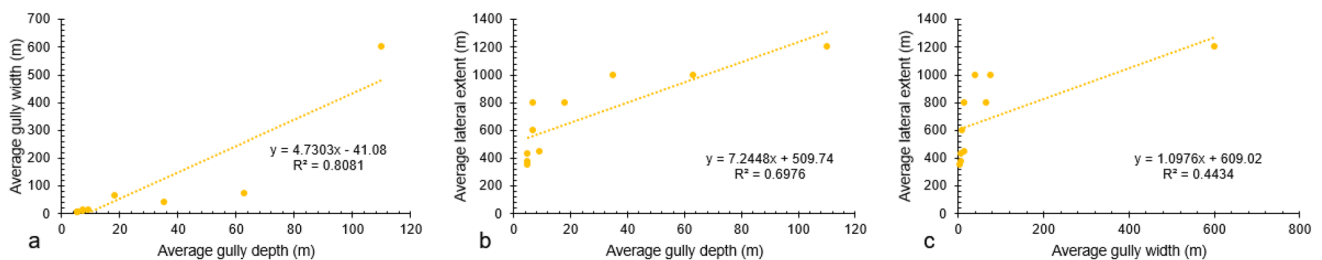
Fig. 5 Regression analytical models for investigating the relationships between gully depth, width, and lateral extent

Additionally, because the soils are porous and mostly sandy, the infiltration of water into the slope materials seems to trigger internal forces that work hand-in-hand with the surface gravitational forces in inducing more and more slides.

Geomechanical characteristics of gully slope materials

The gully slope materials were analyzed for geomechanical properties. The obtained results are summarized in Table 3. Generally, the slope materials showed geomechanical characteristics that are indicative of failure-vulnerable soils. For instance, it was realized that the particle distribution is mostly dominated by fine-medium sands, with few gravels and clays that would enhance their shearing resistance when stress-loaded. The grain distribution curves are shown in Fig. 6. It can be observed that the curves appear to show close similarity of pattern, indicating that the slope materials could have similar failure mechanism and trend. Naturally, gravels in a soil system tend to pose higher densities that would enhance the soils shear mobility when the slope is triggered to fail. Similarly, plastic clay mineral in the soil would also enhance the immobility of the soil flow when saturated with rainwater, thereby minimizing the rate of mass wasting in gullies. However, the presence of fine-medium (especially rounded) sands would easily lead to soil mass failure, peculiarly during saturation.

According to Horton (1945), it is hypothesized that clays tend to resist erosion far more than sands. Hence, sandy slope materials are more susceptible to failure, e.g. landsliding, liquefaction, and piping. The higher resistance of clays to erosive forces is attributed to their higher cohesion than sands. Moreover, on the basis of field observations, the fine-medium sands (and even the gravels) are mostly rounded to well-rounded grains. Only few sub-angular and angular soil particle components were noticed in the soil systems. While the sub-angular and angular soil particles are believed to have higher contribution towards enhancing the shear resistance of the soils, the rounded and well-rounded particles are noted to be more prone to erosion by shearing forces, especially when lubricated by water. Furthermore, from a sedimentological perspective, the low clay contents and rounded/well-rounded nature of the soils demonstrate that the soils and sediments probably underwent several stages (cycles) of reworking and possibly deposited by fluvial flows.

With respect to the grain size distribution, it was realized that all the analyzed soils are within five soil classes—SC, SP, SW, GP, and CL—based on the unified soil classification system (USCS) (Table 3). On the basis of the USCS presented in Arora (2003, 2008), Bell (2007), and Budhu (2015), the SC is described as clayey sand (or sand-clay mixture); SP is defined as poorly-sorted sand (or gravelly sand);

Table 3 Geotechnical properties for slope stability analysis

Gully ID	Town/locality	Formation	USCS	Gravel (%)	Sand (%)	Fines (%)	LL (%)	PL (%)	PI (%)	MDD (g/cm³)	OMC (%)	ρ (g/cm³)	G	C (kPa)	φ (°)	NMC (%)	n (%)	k (m/s)
NK1	Oraukwu	Nanka	SW	10.53	86.27	3.2	0	0	0	1.84	15.28	1.68	2.56	1	36	2	51	4.34E-04
NK2	Nanka	Nanka	SC	16.97	68.06	14.97	22	12	10	1.88	17.1	1.77	2.63	7	33	3	45	8.52E-05
NK4	Nnobi	Nanka	SC	0	79.29	20.71	25	14	11	1.89	14.12	1.86	2.63	6	33	8	49	4.68E-05
NK5	Nimo	Nanka	SP	20.5	64.18	15.32	25	16	9	1.88	13.91	1.75	2.63	3	35	3	38	5.36E-05
NK8	Abagana	Nanka	SP	11.5	73.1	15.4	25	0	0	1.91	13.29	1.75	2.63	3	36	2	44	1.67E-04
OA1	Okija	Ogwashi	CL	0	41.13	58.87	32	19	12	1.89	17.06	1.83	2.69	27	19	3	56	4.22E-06
OA2	Ozubulu	Ogwashi	GP	83.38	11.47	5.15	0	0	0	1.76	15.23	1.90	2.50	6	36	2	39	2.53E-04
OA3	Nnewi	Ogwashi	SC	0	68.6	31.4	24	16	8	1.92	13.85	1.84	2.65	5	35	2	53	2.71E-05
BN1	Uli	Benin	SC	4	73.24	22.76	24	0	0	1.94	13.99	1.86	2.62	6	30	8	51	2.86E-05
BN2	Uli	Benin	SC	0	75.67	24.33	22	0	0	1.92	14.16	1.77	2.58	6	33	2	53	8.52E-05

USCS unified soil classification system, *LL* liquid limit, *PL* plastic limit, *PI* plasticity index, *MDD* maximum dry density, *OMC* optimum moisture content, *ρ* bulk density, *G* specific gravity, *C* cohesion, *φ* frictional angle, *NMC* natural moisture content, *n* porosity, *k* permeability coefficient
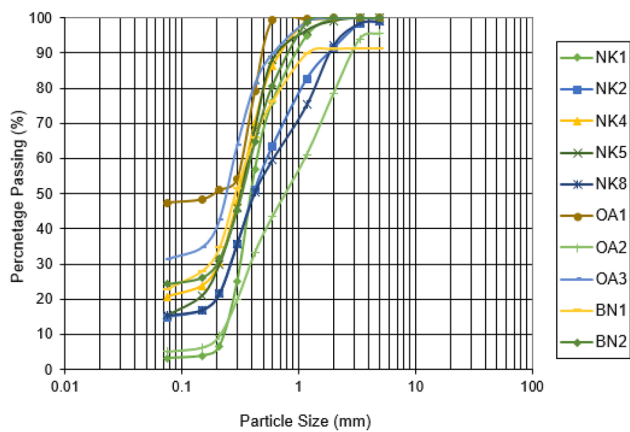
Fig. 6 Particle distribution curves

and the SW is described as well-graded sand (also referred as gravelly sand). While the GP represents a poorly-sorted gravel (or sandy gravel), the CL represents a low-plastic, inorganic sandy clay. Based on the USCS, it is believed that all the soil classes have the potential to fail by landsliding, as they are typically non-cohesive slope materials. However, it appears that the GP and CL soils could be fairly resistant to landslide-inducing shear stresses than the other soil classes.

The natural moisture content (NMC) of the soils, which ranged 2–8 (Table 3), signified that they have low water content. The Atterberg limits provide significant insights for the geomechanical behaviors of the slope materials. In this study, it was observed that the slope materials have Atterberg limits that indicate zero or low plasticity soils (Table 3). This result implies that the soils generally lack the landslide-resistant features that would improve their integrity under shearing stresses. Several authors have indicated that problematic soils could be identified based on their liquid limit (LL) (Msilimba and Holmes 2005; Fauziah et al. 2006; Baynes 2008). For the current study, the LL was found to be in the range of 0–32%. Thus, it is indicated that most of the LL scores are lower or equal to the 25% threshold recommended for stable tropical slope soils (Igwe and Chukwu 2018). However, some researchers have reported LL values > 25% for all the tropical African soils they analyzed. In their research findings, Mugagga et al. (2011) and Igwe and Chukwu obtained LL values > 25%, which made them categorize the soils they analyzed as problematic and vulnerable to sliding. Although the LL observation for this study seems to be comforting, it is pertinent to note that some other factors render the slope materials vulnerable. Alternatively stated, the soils are still considered to be problematic, as other geomechanical parameters have indicated that they are susceptible to landsliding.

Furthermore, it was learned that the CL and SC soils have higher plasticity indices than their counterparts. However,

some of the SC soils are non-plastic. Studies have suggested that the plasticity index (PI) of soils are often correlatable to their fines percentages (Nebeokike et al. 2020). Moreover, the low consistency limits seem to agree very well with the low soils' moisture contents. Based on the insights provided by the low LL and PI, it is believed that the fines components of the gully slope materials have very low expansion potential (Mugagga et al. 2011; Igwe and Chukwu 2018), thus, signifying the absence of swelling clay minerals. Apparently, the LL and PI scores obtained in this study are typical of those for silty clays.

A study conducted by Mugagga et al. (2011) suggested that soil materials with clay content > 20% could be expansive when saturated. On the other hand, Baynes (2008) reported that a threshold of 10% clay content is an acceptable indicator for expansive soils. Nevertheless, in the current study, it was observed that the soils' fines ranged between 0 and 58.87%. While 50% of the total samples showed clay contents > 20, 80% of the samples showed fines contents > 10% (Table 3). However, the assumptions of Baynes (2008) and Mugagga et al. (2011) seem not to hold true for these soils as the Atterberg limits have suggested that they are mostly poorly plastic materials. Traditionally, the ability of a soil to expand when saturated seems to have a direct relationship with its PI. Admittedly, high-plasticity soils have higher expansion potentials (Arora 2003, 2008). Therefore, the analyzed soils are adjudged to have zero-low expansivity. This implies that the non-expansive soils could be experiencing more of abrupt failure mechanism than slow or creep landslide mechanism, which often characterize high-plasticity soils.

The bulk density ranged 1.68–1.90 g/cm^3, with the GP soil having the highest score and the SW soil the least (Table 3). This result suggests that the sandy gravel soil has the least susceptibility to landsliding, due to its higher density. On the other hand, the SW soil seems to be more prone to landsliding due to its lower density. The bulk density result also indicates that the soils are deficient of swelling or expansive clay minerals, as such minerals would give the soil a higher bulk density (Igwe and Chukwu 2018). Further, the slope materials were tested for specific gravity. The results are also presented in Table 3. The values ranged from 2.56 to 2.69, indicating that the soils are mostly silty soils. It was realized that the specific gravities of the soils are approximately within the range of 2.60–2.90 of clayey and silty soils as reported by Tuncer and Lohnes (1977). However, it has been reported that soil materials with specific gravity < 2.65 become problematic and drastically vulnerable to failure when saturated with water (Reidenouer 1970). In the current study, it is realized that, except the CL soil (OA1), all the other samples have specific gravities ≤ 2.65.

Compaction characteristics of the soils were also determined. The compaction curves of the slope materials are
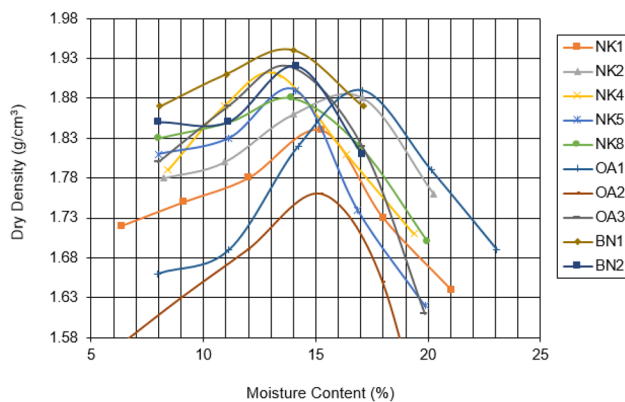
Fig. 7 Compaction curves showing that the soils are generally loose

shown in Fig. 7. The compaction analysis revealed that the optimum moisture content (OMC) and the maximum dry density (MDD) of the soils ranged between 13.29 and 17.10% and 1.76 and 1.94 g/cm³, respectively (Table 3). These values are typical for sandy slope materials and are also suggestive that the materials have average OMC and moderate MDD. Similar OMC and MDD scores were obtained by Maduka et al. (2016) and Igwe and Chukwu (2018), who studied the stability of some tropical soil slopes from other parts of southeastern Nigeria. It was also learnt that the curves are characteristic of very loose, collapsible soil materials. Convincingly, loose slope materials are believed to possess low shear strength while more compact materials exhibit higher shear resistance (Kainthola et al. 2011). Furthermore, these curves obtained for the current study are also indicative that the fines' components have zero-low plasticity nature (Maduka et al. 2016; Igwe and Chukwu 2018). This assertion further confirms the low consistency limits described earlier in this study. However, studies have shown that high-plasticity heavy clays are often characterized by consistently high OMC and very low MDD (Arora 2008; Igwe and Chukwu 2018).

While the porosity of the gully slope materials ranged from 38 to 56%, the permeability coefficients ranged between 4.22×10^{-6} and 4.34×10^{-4} m/s (Table 3). These values suggest that the soils are moderately porous and permeable. This observation aligns well with the particle size distribution, which is composed mostly of coarse-grained materials. While the sandy clay soil (OA1) has the highest porosity, the well-graded sand (NK1) and the sandy gravel (OA2) have the highest permeability. The porosity and permeability results imply that the slope materials could easily allow the percolation of rainwater and the consequent wetting (lubrication) of the soil grain surfaces. The presence of water in soil slopes has been reported to affect their stability (Nebeokike et al. 2020). In such a scenario, the shear resistance of the soils is reduced, thus leading to landsliding.

Moreover, the general perspective for all the slope materials is that they have the tendency to allow pore pressure buildup during saturation. However, it is thought that the CL soil (OA1) with the least permeability coefficient could be experiencing higher (excess) pore pressure buildup during saturation by rainwater.

Whenever soil permeability inhibits the rapid drainage of water from a soil mass, an upsurge in hydrostatic pressure rapidly builds up in the soil (Blyth and de Freitas 2005). Studies carried out by different researchers have shown that, due to the consequent rapid reduction in shear resistance of slope materials during rain infiltration (even under moderate rainfalls), the sliding of inorganic soils is prevalent (Dai et al. 2002; Mugagga et al. 2011). According to Igwe and Una (2019), the matric suction at shallow depths disappears partially or completely as rainwater percolates into the soil slope. With the reduction in the matric suction, the slope material becomes less stable and vulnerable to fail (Li et al. 2005). During periods of complete saturation, the soil matric suction would disappear completely, leading to a drastic reduction in the shear strength of the slope material, the buildup of pore-water pressure, loss of effective stress and eventual failure of the slope (Fukuoka 1980; Wieczorek 1996; Li et al. 2005; Lee et al. 2012).

Shear strength parameters (cohesion and angle of internal friction) provide key insights for verifying the stability of soil slopes. The stability of soil slopes seems to increase with an increase in both shear strength parameters (Muthreja et al. 2012; Coulibaly et al. 2017). However, it is thought that while the angle of internal friction enhances the stability of the slope materials in the dry season, the cohesion of the materials enhances their shear resistance during the rainy season. According to Gupta and Paul (2016), these shear strength parameters, in association with slope geometry, provide definitive and ultimate information regarding the stability of a slope. The results of the parameters for this study are also presented in Table 4. While the cohesion ranged between 1 and 27 kPa, the internal friction angle ranged between 19 and 36°. Similar scores were reported by Igwe (2018) and Igwe and Una (2019). Based on the cohesion and angle of internal friction scores, the gully slope materials are said to have low to moderate shear resistance. This could be attributed to the particle distribution. While the CL soil (OA1) has the highest cohesion, GP, SW and SP soils were observed to exhibit the highest angle of internal friction (Table 3). However, for all the slope materials, rainwater infiltration has the tendency to cause the weakening and failure at varying extents due to reduction in suction and strength (Crosta and Frattini 2008; Igwe 2014; Igwe and Fukuoka 2014; Behara et al. 2016; Igwe and Chukwu 2018). Thus, the slope failure is made obvious when the shear strength is surpassed by the shear stresses acting on the slope.

Table 4 Principal component (PC) loadings

Parameter	PC 1	PC 2	PC 3	PC 4	Communality
Gravel	− 0.740	0.609	0.251	− 0.082	0.988
Sand	0.207	− 0.919	− 0.211	0.020	0.933
Fines	0.902	0.307	− 0.109	0.104	0.930
LL	0.893	− 0.174	0.226	− 0.254	0.944
PI	0.642	0.261	0.051	− 0.536	0.770
MDD	0.723	− 0.630	0.081	0.070	0.932
OMC	0.190	0.668	− 0.514	− 0.108	0.758
ρ	0.187	0.533	0.713	0.333	0.939
G	0.912	− 0.150	− 0.038	− 0.298	0.943
C	0.691	0.659	− 0.222	0.107	0.972
φ	− 0.782	− 0.483	0.206	− 0.213	0.932
NMC	0.354	− 0.182	0.581	0.347	0.617
n	0.630	− 0.132	− 0.406	0.586	0.922
k	− 0.806	− 0.039	-0.494	0.174	0.925
Total	6.298	3.277	1.793	1.136	–
% of variance	44.984	23.410	12.804	8.117	–
Cumulative %	44.984	68.394	81.198	89.316	–

Geostatistical analysis of geomechanical parameters

Principal component analysis

The principal component analysis was performed on the geomechanical parameters using SPSS (v. 22). It was performed to show the key associations (relationships) between the parameters. Four principal component (PC) classes, with their eigenvalues > 1, were extracted and considered (Table 4). A total of 89.316% variability was observed for all the classes. PC values ≥ ±0.5 were considered as significant in this study. The PC 1, with the highest variability of 44.984%, has a high loading on gravel %, fines %, LL, PI, MDD, specific gravity (G), cohesion (C), angle of internal friction (φ), porosity (n), and permeability (k) (Table 4). However, it was observed that some of the parameters in this component class had negative loadings while others had positive loadings. Gravel %, φ, and k had negative loadings, implying that they have closer associations. Closer relationships are also foreseen between the parameters with positive loading in the PC 1 (Table 4). Generally, all the parameters in the PC 1 seem to have special influence on the landslide potentials of the gully slope. The peculiar parameters in this group are the fines and gravels. It has been noted earlier that the soil slopes are generally composed of low fines and gravels. This feature could be responsible for the frequent slides the soil slopes are exposed to.

Based on the PC 1 observation, it is believed that gravel % of the slope materials somewhat influences their frictional angle and permeability. On the other hand, the fines % was found to have closer relationships with the LL, PI, MDD, C, and n. Research has shown that an increasing fines content has a direct influence on the LL, PI, and C (Nath and Dalal 2004; Isik and Keskin 2008; Sudha Rani and Phani Kumar 2011; Sen and Pal 2014; Maduka et al. 2017; Nebeokike et al. 2020). The confirmed relationship between the fines content and the MDD and n equally suggests that an increase in the fines has a positive influence on the dry density and porosity of the slope material. This observation seems to agree with the findings of Arora (2003, 2008) and Igwe and Chukwu (2018). While Arora (2003, 2008) noted that fines generally have higher n than the other soil grains, Igwe and Chukwu (2018) submitted that the association between fines content and dry density could be reflective of the amount of fines present in the soils.

The PC 2 is composed of other important parameters that typically influence slope failures. This component class explained about 23.410% of the total variances and has significant loading on gravel %, sand %, MDD, OMC, bulk density (ρ) and C. While positive loadings were observed on gravel, OMC, ρ, and C, negative loadings were observed on sand and MDD (Table 4). It is revealed in this class that the gravel % influences the OMC and ρ of the soils. Although fines content has been observed to influence the dry density of the soils, the relationship between the sand % and ρ suggests that sand content could partly be influencing the ρ.

While PC 3 explains 12.804% of the total variabilities, PC 4 explains about 8.117% (Table 4). For the PC 3, it was shown that natural moisture content (NMC) also has positive influence on the ρ, whereas the OMC seems to have negative influence on the ρ. For the PC 4, no obvious association seems to exist between the PI and n. Moreover, it is believed that the parameters enlisted in the PCs 3 and 4 play lesser roles (than those in PCs 1 and 2) regarding the landslide vulnerability of the gully slopes.

Linear regression analysis

In this study, linear regression modelling was introduced to help validate the principal component analysis and to better predict and understand the relationships between the analyzed geomechanical parameters. The results of this analysis are shown in Fig. 8. Only significant relationships are reported in Fig. 8. Overall, the results of the linear regression seem to aptly validate the findings of the principal component analysis.

Figure 8a–c showed more of negative significant relationships while Fig. 8d–f reveal more of significant positive associations between the geomechanical parameters. Based on the information provided in Fig. 8a–f, the following deductions can be made: (1) the percentage of gravel that could enhance the resistance of the soils to sliding decreases as the sand content increased, and vice versa (Fig. 8a); (2)
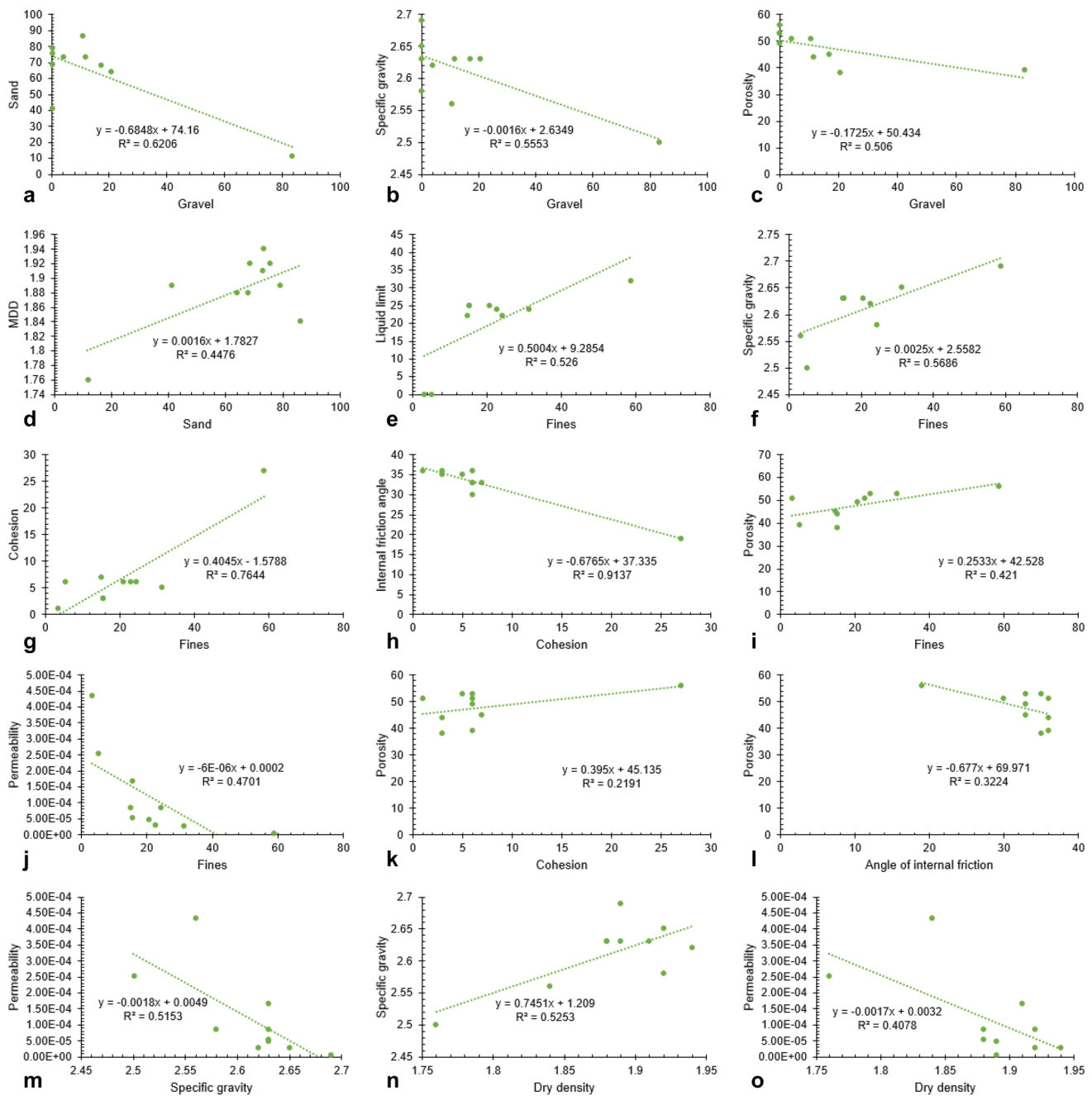
Fig. 8 Regression analytical models for predicting the relationships between the geomechanical parameters

the gravel content inversely influences the soils' specific gravity and porosity (Fig. 8b, c); (3) the sand content directly influences the dry density of the soils, thus, it is predicted that an increase in the sand content increases the dry density (Fig. 8d); and (4) the fines content directly influences the liquid limit and specific gravity of the slope materials (Fig. 8e, f).

Furthermore, on the basis of the information obtained from Fig. 8g–l, some important deductions can be made: (1)

the fines content predicts the cohesion of the slope materials, as a direct positive relationship was observed between the both parameters (Fig. 8g); (2) the cohesion has an inverse association with the angle of internal frictions, thus, the cohesion that would enhance the resistance of the soils to sliding during rain saturation decreases with an increasing angle of internal friction (Fig. 8h); (3) the fines content seems to directly influence the porosity of the slope materials, as an increase in fines was observed to increase their

porosity (Fig. 8i); and (4) the permeability of the slope materials decreases with an increasing fines content (Fig. 8j).

Although the association was weak, the cohesion seems to increase with an increasing porosity (Fig. 8k). This observation could be due to the fact that the both parameters are directly influenced by the fines content. Hence, an increasing fines content directly influences the porosity and cohesion of the slope materials. However, the negative association between the porosity and frictional angle (Fig. 8l) suggests that the more porous the materials are, the lesser their effective stress, which, in turn, is directly related to the angle of internal friction. Analysis of the geomechanical properties of the soils had shown that the slope materials are porous, thus, possessing poor shear strength (ϕ) characteristics.

Figure 8m–o reveal that (1) an inverse relationship exists between the soils' permeability (k) and specific gravity (G) (Fig. 8m), implying that the k is not a function of G and vice versa; (2) the dry density increases as the G increases (Fig. 8n); and (3) similar to the association between k and G, it was learnt that the k also has an inverse relationship with the dry density (Fig. 8o), signifying that the density of the slope materials cannot be used to predict their permeability.

Gully slope stability assessment

Over the years, many lives and properties have been lost to the persistent gullying, often associated with landsliding, in the study area. Therefore, it is important to simulate and analyze the gully slope stability for the following reasons: (1) to forecast/predict the stability of the natural slopes; (2) to enhance environmental impact assessment; (3) to understand the mechanism for the continuous increase in the number of micro and macro erosion gullies with slopes that fail especially during the rainy season; (4) to generate useful information that would allow for a more precise and effective mitigation planning; and (5) to give insights that would aid in the evacuation planning for inhabitants being threatened by this menace.

The stability analysis of the gully slopes was performed based on numerical analytical approach. For the current study, the Morgenstern and Price (1965) limit equilibrium simulations were utilized. The slope stability simulations provide useful information regarding the factor of safety (i.e., the ratio at which a soil's shear strength (resistance) responds to shear stress) required for this analysis. Hence, for a soil slope to be considered stable, the soil strength and soil stress must be in equilibrium. Some gullies were selected across the geologic formations as representatives for the stability analysis. The slope stability models showing the slope morphology and landslide patterns are presented in Fig. 9. While Fig. 9a presents insights for the stability of the soil slopes in unsaturated condition, Fig. 9b provides information about the soil slope stability in saturated condition.

Traditionally, FS < 1 usually indicates an unstable slope whereas FS > 1 roughly indicates a stable slope. Meanwhile, a slope factor of 1 indicates incipient failure (Coduto 2007). Similarly, Mugagga et al. (2011) opined that even FS > 1 is indicative of a conditionally stable slope. However, according to Maduka et al. (2017), it is safer to express the extent of stability and instability based on FS values with respect to 1.5 and 1.0, respectively. According to them, the option of using larger FS values is considered "because of (1) the uncertainties in analysis that must be accounted for, and (2) the presence of triggers in the field that could still be able to cause large soil movements." Therefore, in the present study, (1) FS < 1 is considered to represent an unstable slope; (2) FS = 1 represents a critically stable slope; (3) > 1 FS < 1.5 can be used to indicate a moderately stable slope; and (4) FS > 1.5 is considered a score for satisfactory stability.

Generally, for the unsaturated condition, it is realized that the soil slopes generally have low to moderate FS scores, indicating that the slopes are mostly vulnerable to failure by sliding and collapsing. However, OA2 (a sandy gravel soil) was observed to have a higher FS score of 1.67 (Fig. 9a). This indicates that although this soil has little cohesion (as a result of low fines), it is the most stable and would better resist shear stresses that act on the slopes in the dry season. Nevertheless, the slope stability analysis was also simulated for the rainy season to show the impact rain infiltration could have on the slopes. An obvious decline in the FS of all the slopes was realized (Fig. 9b). This implies that rainfall loading significantly influences the stability of these slope materials by adding extra stresses against their shear strength. This observation is similar to reports of Igwe and Chukwu (2018) and Nebeokike et al. (2020), who studied some soil slopes in different localities in the southeastern Nigeria. Moreover, the obtained FS scores for the Nanka Formation were observed to be within the ranges reported by Igwe and Una (2019).

Furthermore, given the increasing annual rainfall in the study region, the impact of pore-water pressure on the slope stability was also considered in this study. The rainfall intensity, which could be up to 2000 mm per annum, could be detrimental to the slopes by increasing the infiltration and seepage rates of the slope materials. Thus, rainfall-triggered landslides in the mega-gullies are to be anticipated, as the pore-water pressure within the slope materials could rise above normal. The result of the pore-water pressure modelling is shown in Fig. 10. Different intensities of pore-water pressures have been revealed. While it is predicted that the pore-water pressure could only have a fair impact on the slopes in the dry season (unsaturated condition) (Fig. 10a), it is predicted that it could rise up to higher levels in the rainy season (Fig. 10b). This result suggests that the pore-water pressure increase could lead to rapid increase in the acting

Fig. 9 **a** Slope models for selected gully locations/slopes (unsaturated condition). **b** Slope models for selected gully locations/slopes (saturated condition)
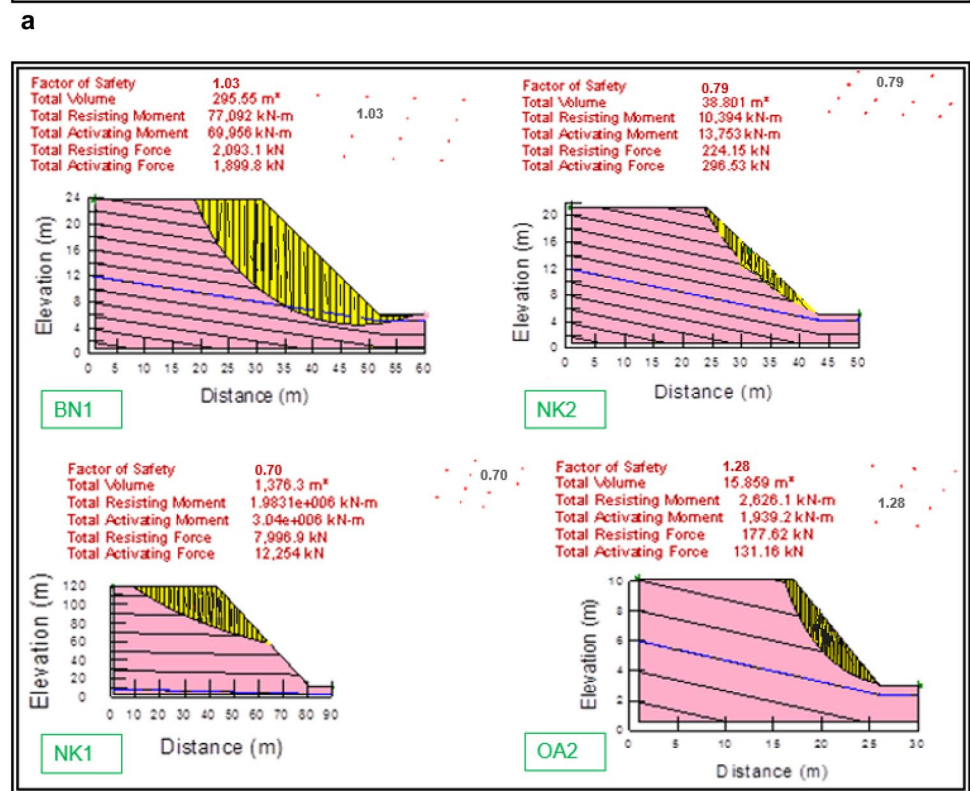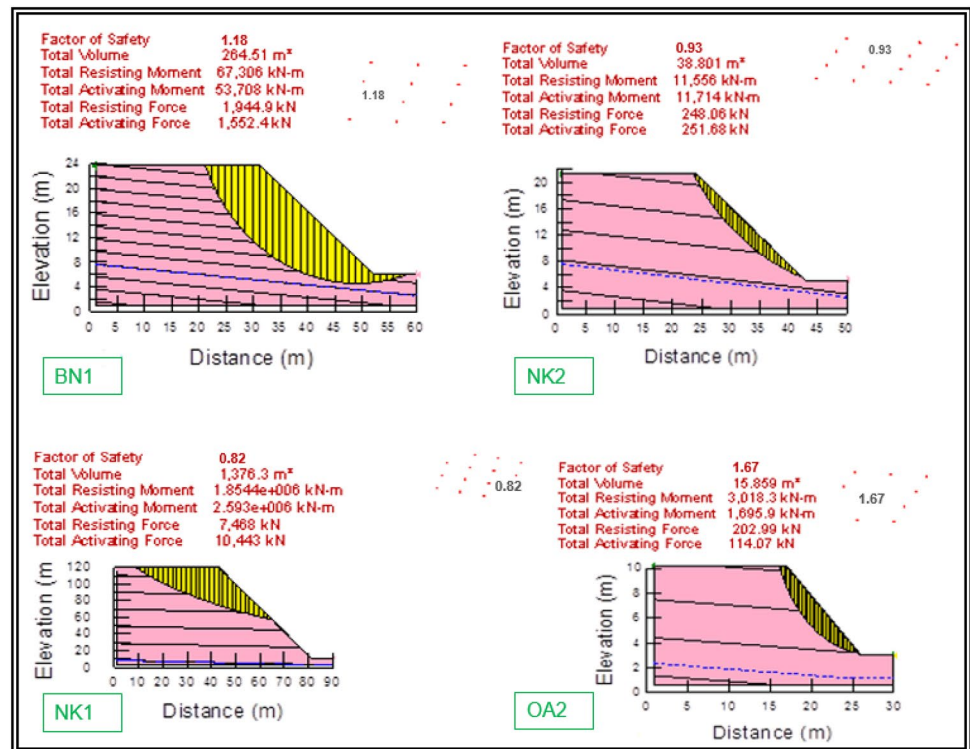
shear stresses on the slope materials, consequent reduction of FS (Behera et al. 2016), and more occurrences of landslides in the rainy season. With more water surges into the slope materials (during extreme rainfalls), the FS

scores could drastically reduce beyond the one predicted and the volume of wasting soil masses may increase further.

Fig. 10 **a** Pore-water pressure models for selected gully locations/slopes (unsaturated condition). **b** Pore-water pressure models for selected gully locations/slopes (saturated condition)
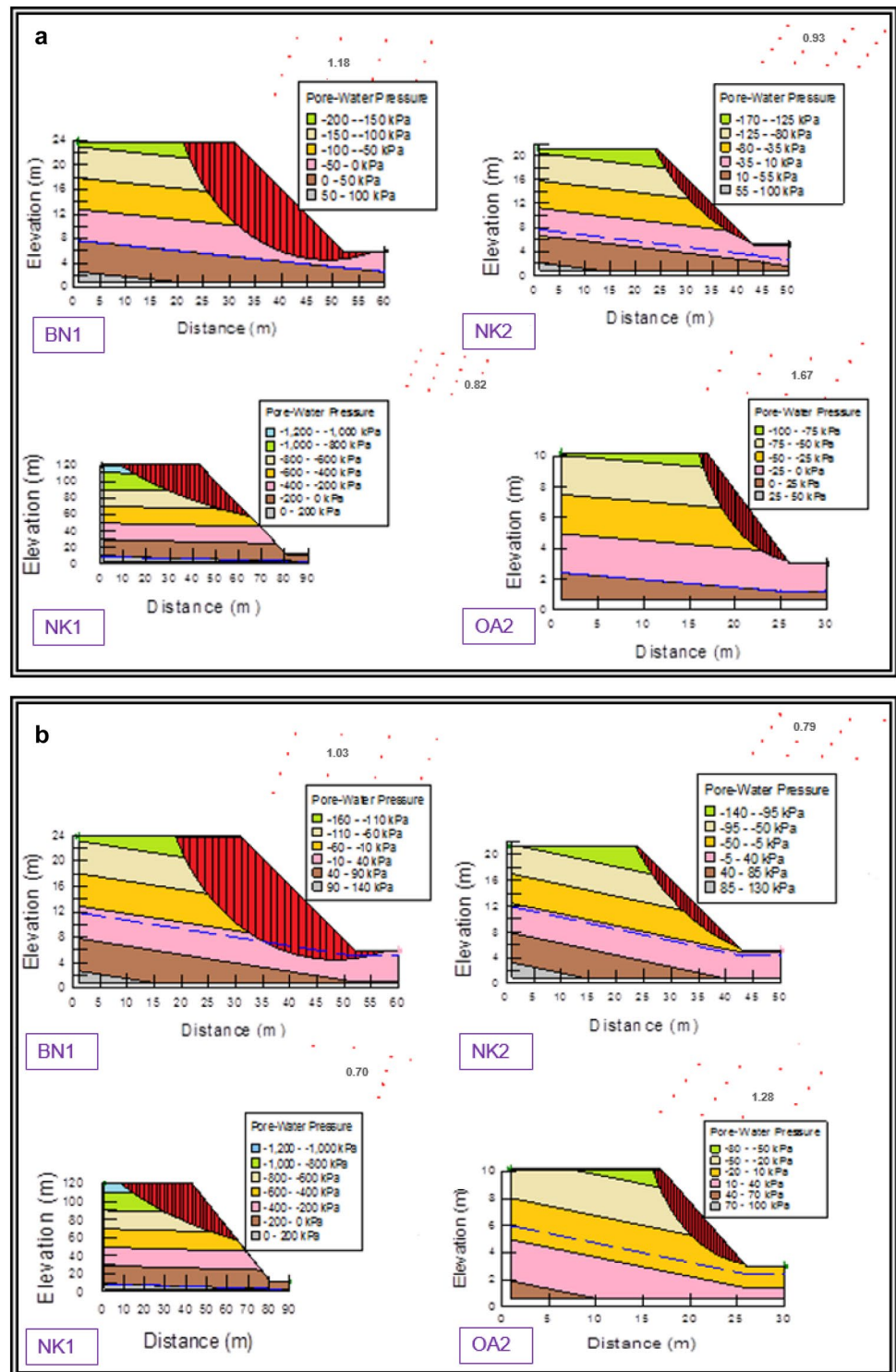

Erosion risk characterization based on factor of safety

Based on the field and analytical evidences provided so far, it is obvious that all the soil slopes are generally vulnerable to landsliding. However, safety maps were generated for the studied area, based on several trial slide models.

The red bands in Fig. 11 are indicative of the most critical, vulnerable slopes. The purple bands are suggestive of zones of stable soil slopes. As shown in Fig. 11, the FS for the study area generally range from 0.82 to 1.72 in unsaturated condition (Fig. 11a) while the FS for saturated condition ranges between 0.70 and 1.33 (Fig. 11b). On this

Fig. 11 a Safety maps for selected gully locations/slopes (unsaturated condition). **b** Safety maps for selected gully locations/slopes (saturated condition)
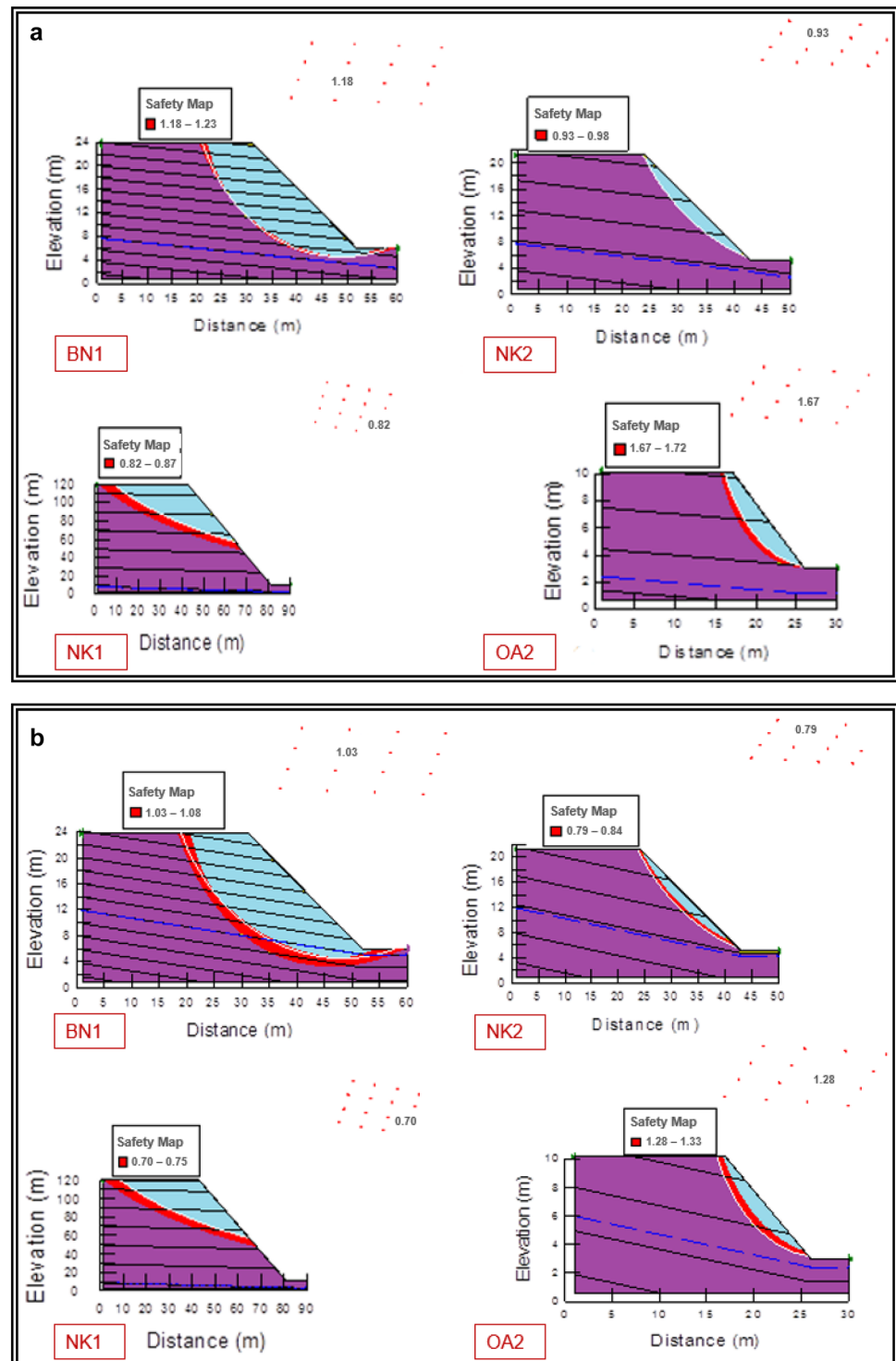
premise, it is adjudged that the gully slopes are more predisposed to high erosion risks in saturated condition than in unsaturated condition. Thus, it is further predicted that majority of the landslides in the study area are rainfall-induced. Under similar conditions, it is also predicted that areas with higher slope angles will experience more failures before areas with lower slope angles (Igwe and Una

2019). Moreover, it is fair to state that the areas (within the Nanka Formation) with higher slopes will likely have higher volumes of potential sliding masses than the areas (within the Ogwashi and Benin formations). Nevertheless, it was realized in this study that GP soil slope was more resistant than the SW, SC, CL and SP slope materials.

Gully slope failure types

There seems to be multiple types and processes of mass wasting in the study area. Specifically, field observations indicate that the area experiences soil slides and debris flows/avalanches. These types of mass wasting have been described by Cruden and Varnes (1996). While soil slides were common to all the slope angle ranges in this study, few debris flows (which sometimes prevail in soil materials with < 50% fines (Cruden and Varnes 1996) were peculiar in some high angle (steep) slopes. The evidences of the debris flow are indicated by the debris fan deposits at the toe of some gully slopes.

It is identified that the saturation (by rainfall, runoff flooding, or groundwater) of gully slope materials is a fundamental cause of landslides in the area. Based on the slope models provided in Figs. 9, 10, 11, the slides are predicted to range from shallow to moderate to high magnitude soil movements. It was also noticed that an increase in the slope angle increased the instability of the gully slopes. For the current study area, the slope heights and lengths are believed to play key roles in determining the slope angles (Igwe and Una 2019).

Additionally, it is pertinent to note that the study area is characterized by complex landslides, since most of the gullies are associated with more than one mode of slope failures. It was observed that the failure mechanism of the gully slopes would more likely follow a rotational (semi-circular) or translational path with substantial sliding masses. However, rotational failure (which is mostly associated with concave slopes (Cruden and Varnes 1996)) is more prevalent in this area than translational failure mechanism. Very high angled slopes were more characterized by translational modes of failures. While some failure surfaces are predicted to pass just below the gully slope toes, some are not.

Measures for slope failure control

So far, the gross findings of this research have indicated that the gully slopes are prone to sliding, which will further impact on the gullying processes, the environment, inhabitants and properties and economy of the study area. Therefore, the following countermeasures are suggested to mitigate the situation.

1. Reduction of gully slopes: benching method seems to be the most commonly–used and inexpensive approach to minimize slope failures (Maduka et al. 2017; Igwe and Chukwu 2018).
2. Stabilization techniques: these include the use of slope material grouting and biotechnical slope protection.
3. Dewatering of slopes: this could heighten the FS and improve the stability of the gully slopes.

4. Adequate construction of surface drainage systems: this could ensure that surface runoffs are well channeled out of these gullies, thereby reducing the shearing stresses on the gully materials and also minimize slope toe cutting by the surface runoffs and floods.
5. Creation and adequate management of landslide database: when landslide hazard information are considered and taken care of in urban and rural planning (e.g. road construction, housing, evacuation), the occurrences and negative effects of the hazard would be kept at barest minimum.

Conclusion

In southern Anambra State, Nigeria, many lives have been lost and families have been displaced due to gully erosion and landsliding. Also, many agricultural lands have been lost; thus, threatening the food security in the area. Moreover, many buildings, roads, other infrastructures as well as socioeconomic events have been hampered due to erosion and landslides. Therefore, it is important to study the dominant erosional processes connected to these environmental hazards. The gully slopes within the current study area were extensively studied to understand the erosion and landslide vulnerability of the area. As revealed by the geomechanical analysis (e.g. particle size distribution, USCS, Atterberg limits, mass-volume and compaction properties, porosity and permeability coefficients) the gully slope materials possess characteristics indicative of high vulnerability to erosion and landsliding. The geostatistical tools (principal component analysis and regression analysis) were useful in determining the interrelationships between the analyzed gully slope parameters. The limit equilibrium simulations used in this study revealed that the slope materials generally have low factor of safety (FS), thus indicating that the slopes are unstable and vulnerable whereas others are critically to moderately stable. While the slopes recorded FS in the range of 0.82–1.72 in unsaturated condition, the FS for saturated condition ranged from 0.70 to 1.33. This result indicated that the gully slopes are more vulnerable in wet season (than in dry season), due to rainwater infiltration, pore-water pressure buildup and reduction in shear strength. Several recommendations have been given to aid the mitigation of this environmental menace in the study area.

Declarations

Conflict of interest The authors hereby declare there is no conflict regarding this paper.

References

Arora KR (2003) Soil mechanics and foundation engineering, 6th edn. Standard Publishers Distributors, Delhi

Arora KR (2008) Soil mechanics and foundation engineering (geotechnical engineering), 8th edn. Lomus Offset Press, Delhi

Baynes FJ (2008) Anticipating problem soils on linear projects. In: Conference proceedings on problem soils in South Africa, vol 34, pp 9–21

Behera PK, Sarkar K, Singh AK, Verma AK, Singh TN (2016) Dump slope stability analysis—a case study. J Geol Soc India 88:725–735

Blyth FGH, de Freitas MH (2005) A geology for engineers. In: Arnold intern students, 7th edn. Arnold Publishing, London

Budhu M (2015) Soil mechanics fundamentals. John Wiley & Sons, United Kingdom

Burman A, Acharya SP, Sahay RR, Maity D (2015) A comparative study of slope stability analysis using traditional limit equilibrium method and finite element method. Asian J Civil Eng (BHRC) 16(4):467–492

Chikwelu EE, Ogbuagu FU (2014) Geotechnical investigation of soil around Mbaukwu Gully Erosion Sites, South-Eastern Part of Nigeria. J Appl Geol Geophys 2(4):6–17

Coduto DP (2007) Geotechnical Engineering: principles and practices. Prentice Hall, Boston, pp 528–529

Coulibaly C, Tikou B, LiZhen C (2017) Numerical analysis and geophysical monitoring for stability assessment of the Northwest tailings dam at Westwood Mine. Int J Min Sci Technol. https://doi.org/10.1016/j.ijmst.2017.05.01

Crosta G, Frattini P (2008) Rainfall-induced landslides and debris flows. Hyd Proc 22(4):473–477

Cruden DM, Varnes DJ (1996) Landslide types and processes. In: Turner AK, Schuster RL (Eds) Special report 247: landslides investigation, mitigation. National Research Council, Transportation Research Board, Washington, DC, pp 36–75

Dai FC, Lee CF, Ngai YY (2002) Landslide risk assessment and management: an overview. Eng Geol 64(1):65–87

Egboka BCE, Nwankwor GI (1985) Hydrogeological and geotechnical parameters as agents for gully-type erosion in the rain-forest belt of Nigeria. J Afr Earth Sci 3:417–425

Egbueri JC, Igwe O (2020) The impact of hydrogeomorphological characteristics on gullying processes in erosion-prone geological units in parts of southeast Nigeria. Geol Ecol Landsc. https://doi.org/10.1080/24749508.2020.1711637

Egbueri JC, Igwe O, Nnamani CH (2017) Assessment of the engineering properties and suitability of some tropical soils as backfill materials. Int J Trends Sci Res Dev 2(1):590–605. https://doi.org/10.31142/ijtsrd7041

Emeh C, Igwe O (2018) Effect of environmental pollution on susceptibility of sesquioxide-rich soils to water erosion. Geol Ecol Landsc. https://doi.org/10.1080/24749508.2018.1452484

Ezechi JI, Okagbue CO (1989) A genetic classification of gullies in Eastern Nigeria and its implications on control measures. J Afr Earth Sci 9(3–4):711–718

Fauziah A, Yahaya AS, Farooqi MA (2006) Characterization and geotechnical properties of Penang residual soils with emphasis on landslides. Am J Environ Sci 2(4):121–128. https://doi.org/10.3844/ajessp.2006.121.128

Fukuoka M (1980) Landslides associated with rainfall. Geotech Eng 11:1–29

Gupta AK, Paul B (2016) Augmenting the stability of OB dump by using fly ash: a geotechnical approach to sustain-ably manage OB dump at Jharia Coal Field. India Current World Environ 11(1):204–211

Horton RE (1945) Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. Geol Soc Am Bull 56(3):275–370

Igwe CA (2012) Gully erosion in southeastern Nigeria: role of soil properties and environmental factors. In: Danilo G (ed) Research on soil erosion. InTech. doi: https://doi.org/10.5772/51020

Igwe O (2014) The compressibility and shear characteristics of soils associated with landslides in geologically different localities—case examples from Nigeria. Arab J Geosci. https://doi.org/10.1007/s12517-014-1616-3

Igwe O, Chukwu C (2018) Evaluation of the mechanical properties and critical slope parameters of mine tailings at Enyigba, Southeastern Nigeria. Geo-Engineering 9:7. https://doi.org/10.1186/s40703-018-0075-1

Igwe O, Egbueri JC (2018) The characteristics and the erodibility potentials of soils from different geologic formations in Anambra State, Southeastern Nigeria. J Geol Soc India 92(4):471–478. https://doi.org/10.1007/s12594-018-1044-1

Igwe O, Fukuoka H (2014) The effect of water-saturation on the stability of problematic slopes at the Iva Valley area, Southeasat Nigeria. Arab J Geosci. https://doi.org/10.1007/s12517-014-1398-7

Igwe O, Una CO (2019) Landslide impacts and management in Nanka area, Southeast Nigeria. Geoenviron Dis 6:5. https://doi.org/10.1186/s40677-019-0122-z

Ilori AO, Wadud MA, Ese EE (2017) Geo-risk analysis of slopes bounding a deep gully erosion site in Uyo, Akwa-Ibom State, Southeastern Nigeria. Innov Infrastruct Solut 2:8. https://doi.org/10.1007/s41062-017-0056-9

Isik Y, Keskin Y (2008) GIS based statistical and physical approaches to landslide susceptibility mapping (Sebinkara-hisar, Turkey). Bull Eng Geol Environ 68:459–471

Kainthola A, Verma D, Gupte SS, Singh TN (2011) A coal mine dump stability analysis—a case study. Int J Geomater 1:1–13

Kalinski ME (2011) Soil mechanics lab manual, 2nd edn. Wiley, Hoboken, p 193

Lee CC, Zeng LS, Hsieh CH, Yu CY (2012) Determination of mechanisms and hydrogeological environments of Gangxianlane landslides using geoelectrical and geological data in Central Taiwan. Environ Earth Sci 66(6):1641–1651

Li AG, Yue ZQ, Tham LG, Lee CF, Law KT (2005) Field-monitored variations of soil moisture and matric suction in a saprolite slope. Can Geotech J 42:13–26

Maduka RI, Ayogu NO, Ayogu NC, Gbakurun GA (2016) Role of smectite-rich shales in frequent foundation failures in southeast Nigeria. J Earth Syst Sci. https://doi.org/10.1007/s12040-016-0727-5

Maduka RI, Igwe O, Ayogu NO, Ayogu CN, Nwachukwu M (2017) Geotechnical assessment of road failure and slope monitoring along Nsukka-Aduru-Idah highway, Southeastern Nigeria. Environ Monit Assess 189:1–18

Morgenstern NR, Price VE (1965) The analysis of the stability of general slip surfaces. Geotechnique 15:79–93

Msilimba GG, Holmes PJ (2005) A landslide hazard assessment and vulnerability appraisal procedure vunguvungu/Banga catchment. Northern Malawi Nat Hazards 34(2):199–216. https://doi.org/10.1007/s11069-004-1513-2

Mugagga F (2011) Land use change, landslide occurrence and livelihood strategies on Mount Elgon slopes, eastern Uganda. Unpublished PhD thesis. Nelson Mandela Metropolitan University, Port Elizabeth

Mugagga F, Kakembo V, Buyinza M (2011) A characterisation of the physical properties of soil and the implications for landslide occurrence on the slopes of Mount Elgon. Nat Hazards, Eastern Uganda. https://doi.org/10.1007/s11069-011-9896-3

Muthreja IL, Yerpude RR, Jethwa JL (2012) Role of site selection on the stability of surface coal mine waste dumps. Indian Min Eng J 51:9

Nath A, Dalal SS (2004) The role of plasticity index in predicting compression behavior of clays. Elect J Geotech Eng 9:1–7

Nebeokike UC, Igwe O, Egbueri JC, Ifediegwu SI (2020) Erodibility characteristics and slope stability analysis of geological units prone to erosion in Udi area, southeast Nigeria. Model Earth Syst Environ 6(2):1061–1074. https://doi.org/10.1007/s40808-020-00741-w

Nwajide CS (2013) Geology of Nigeria's sedimentary basins. CSS Press, Lagos

Obiadi II, Nwosu CM, Ajaegwu NE, Anakwuba EK, Onuigbo NE, Akpunonu EO, Ezim OE (2014) Gully erosion in Anambra State, South East Nigeria: issues and solution. IJES 2(2):796–804

Okagbue CO (1992) The 1988 Nanka landslide, Anambra state. Nigeria Bull Int Assoc Eng Geol 46(1):79–87

Okoyeh EI, Akpan AE, Egboka BCE, Okeke HI (2014) An assessment of the influences of surface and subsurface water level dynamics in the development of Gullies in Anambra State, Southeastern Nigeria. Earth Interact 18:1–24

Reidenouer DR (1970) Shale suitability, Phase II: Pennsylvania Department of Transportation, Bureau of Materials. Test Res Interim Rep 1:198

Schuster RL, Highland LM (2003) Impact of landslides and innovative landslide-mitigation measures on the natural environment. In: Proceedings of the international conference on slope engineering. University of Hong Kong, Hong Kong

Sen B, Pal SK (2014) Index properties of soils collected from different locations and correlations of parameters. Elect J Geotech Eng 19:3443–3452

Sudha Rani CH, Phani Kumar V (2011) Prediction of compression index of soils using artificial neural networks (ANNs). Int J Eng Res Appl (IJERA) 1(4):1554–1558

Tuncer OD, Lohnes CG (1977) Specific gravity of soils. J Geol 75:432–534

Wang D, Fan H (2019) Distribution characteristics of gullies with slope gradient in Northeast China. Environ Monit Assess 191:379. https://doi.org/10.1007/s10661-019-7501-5

Wieczorek GF (1996) Landslides triggering mechanisms. In: Turner AK (ed) Landslides investigation and mitigation, pp 76–90. National Research Council, Transportation Research Board, Washington

Yalcin A (2007) Environmental impacts of landslides: A case study from East Black Sea region. Turkey Environ Eng Sci 24(6):821–833