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Integrated geotechnical, hydromechanical, and remote sensing assessment of gully erosion dynamics and slope instability in Edda, Southeastern Nigeria under changing rainfall regimes

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Abstract

Gully erosion in southeastern Nigeria is commonly expressed as rapid channel incision and headward and lateral expansion, yet the interaction between surface hydraulic erosion and rainfall-induced slope instability in sandstone–shale terrains remain insufficiently resolved. This study investigates the controls and evolution of gully erosion in Edda, southeastern Nigeria, by integrating geological and field observations, geotechnical characterization, slope-stability analysis, rainfall records, and multi-temporal remote sensing. Twenty (20) gully sites were investigated, and representative near-surface soil samples were analysed for natural moisture content, particle-size distribution, Atterberg limits, compaction characteristics, bulk density, specific gravity, permeability, and shear-strength parameters. The investigated materials, derived from the Campanian Nkporo Shale and overlying Afikpo Sandstone, contain 33–94% sand and 4–45% clay and are predominantly classified as poorly to well-graded sands and silty to clayey sands. Specific gravity ranges from 2.57–2.67, bulk density from 1.54–1.96 g/cm³, and plasticity index from non-plastic to 13.67%, indicating predominantly loose, weakly cohesive and erodible materials. Representative gully-slope geometries and geotechnical parameters were analysed in SLOPE/W using the Morgenstern–Price limit-equilibrium method. Factors of safety range from 0.60–0.92 under saturated conditions and 0.63–1.20 under unsaturated conditions, demonstrating substantially greater susceptibility to gravitational failure during wet conditions. Multi-temporal satellite analysis shows progressive gully elongation from 105 m in 2008 to 200 m in 2024, equivalent to approximately 5.94 m/year, accompanied by marked lateral enlargement. The combined evidence indicates that gully development is not governed by a single process but by an interacting erosion–failure system: rainfall and concentrated runoff promote soil detachment, transport and channel incision, while wetting-related weakening of gully margins reduces slope resistance and facilitates gravitational collapse. The study therefore provides an integrated, site-based framework linking material erodibility, rainfall, gully morphometric change and slope instability, offering transferable insight for erosion assessment and targeted mitigation in sandstone–shale landscapes of southeastern Nigeria and comparable humid tropical regions.

Keywords: Environmental impact; Factor of safety; Geotechnical analysis; Gully erosion; Satellite imagery.

1. INTRODUCTION

The term "erosion" originates from the Latin word "rodere," meaning "to gnaw." Erosion is broadly defined as the process by which soil and rock are detached from the Earth's surface due to exogenic forces such as wind and water flow, subsequently transported, and deposited in other locations. Ofomata (2002) characterizes soil erosion as the systematic removal of soil, including essential plant nutrients, from the land surface due to denudational agents. This process occurs at an accelerated rate, resulting in the displacement and transport of soil faster than its natural regeneration. Wind and water are the primary drivers of erosion, with water playing a dominant role. The erosional process begins with the impact of raindrops on the soil surface, which dislodges particles. These loosened

particles are then mobilized by surface runoff through drag and tractive forces. Anthropogenic activities such as deforestation and improper land use further exacerbate soil erosion. Typically, erosion follows weathering processes, where rocks and minerals degrade into smaller, transportable particles that are later relocated, often assisted by gravitational forces.

Among various forms of soil erosion, gully erosion is a significant environmental hazard affecting the Edda region and its environs in the Afikpo South Council of Ebonyi State (Fig. 1), in the southeast geopolitical zone of Nigeria. The region has experienced extensive weathering and erosion due to its humid tropical climate, leading to the development of deep gullies and other erosional features. The interplay of underlying geology, precipitation patterns, and human activities has rendered Afikpo South (Edda) highly vulnerable to rapid soil loss, particularly through gully erosion. This phenomenon adversely impacts agriculture, infrastructure, and socio-economic development in both urban and rural settings. In response to this challenge, an integrated geological and geotechnical investigation was undertaken to evaluate the factors controlling erosion in the study area contributing to gully erosion formation and expansion. The findings facilitated the formulation of recommendations for effective erosion control measures tailored to the affected areas.

Experimental investigations employing simulated rainfall under both ambient and controlled conditions have been widely conducted to evaluate the influence of key factors and processes governing soil erodibility. However, a comprehensive understanding of erosion dynamics requires the integration of soil genesis and classification, intrinsic soil properties, and prevailing geomorphic and climatic controls, as well as consideration of the fundamental mechanisms of soil erosion. In southeastern Nigeria, gully erosion has emerged as one of the most severe environmental challenges confronting numerous towns and rural communities (Okorafor et al., 2017). The rapid expansion of gullies has rendered large portions of the region increasingly unsafe for human habitation, resulting in the displacement of hundreds of people annually. In addition, extensive tracts of agricultural land have become unsuitable for cultivation, as erosion degrades soil quality and significantly reduces agricultural productivity (Egboka et al., 2019). Effective land management is therefore critical in southeastern Nigeria, where the combined effects of geotectonic setting, geological framework, and hydrogeological conditions predispose many areas to severe gully erosion. Prominent geomorphic features such as cuestas, fractures, and joints are widespread in erosion-prone terrains across the region and have been identified as major structural controls influencing gully initiation and development (Gobin et al., 1999; Okagbue and Uma, 1987).

Globally gullies have contributed largely to soil fertility depletion, building collapse, pavement destruction, soil structure degradation, reducing effective rooting depth reduction and destroying the most basic of all natural resources, Lal, R. (2003); Meliho et al (2018); Hitouri et al (2024). Soil erosion has become an endemic environmental problem; however, its impacts are particularly pronounced in southeastern Nigeria (Ofomata, 1987; Ogbukagu, 1976; Egboka and Okpoko, 1984; Okagbue and Uma, 1987). In Ebonyi State, several areas initially classified as high-risk erosion zones progressively evolved into extreme erosion hotspots between 2002 and 2011, reflecting the intensification of erosion processes and the growing severity of land degradation in the region (Akpokodje et al., 2010; Ezezika and Adetona, 2011; Obiadi et al., 2011).

Despite extensive global research on gully erosion susceptibility in southeastern Nigeria, important uncertainties remain regarding how material properties, rainfall-driven hydrological changes, slope geometry, and gravitational instability interact during gully development. Previous studies have commonly examined soil erodibility, rainfall–runoff processes, geomorphological change, or slope instability as individual controls, with comparatively limited

integration of these processes within a single site-based assessment (Wei et al., 2022; Conforti et al., 2011; Meliho et al (2018); Hitouri et al (2024)).

This study addresses this gap by developing an integrated erosion–slope instability framework for the Edda region. The framework conceptualizes gully development as a sequence of interacting processes in which rainfall generates surface runoff and infiltration; these processes influence soil moisture and pore-water conditions, while the resulting changes in effective stress and shear resistance affect the stability of gully margins. At the same time, soil texture, gradation, permeability, cohesion, and slope geometry influence the susceptibility of the material to detachment and gravitational failure. Progressive headward and lateral gully expansion observed from multi-temporal imagery provides field-scale evidence of the resulting geomorphic response.

The novelty of the study therefore lies not in the use of a new individual analytical method, but in the integration of geotechnical characterization, slope-stability modelling, rainfall analysis, soil erodibility assessment, and multi-temporal gully morphometry to establish a process-based interpretation of gully evolution in a sandstone and shale terrain. This integrated framework provides a basis for distinguishing surface erosion processes from the gravitational failure processes that contribute to gully widening and headward propagation.

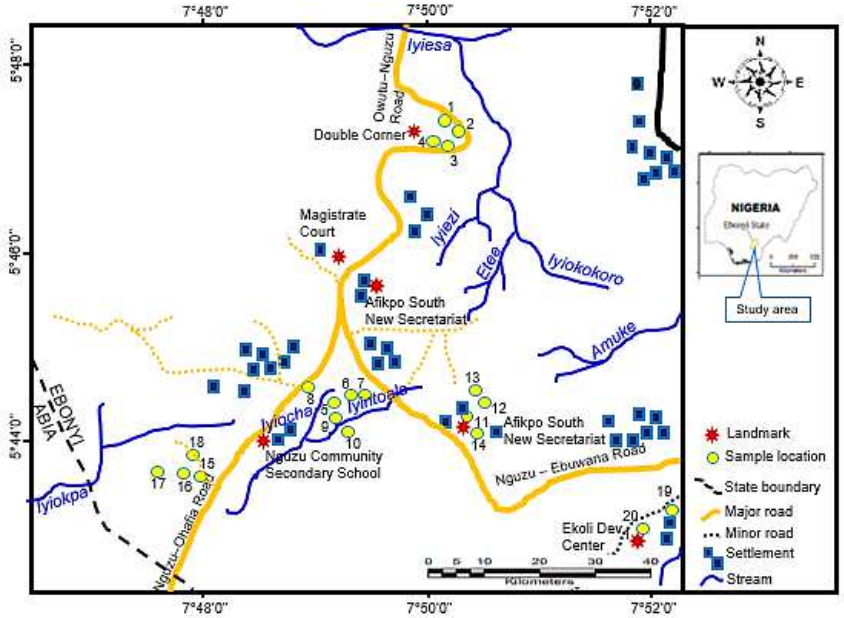


Fig. 1. Location and accessibility map of Edda area and environs (After Amah et al., 2021) (Insets: Maps of Nigeria)

2. STUDY AREA DESCRIPTION

The study area is located in Afikpo South Council of Ebonyi State, as shown in Fig. 2. It lies between longitudes 7° 48′ E and 7° 53′ E and latitudes 5° 44′ N and 5° 48′ N, covering an estimated aerial extent of about 62 km². Afikpo South council (locally referred to as 'Edda') is a region in the southeastern Nigeria geopolitical comprising several communities, including Ndienomenyi, Ufueseni, Ama-Ekpe, Owutu, Ndiba, Amoba, Igbara, Ekeje, Amaiyi, Nkakwu, Ebunwana, Achara, Amamini, Ndi-Olughu, Letu, Okponta, Ogwuma, Ekoli, Elegu, and Nguzu. The area is characterized by a diverse topography, with undulating hills, valleys, and river networks that influence settlement patterns and land use. Edda serves as a key administrative and socio-economic hub within Afikpo South, with agriculture, trade, and local industries playing a vital role in the livelihoods of its inhabitants. The region is accessible via a network of roads that connect it to neighboring communities and urban centres (Okeke et al., 2015).

The geology of Edda in Ebonyi State is characterized by sedimentary rock formations (Fig. 2) that were deposited during the Mesozoic and Cenozoic eras due to tectonic rifting and subsidence. The region is primarily underlain by the Campano-Maastrichtian Nkporo Formation and Afikpo Sandstone, composed of shale, sandstone, and clay.

These deposits were influenced by ancient rivers and seas, with multiple marine transgression and regression cycles shaping the stratigraphy. The Nkporo Formation consists mainly of dark shales and mudstones, often rich in organic matter, indicating potential hydrocarbon presence. It also contains minor interbeds of sandstone and siltstone. The Afikpo Sandstone, on the other hand, is composed of thick, well-bedded, coarse-to-medium-grained sandstones, suggesting deposition in a fluvial to shallow marine environment. The area also exhibits evidence of weathering and erosion, contributing to the formation of gullies and land degradation, which impact agriculture and settlement patterns.

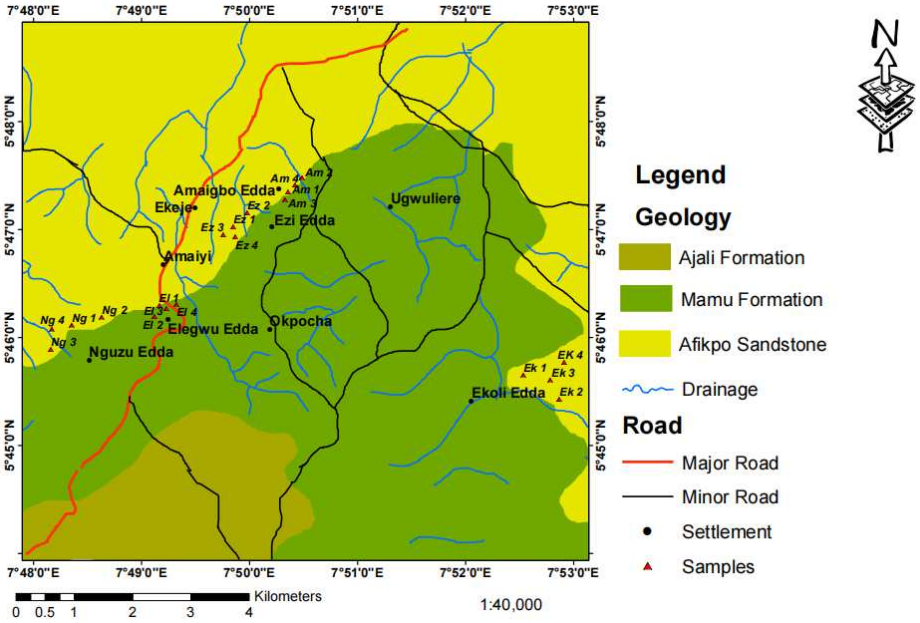


Fig. 2. Geological map of the Edda area and environs

Edda area exhibits a diverse geomorphological landscape characterized by undulating hills, valleys, and low-lying plains. The terrain is shaped by prolonged erosion, fluvial activities, and weathering, which contribute to the formation of deep gullies and rugged topography (see Fig. 3). The area is primarily divided into three principal ecological zones: the forest, savannah, and swampy forest. However, these zones have been significantly altered due to natural processes and human activities such as deforestation, agriculture, and urbanization. The climate of Edda aligns with that of southeastern Nigeria, experiencing two major seasons: the rainy season (April to October) and the dry season (November to March). The southwesterly winds bring substantial rainfall, with mean monthly values peaking in July (20.41 mm) and September (21.20 mm), while the harmattan season, driven by the northeasterly trade winds, is characterized by dry conditions and low humidity between December and February. The region's drainage system is dominated by the Cross River and its tributaries, including the Obumkpuma, Ugwuakalilu, Amoba, Wowo, and Ipoko streams. These water bodies play a crucial role in local agriculture and water supply but also contribute to erosion and sediment transport, further shaping the area's geomorphology. A combined drainage and elevation contour map of the area is presented in Fig. 4.

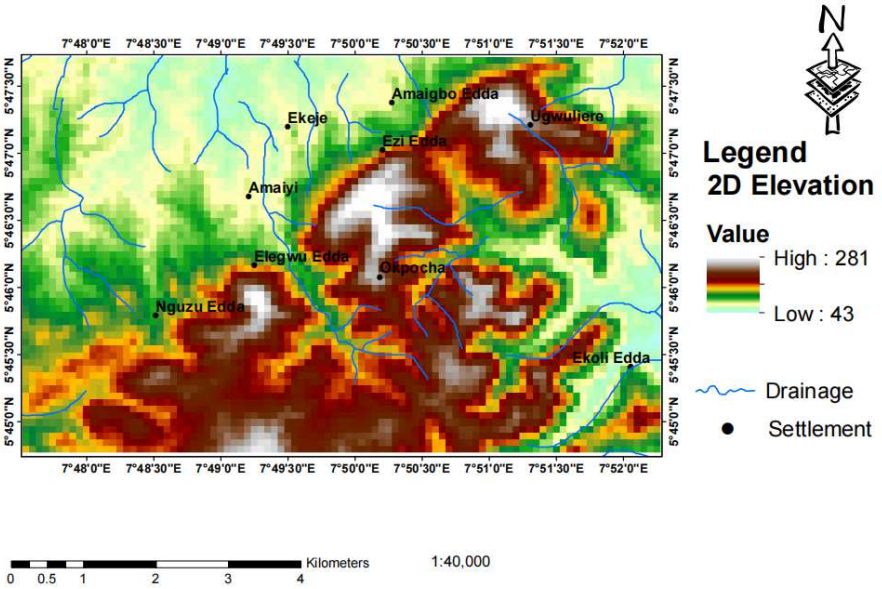


Fig. 3a. 2D-Digital elevation model of Edda area and environs

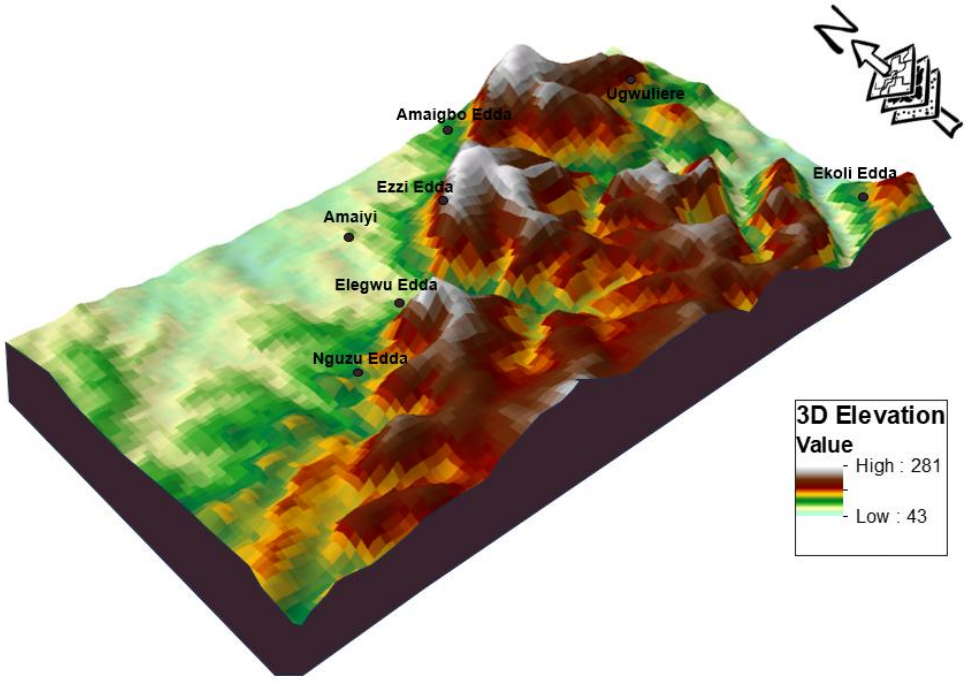


Fig. 3b. 3D-Digital elevation model of Edda area and environs

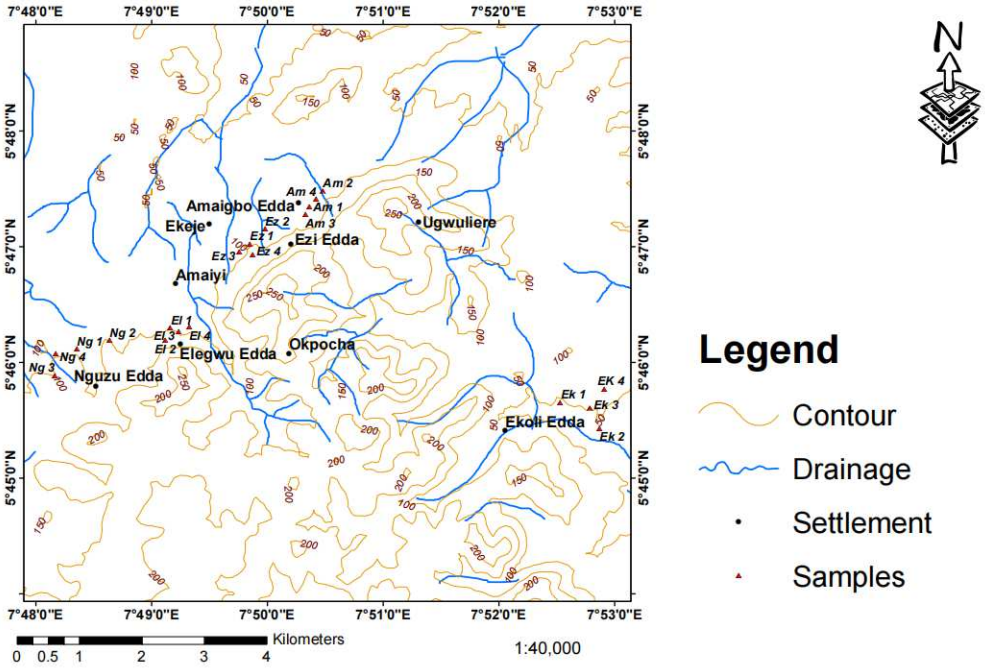


Fig. 4. Drainage and elevation contour map of the study area

The underlying lithostratigraphic units observed in the study area are the Nkporo Group which comprises of blue-grey shale with high fissility and the overlying Afikpo Sandstone comprising of unconsolidated sandstone with gradual facie change to shally-sand while moving from Owutu towards Nguzu. It is interbedded by ironstone. The two units mapped within the Nkporo Shale are herein designated as Units A to C, and are described as follows.

Unit A (Shales): It is the oldest sediment in the study area. It is grey in colour with shiny spots of mica minerals. The shales are highly fissile with siderite concentration and also highly fossiliferous in some areas, with only few species being able to survive due to harsh condition of the environment. They contain mica mineral mostly muscovite. Shales occurred at various locations in the study area such as, Ekeje Edda, Ameyi, Ebunwana, and Nguzu Edda. There was a boundary between the shale and the sandstone. The boundary was observed along Ekeje-Amoba stream. At Achara and Ebunwana, the shales are highly jointed. The joints were filled with iron materials. The shale strikes in a NE-SW direction with an angle of dip ranging from 5 to 10°. The shales as observed at Ekeje, about 15meters away from ekeje primary school which are very dark in colour and fissile indicating that the shale must have been deposited in a deep anoxic marine environment. Reddish brown discolouration on the shale in some part indicates weathering (chemical). Mineralogical composition; presence of clay mineral, most likely to be Kaolinite, plant fragment and abundant gypsum ($CaSO_42H_2O$) are present in the shale.

Unit B (Sandy-shales): The sandy-shale intercalation was observed along ebunwana road in the study area. It is interbedded with little ironstone, of which the coordinates were taken to be latitudes 5° 46' 06.7" N and longitudes 7° 57' 51.8" E with an elevation of 78 ± 3 m above sea level. The sandy-shale represents thick section weathered shale that has been mixed with sandstone. The shales are occurring as laminas and are fissile and dry. The shales at the base of this outcrop are very dark grey and highly laminated. The sandstone in between these shales are greyish white in colour, with fine to medium grain size and are poorly sorted. Iron stone and mica are scattered throughout the clay. The outcrop strikes in a NE-SW direction with a dip amount of 5°.

Unit C (Sandstones): The Afikpo Sandstone, of Campanian age, forms part of the Nkporo Group and conformably overlies the Nkporo Shale. This unit was observed within the study area at Ezzi Edda (latitude 5° 48′ 31.0″ N and longitude 7° 50′ 36.0″ E). Field observations reveal that the sandstone is highly friable, with grain sizes ranging

from fine to coarse, though predominantly medium-grained. The lithology exhibits a milky to dirty white coloration and trends in a NE–SW direction, with dip angles varying between 15° and 47°.

Notably, the formation is poorly sorted and predominantly matrix-supported rather than grain-supported, indicating weak intergranular bonding. Visual inspection further shows that the sandstone is highly susceptible to erosion, as evidenced by its loose texture, lack of cohesion, and ease of disintegration under minimal mechanical disturbance. Sedimentary structures such as herringbone cross-bedding and joints are present, and their orientations were measured during field investigations. These structural features, combined with the friable and poorly consolidated nature of the sandstone, significantly enhance its vulnerability to weathering and erosional processes.

3. MATERIALS AND METHODS

3.1 Field investigation and soil sampling

A detailed field study of the Edda area was carried out in February 2025. During this period, a total of 20 gully erosion sites were visited within the Edda communities, where representative soil samples were collected for testing. A representative gully site studied is presented in Fig. 5. The soil samples were placed in a well-sealed and labelled sampling bag to minimize the loss of the soil natural moisture. It involved detailed geologic descriptions of out cropping units with emphases on their texture, colour and structures. At every sampling point, about 5 kg of soil samples were collected after the removal of the top soil from a depth of 25 – 30 cm to ensure that a true and fresh representative soil sample devoid of humus was obtained.

3.2 Laboratory testing

The samples were analyzed at the Materials Laboratory of the Ebonyi State Ministry of Works and Transport, Abakaliki. Soil engineering and geotechnical tests were carried out following standard procedures. The tests and the relevant American Society for Testing and Material (ASTM) procedures followed included specific gravity (ASTM D-18 (2006)), permeability (ASTM D5084 (2010)), shear strength parameters (cohesion, c, and angle of internal friction, φ, ASTM D3080 (2011)), particle size distribution (ASTM D422–63 (2007)), and compaction characteristics (maximum dry density, ρ_d, optimum moisture content, m_{opt}, ASTM D-18 (2009)). The other tests included natural moisture content, m_c (ASTM D (2010)), Atterberg limits (liquid limit, I_L, plastic imit, I_P, and plasticity index, PI (ASTM D4318 (2017)).

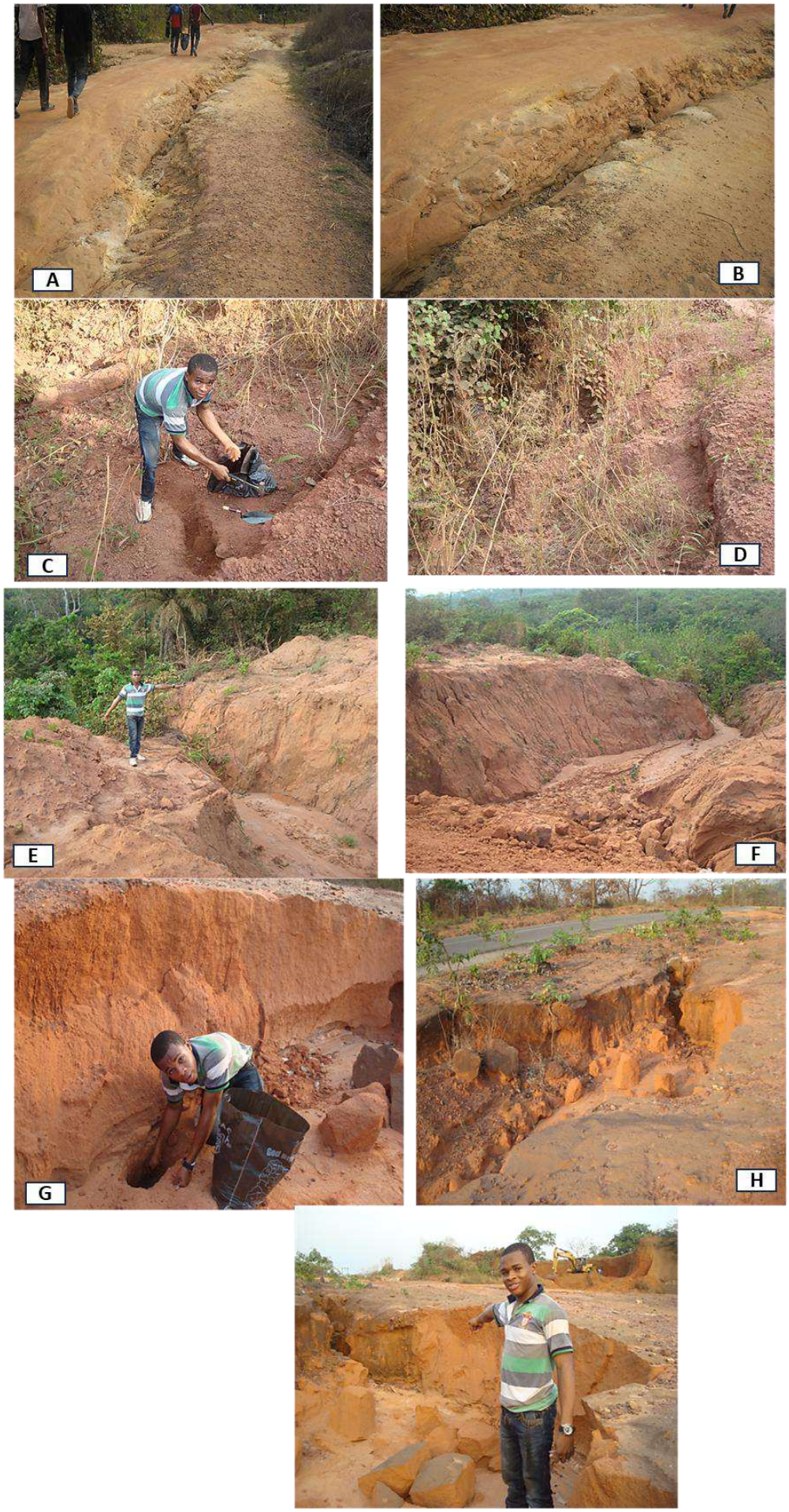


Fig. 5. Representation of some studied gully sites and sampled points; (a) Far view road cut caused by erosion at Amaigbo, (b) Near view of the gully at Amaigbo site, (c) Sample collection at Elegu gully site, (d) Side view of the Elegu gully site, (e) Side view of deep gully site at Nguzu Edda, (f) Front view of the gully at Nguzu Edda, (g) Active head cut erosional site at Ekoli, and (h) Sample collection at Ekoli gully site. (Source: field work 2023)

3.2.1 Slope Stability Analysis

The results obtained from the field investigations and laboratory testing were integrated into SLOPE/W, GeoStudio Version 2012, to develop representative numerical models of the investigated gully slopes and evaluate their stability and potential failure mechanisms. The slope geometry was defined using field derived measurements, including the gully slope height, width, and slope angle. These geometric parameters were used to construct a representative model of the existing gully slope morphology within the software environment. Laboratory-derived geotechnical parameters, including cohesion (c), angle of internal friction (φ), and unit weight (γ), were subsequently assigned to the corresponding soil materials within the model.

Slope stability analysis was performed using the Morgenstern–Price limit equilibrium method (LEM) (Morgenstern and Price,1965), a rigorous method of slices that satisfies both overall force and moment equilibrium and is widely applied in engineering geology and geotechnical engineering for evaluating the stability of natural and engineered slopes. Although commonly applied to landslides and other slope failures, the method was employed in this study specifically to investigate the stability conditions of the gully slopes. The analysis was used to identify potential critical slip surfaces, determine the corresponding Factor of Safety (FoS), and predict the likely failure mechanisms under the modelled conditions. The results provided a quantitative assessment of gully slope stability and susceptibility to slope failure.

Two moisture-state scenarios were considered to represent contrasting seasonal boundary conditions. The saturated scenario was used as a wet-season end-member condition, representing a conservative state in which the beneficial contribution of matric suction to apparent shear strength is assumed to be negligible. The unsaturated scenario was used as a dry-season end-member condition to represent the comparatively greater shear resistance associated with unsaturated soil conditions. These scenarios were used for comparative stability assessment rather than as a transient simulation of rainfall infiltration.

Because field measurements of matric suction, soil-water characteristic curves, groundwater levels, and transient pore-water pressure were not available, the analysis does not constitute a fully coupled hydro-mechanical or transient seepage model. Instead, the difference between the saturated and unsaturated cases is interpreted as an assessment of the potential influence of seasonal moisture conditions on gully-slope stability. The resulting FoS values were subsequently evaluated together with field observations, rainfall trends, soil properties, and multi-temporal gully expansion to establish the likely role of wet-season conditions in promoting gully-wall instability.

3.2.2 Satellite imagery analysis

Aerial imagery obtained from Google Earth Pro was utilised to monitor and assess the temporal development of gullies within the Nguzu Edda area over a fifteen-year period. Historical images representing different observation periods were examined to evaluate changes in gully morphology and spatial extent. The longitudinal and lateral dimensions of the gullies were measured using the ruler tool available in Google Earth Pro. These measurements were subsequently compared across the selected years to determine the rates and patterns of gully expansion. The analysis provided quantitative estimates of gully growth in both length and width, thereby enabling an assessment of the temporal progression and geomorphological evolution of the gully systems.

3.3 Calculation of soil erodibility factor

The soil erodibility factor (K) was determined using the formula introduced by Jain and Singh (2003). This factor characterizes a soil's susceptibility to erosion and is integral to erosion prediction models such as the Revised Universal Soil Loss Equation (RUSLE). The soil erodibility factor (K) is expressed as shown in Eq (1):

$$K_{fact} = 1.292\ [2.1 * 10^{-6}\ F_p^{1.14}\ (12- P_{om}) + 0.0325\ (S_{struc} - 2) + 0.\ 025\ (F_{perm} -3)] \quad (1)$$

Where, F_p is the particle size parameter, P_{om} is the percentage of organic matter, S_{struc} is the soil structure index, F_{perm} is the profile-permeability class factor, and P_{clay} is the percentage of clay content.

F_p is computed using Eq (2) as;

$$F_p = P_{silt}\ (100 - P_{clay}) \quad (2)$$

Values were assigned to soil structure and permeability class factors based on specific classifications. For soil structure, values were designated as follows: 1, very fine granular soil; 2, fine granular soil; 3, Medium or coarse granular soil; and 4, blocky, platy, or massive soil. Similarly, for permeability class, values were assigned as follows: 1, very slow infiltration; 2, slow infiltration; 3, low to moderate infiltration; 4, moderate infiltration; 5, moderate to rapid infiltration; and 6, rapid infiltration.For the study area, the following F_p values were used: organic matter (P_{om}) = 0.1; soil structure index (S_{struc}) = 2.5, and permeability class factor (F_{perm}) = 6. Based on K, the studied sites were classified as presented in Table 1.

Table 1. Description of the gully sites and sampled points

Location no.	Location name	Coordinates		Status	Gully depth (m)	Gully width (m)	Slope angle (°)
		Lat.	Long.				
1	Nguzu	05^{0}46'38.2"	007^{0}48'29.2"	Very active	21	12	87
2	Nguzu	05^{0}46'37.2"	007^{0}48'30.1"	Very active	23	11	82
3	Nguzu	05^{0}45'41.2'	007^{0}48'30.2"	Very active	24	5	90
4	Nguzu	05^{0}46'43.7"	007^{0}48'30.6"	Very active	31	17	85
5	Ekoli	05^{0}45'52.9"	007^{0}49'49.1"	Active	4	3	87
6	Ekoli	05^{0}45'53.9"	007^{0}49'47.1"	Active	5	4	81
7	Ekoli	05^{0}45'56.1"	007^{0}49'51.1"	Active	7	2	78
8	Ekoli	05^{0}45'57.3"	007^{0}49'54.7"	Very active	7	4	80
9	Ezzi	05^{0}48'31.0"	007^{0}50'36.0"	Active	4	5	75
10	Ezzi	05^{0}48'33.0"	007^{0}50'36.7"	Very active	4	4	85
11	Ezzi	05^{0}48'34.0"	007^{0}50'36.9"	Active	6	3	70
12	Ezzi	05^{0}48'39.0"	007^{0}50'35.0"	Partially active	7	4	70
13	Amaigbo	05^{0}47'47.5"	007^{0}49'53.5"	Active	4	4	75
14	Amaigbo	05^{0}47'47.9"	007^{0}49'54.1"	Partially active	2	1	70
15	Amaigbo	05^{0}47'48.2"	007^{0}49'54.2"	Partially active	3	2	81
16	Amaigbo	05^{0}47'48.4"	007^{0}49'54.7"	Active	4	3	75
17	Elugwu	05^{0}46'07.6"	007^{0}49'29.8"	Partially active	3	3	57
18	Elugwu	05^{0}46'07.9"	007^{0}49'29.9"	Active	2	2	60
19	Elugwu	05^{0}46'09.6"	007^{0}49'30.21"	Partially active	5	3	45
20	Elugwu	05^{0}46'09.7"	007^{0}49'30.16"	Partially active	3	2	54

4. RESULTS AND DISCUSSION

4.1 Field observation

The gullies identified within the study area are characteristically deep, elongated, and laterally expanding, reflecting the inherent geotechnical properties of the soils. They are defined by steep to near-vertical sidewalls, which indicate active headward erosion and progressive sidewall collapse. Surface runoff generated during intense seasonal rainfall is strongly channelized along natural drainage lines, footpaths, road corridors, and inadequately designed drainage outlets. This concentration of runoff significantly accelerates gully initiation and enlargement, particularly in Nguzu and Ekoli Edda. The soils exposed within the gully walls are predominantly sandy to sandy–clayey, poorly graded, and characterized by low cohesion and moderate to high permeability. These properties promote rapid infiltration (Obasi et al., 2013, Yusong et al 2019), reduce matric suction, and encourage internal erosion processes such as piping, thereby increasing the susceptibility of the gully walls to failure. In contrast,

gullies observed in Amaigbo and Elegu Edda exhibit relatively lower levels of activity, largely due to higher clay content, which enhances cohesion and provides greater resistance to erosion. Despite this relative stability, evidence of infrastructural damage remains apparent, with gullies encroaching on and in some cases bisecting roadways.

Spatial analysis indicates that most gullies within the area exhibit a dominant NW–SE orientation, with measured side slope angles ranging from 45° to as high as 90°. The steeper slopes recorded in Nguzu and Ekoli Edda contribute to increased instability of gully walls when compared to those in Amaigbo and Elegu Edda, resulting in higher erosion intensity and rates of gully expansion. The elevated relief and steep slope gradients within the Edda gully environment contribute significantly to slope instability by increasing the gravitational driving forces and reducing the effective resistance of the soil to shear failure. This observation is consistent with the findings of Egbueri et al. (2021), who reported an undulating topographic and morphological setting characterised by steep highlands and gently sloping lowlands in a gully-affected area of Anambra State. Such topographic conditions can enhance surface runoff concentration and accelerate erosional processes, thereby increasing slope susceptibility to failure and continued gully development. Although Elegu Edda occupies a relatively higher topographic position with gentler slopes, the downslope movement of runoff toward lower elevations enhances erosive energy in Nguzu Edda, thereby exacerbating gully development in this area.



Fig 6: Gullies observed at Ekoli and Nguzu Edda respectively (Sources: field work 2025)

4.2 Geotechnical properties

4.2.1 Natural moisture content (m_c)

The $\mathbf{m_c}$ of soil plays a critical role in assessing its shear strength and load-bearing capacity. Understanding $\mathbf{m_c}$ variations across different soil samples provides valuable insights into the geotechnical characteristics of the study area. The test results for $\mathbf{m_c}$ across various locations are presented in Table 2, revealing moisture content variations as follows: Nguzu Edda 3.62 – 4.22 %, Ekoli Edda 1.25 – 1.34 %, Ezzi Edda 0.42 – 0.76 %, Amaigbo Edda 5.98 – 6.83 %, and Elegu Edda 8.98 – 9.26 %. These variations indicate distinct differences in soil composition and water retention capacity. Soil samples from Nguzu Edda, Ekoli Edda, and Ezzi Edda exhibit low moisture content, suggesting limited water retention capabilities. This characteristic can be attributed to the loose particle structure of the soil, which facilitates rapid drainage and reduces water saturation levels.

Consequently, such soils exhibit weak cohesive forces between particles, resulting in minimal water-holding capacity. The low saturation levels make these soils highly susceptible to desiccation and erosion, potentially leading to increased soil degradation within these regions (Nzereogu et al., 2023). Conversely, soil samples obtained from Amaigbo Edda and Elegu Edda exhibit significantly higher moisture content values. This trend suggests a higher clay content in the soil, leading to increased particle cohesion and reduced permeability. The compact nature of clay-rich soils enhances their ability to retain moisture, which in turn influences their overall stability and resistance to erosion. Areas characterized by high moisture content are generally more resistant to immediate erosion due to their enhanced binding properties; however, excessive water retention could also contribute to soil instability under certain conditions. Regions with lower $\mathbf{m}_c$ values are more prone to rapid erosion due to reduced water-holding capacity, which accelerates surface runoff and soil particle displacement. On the other hand, while soils with higher NMC values may initially resist erosion, prolonged water retention could lead to increased u, potentially resulting in soil failure.

Table 2. Summary of the results of geotechnical analyses of soil samples from the study area

Sample no.	m_c (%)	Atterberg limits			G_s	Compaction		ρ (g/cm³)	Particle size distribution					Permeability	Shear strength		FoS	
		LL (%)	PL (%)	PI (%)		ρ_d (Kg/m³)	m_{opt} (%)		Gravel (%)	Sand (%)	Clay (%)	C_c	C_u	(m/s)	c (kPa)	φ (°)	Wet	Dry
1	4.22	22	NP	NP	2.62	-	-	1.54	2	93	5	1.69	2.96	6.50×10^{-4}	2	33	0.603	0.637
2	3.62	NP	NP	NP	2.63	-	-	1.53	2	92	6	1.71	2.98	4.80×10^{-4}	3	32	0.606	0.641
3	3.91	NP	NP	NP	2.64	-	-	1.54	3	92	5	1.74	2.98	5.60×10^{-4}	1	33	0.604	0.639
4	4.12	NP	NP	NP	2.64	-	-	1.52	3	91	6	1.75	2.87	3.80×10^{-4}	1	31	0.605	0.641
5	1.25	21	19	2	2.68	-	-	1.64	2	94	4	1.77	3.00	7.20×10^{-4}	3	29	0.676	0.725
6	1.34	22	NP	NP	2.66	-	-	1.62	3	93	4	1.76	3.07	6.00×10^{-4}	1	30	0.679	0.728
7	1.27	NP	NP	NP	2.68	-	-	1.62	3	92	5	1.81	2.98	4.50×10^{-4}	1	32	0.682	0.729
8	1.29	23	NP	NP	2.65	-	-	1.63	2	94	4	1.71	3.09	6.80×10^{-4}	1	30	0.681	0.727
9	0.67	21	19	2	2.63	-	-	1.71	1	81	15	1.8	3.11	4.50×10^{-5}	2	31	0.691	0.786
10	0.88	20	19	1	2.62	-	-	1.71	3	86	11	1.76	2.97	8.00×10^{-5}	2	29	0.695	0.787
11	0.76	NP	NP	NP	2.63	-	-	1.73	1	92	7	1.82	3.17	2.80×10^{-4}	3	27	0.694	0.789
12	0.42	20	19	1	2.63	-	-	1.69	4	87	9	1.93	3.04	1.50×10^{-4}	2	28	0.698	0.792
13	6.83	24.85	19.83	5.02	2.61	1.81	11.58	1.79	3	67	30	2.12	4.28	6.00×10^{-6}	5	26	0.734	0.847
14	5.98	24.72	19.64	5.08	2.58	1.82	10.68	1.77	4	81	15	2.24	4.32	4.50×10^{-5}	4	22	0.741	0.849
15	6.42	24.21	19.25	4.96	2.56	1.89	11.55	1.76	5	80	15	2.03	4.03	3.80×10^{-5}	6	21	0.736	0.848
16	6.23	23.53	19.55	3.98	2.57	1.86	10.96	1.69	4	74	22	2.16	4.17	1.50×10^{-5}	8	20	0.734	0.851
17	9.26	48.09	35.57	12.52	2.57	1.68	18.03	1.96	22	33	45	-	-	8.00×10^{-7}	11	21	0.897	1.160
18	9.21	49.23	36.87	12.36	2.59	1.67	17.22	1.82	16	51	33	-	-	5.00×10^{-6}	9	23	0.907	0.990
19	8.98	48.24	34.57	13.67	2.52	1.66	18.21	1.89	17	43	40	-	-	1.50×10^{-6}	12	21	0.921	1.180
20	9.06	47.06	35.89	11.17	2.53	1.69	18.01	1.93	20	39	41	-	-	1.00×10^{-6}	8	25	0.922	1.204

- indeterminate

4.2.2 Particle Size Distribution

The particle size analysis of the soils in the study area, as presented in (Table 2 and Fig 6a to e), indicates varying proportions of sand, clay, and gravel across different locations. Specifically, the soil composition at Nguzu consists of sand 91 – 93 %, clay 5 – 6 %, and gravel 2 – 3 %, while at Ekoli, the distribution is sand 92 – 94 %, clay 4 – 5 %, and gravel 2 – 3 %. Similarly, Ezzi exhibits sand 81 – 92 %, clay 7 – 15 %, and gravel 1 – 4 %. In contrast, Amaigbo has a relatively lower sand content of 67 – 80 %, with clay 15 – 30 %, and gravel 3 – 5 %. The most clay-rich soils are found in Elegu, where sand ranged from 33 – 52 %, clay 33 – 45 %, and gravel 16 –22 %. The predominance of sand, coupled with low clay and gravel content in Nguzu, Ekoli, and Ezzi (where sand particles exceeded 70 %), renders these soils highly susceptible to erosion. This is due to the weak cohesion between sand particles, which results in reduced soil stability. In contrast, the relatively higher clay content in Amaigbo and Elegu (clay >12 %) enhances soil cohesion, thereby reducing susceptibility to erosion and gully formation. The increased fine content in these areas contributes to greater interparticulate cohesion, which enhances soil stability and decreases the likelihood of erosion-related failures.

Additionally, the gradation characteristics of the soils, represented by the coefficient of uniformity (Cu) and coefficient of curvature (Cc), further support these observations. The Cc and Cu values for each location are as follows: Nguzu ranges from 1.69 to 1.75 for Cc and 2.87 to 2.98 for Cu; Ekoli has Cc values between 1.71 and 1.81 and Cu values from 2.98 to 3.09; Ezzi exhibits Cc values from 1.76 to 1.93 and Cu values ranging between 2.97 and 3.17; while Amaigbo has Cc values from 2.03 to 2.24 and Cu values ranging between 4.03 and 4.32. Cu and Cc could not be determined for Elegu because the soils there are dominated by fines (clay 33 – 45 %). According to Arora (2008), well-graded sands are characterized by $Cu \geq 6$ and Cc between 1 and 3. Although the Cc values of the sandy soils fall within the 1 – 3 range, their Cu values are all below 6, so the soils are poorly graded, meaning they contain a limited range of particle sizes, which may lead to lower compaction and weaker shear strength. Given that well-graded soils generally exhibit higher shear strength (Arora, 2008), it follows that the soils in the study area are likely to have low shear strength, further predisposing them to erosion and instability. These findings align with the research conducted by Nzereogu et al. (2023), which also identified the soils in this region as susceptible to failure due to their poor gradation and low cohesion.

Based on the Unified Soil Classification System (USCS), the dominant soil types in the study area include poorly graded sand (SP) and clayey sand (SC). Notably, Nguzu, Ekoli, and Ezzi are predominantly classified as poorly graded sand (SP), which contributes to their higher vulnerability to shear failure due to their inherently low shear resistance. This classification is further supported by natural moisture content data, which correlates with the high erosion susceptibility of these locations compared to Amaigbo and Elegu. Despite the erosion-prone nature of these soils, their classification under the American Association of State Highway and Transportation Officials (AASHTO) system indicates that the soils in Nguzu, Ekoli, and Ezzi fall within the good to excellent granular material range, making them suitable for construction purposes. This classification explains the widespread anthropogenic activities observed in these regions, particularly the extensive excavation of soil materials for use in building and infrastructure projects. However, while the soils are valuable for engineering and construction, their continuous extraction and disturbance contribute significantly to increased erosion rates and gully expansion. The removal of these materials accelerates slope instability, leading to further soil loss and degradation of the landscape. Therefore, sustainable soil management practices should be considered to balance construction needs with environmental conservation, ensuring that excavation activities do not exacerbate erosion hazards in these vulnerable areas.

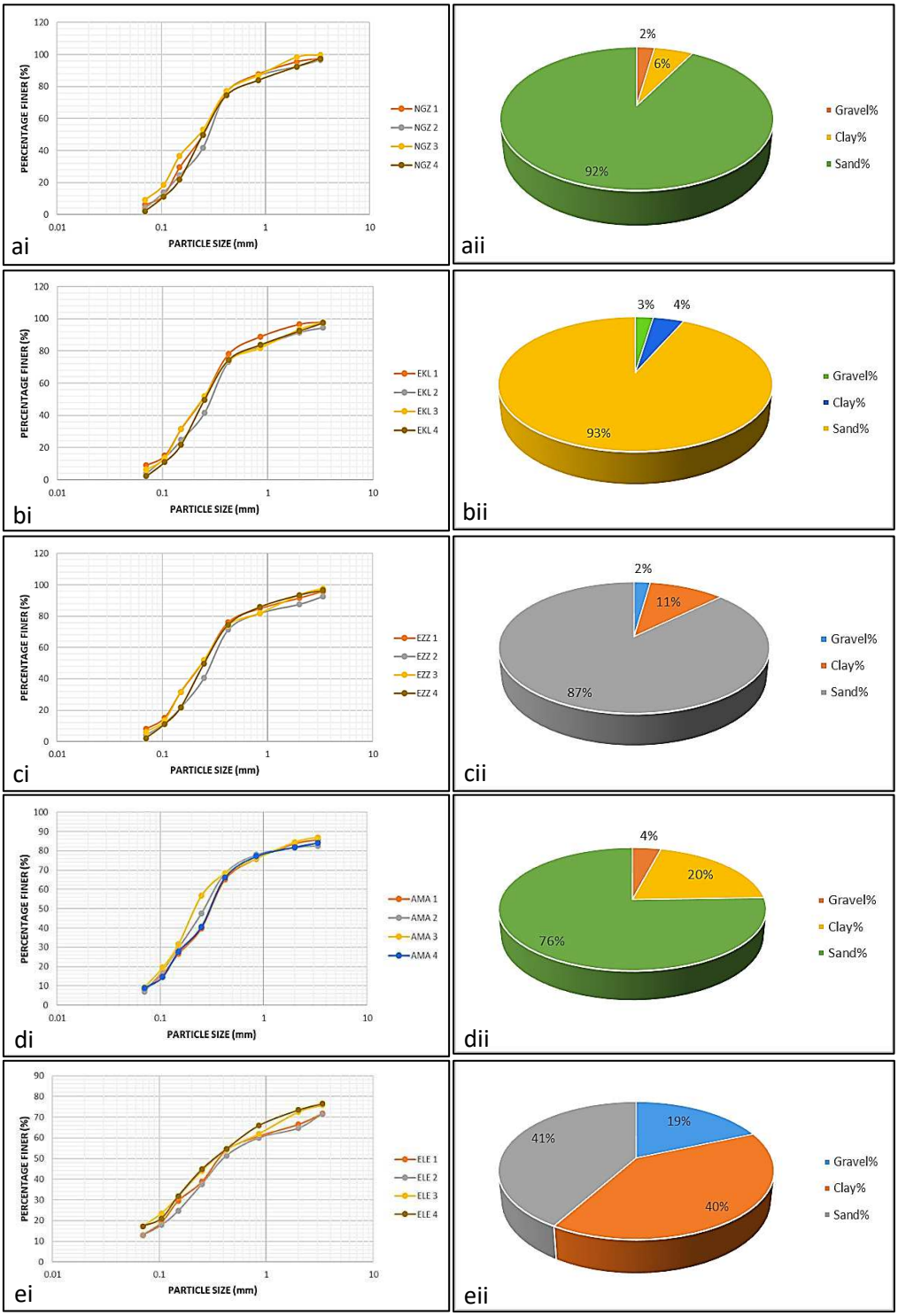


Fig. 6. Gradation curves (i) and results (ii) of particle size distribution tests on soil samples from the study area; (a) samples 1 – 4, (b) 5 – 8, (c) 9 – 12, (d) 13 – 16, and (e) 17 – 20

4.2.3 Atterberg Limits

The classification of fine-grained soils is typically concluded by plotting the results of the Atterberg limit tests on the Casagrande Plasticity Chart, presented in Fig. 7. This graphical representation facilitates the categorization of soils based on their liquid limit (LL), plastic limit (PL), and plasticity index (PI). The Atterberg limit values obtained for the soil samples, summarized in Table 2, provide insights into the soil behaviour across different localities within the study area. The results indicate that soil samples from Nguzu exhibit LL ranging between non-plastic (NP) and 22 %, with corresponding PL and PI values also categorized as NP. Similarly, soil samples from

Ekoli demonstrate LL between NP and 23 %, plastic limits between NP and 19 %, and PI ranging from NP to 2 %. The Ezzi samples presented a similar trend, with LL from NP to 21 %, PL between NP and 19 %, and PL ranging from NP to 2.00%. Conversely, the soil samples from Amaigbo exhibit slightly higher values, with $\mathbf{I_L}$ ranging from 24.21 to 24.85 %, PL between 19.25 and 19.83 %, and PI within 3.98 to 5.08%. The most distinct soil characteristics are observed in Elegu, where the $\mathbf{I_L}$ range from 47.06 to 49.23%, $\mathbf{I_P}$ varies between 34.57 and 36.87 %, and the PI falls within 12.36 to 13.67 %.

A geotechnical assessment of these results reveals that the soils from Nguzu, Ekoli, and Ezzi are predominantly NP, indicating a significant susceptibility to liquefaction (see Fig. 8). Soils exhibiting NP characteristics typically contain minimal or no cohesive fines, relying primarily on φ for strength. This renders them highly vulnerable to erosion and water-induced displacement. The high liquefaction potential of these soils aligns with findings by Seed et al. (2003), which suggests that soils with PI below 12 % and LL below 37 % are highly prone to liquefaction. However, the soils from Elegu exhibit a notably higher plasticity index (PI), indicating greater cohesion and reduced susceptibility to erosion compared to the other locations. The increased fine content in these samples suggests improved resistance to erosion, though such soils may still be vulnerable to failure under high *u*. The classification and geotechnical behaviour observed in this study align with the grain size distribution and natural moisture content analysis presented earlier. The results suggest that soils with a higher proportion of fines may offer some resistance to erosion, but their stability remains contingent on *u* conditions. In contrast, non-plastic soils with minimal fines are inherently weaker and more susceptible to movement, particularly in environments where water infiltration is prevalent.

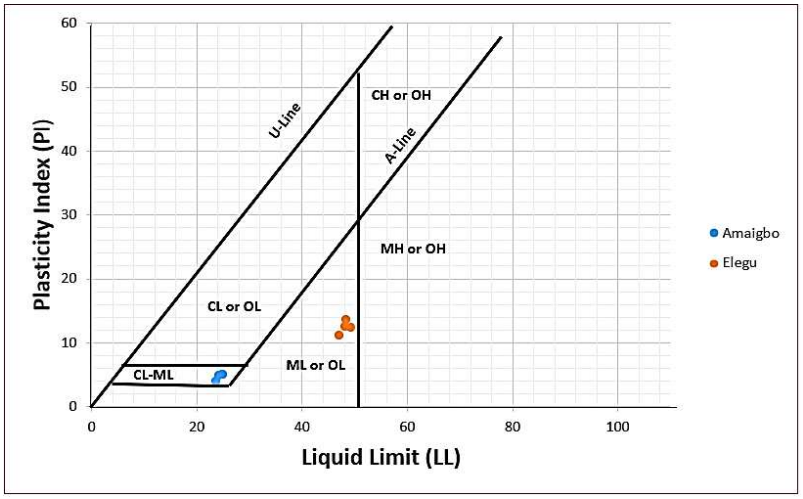


Fig. 7. Plots of the tested soil samples on the Casagrande plasticity chart

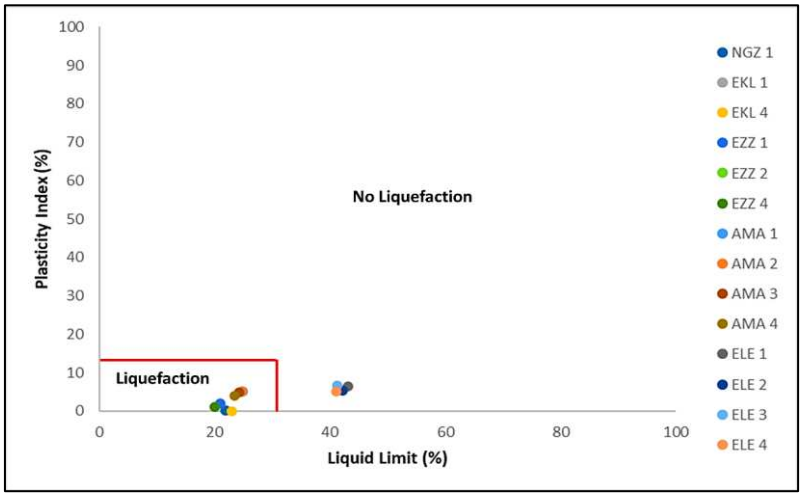


Fig. 8. Plots of the tested soil samples on the liquefaction chart (after Seed et al., 2003)

4.2.4 Shear strength

Shear strength characteristics (cohesion, c, and internal friction angle, φ) of the soils were evaluated to determine the ability of the soil materials to resist deformation and failure under shear stress *in situ* (i.e., in their natural state). According to Arora (2008), the higher φ in sands, the higher the degree of interlocking among grains. Hence, the higher the ability to withstand shear failure of such soil (Nzereogu et al., 2023). Furthermore, the lower the shear strength of the material the higher their erodibility and vulnerability to gullying. The values of the shear strength parameters (c and φ) of the analysed soils are presented in Table 2. Generally, all the soils samples had low cohesion values ranging from 1 – 12 kPa indicating weak interparticulate bonding and minimal cementation; conditions typically associated with sandy or silty soils that have undergone substantial weathering. Similarly, the internal friction angle values ranged from 20 – 33° for study area, which suggests that the soils have generally low shear strength as cohesion is a major component of shear strength of a soil (Ukor et al,. 2023) and are susceptible to shear failure (Nzereogu et al., 2023). Overall, these results confirm that the soils in the study area possess generally low shear strength. As cohesion is a major component of shear strength in fine-grained soils, the low c values observed suggest that these materials have limited resistance to shear stress, making them more susceptible erosion.

4.2.5 Specific gravity

Specific gravity (G_s) is a critical physical property of soil that reflects the density of soil particles relative to water. It is significantly influenced by factors such as mineral composition, texture, structure, and the degree of compaction. This parameter plays a vital role in determining the soil's water retention capacity and hydraulic conductivity, both of which are essential for understanding soil behaviour in geotechnical and environmental applications. Generally, G_s of most soil-forming minerals ranges between 2.0 and 2.9. Quartz-rich sandy soils typically exhibit higher specific gravity values, averaging around 2.60, while clayey and silty soils, composed of lighter phyllosilicate minerals, tend to have G_s slightly lower values, generally ranging from 2.35 – 2.70, in accordance with AASHTO soil classification standards. In the present study, G_s measurements were conducted for soil samples collected from Nguzu, Ekoli, Ezzi, Amaigbo, and Elegu. The results show that the G_s values fall within the following ranges: 2.62 – 2.64 for Nguzu, 2.65 – 2.68 for Ekoli, 2.62 – 2.65 for Ezzi, 2.56 – 2.61 for Amaigbo, and 2.52 – 2.57 g/cm³ for Elegu, respectively (Table 2). The relatively higher G_s values observed in Nguzu, Ekoli, and Ezzi suggest a dominance of quartz minerals, typical of sandy soils. Conversely, the slightly lower values in Amaigbo and Elegu Edda indicate a higher proportion of finer clay and silt particles. These findings

align with the results obtained from grain size distribution analysis and suggest that soils from Nguzu, Ekoli, and Ezzi may be more susceptible to erosion due to their coarser texture, while those from Amaigbo and Elegu, being finer-grained, may exhibit better cohesion and reduced erodibility.

4.2.6: Coefficient of permeability.

The coefficient of permeability (k) is a direct measure of the capacity of a soil to transmit water through its pore spaces and, consequently, reflects its infiltration potential (Arora, 2008). Higher permeability promotes the rapid movement of water through interconnected voids within the soil mass, thereby enhancing infiltration and subsurface water flow. The estimated permeability values for the soils investigated in the present study range from approximately 5.0×10^{-7} to 8.0×10^{-4} m/s, demonstrating considerable spatial variation in the hydraulic behaviour and water-transmitting capacity of the soils across the different study locations.

The grain-size distribution results presented in Table 2 and Figure 6 indicate that the soils at Nguzu, Ekoli, and Ezzi are predominantly coarse-grained and sandy, with relatively limited fine material. Consistent with these grain-size characteristics, their estimated permeability values are generally higher than those obtained for the relatively fine-grained soils at Amaigbo and Elegu. In particular, the soils at Nguzu and Ekoli exhibit permeability predominantly within the order of 10^{-4} m/s, whereas those at Ezzi range from approximately 4.5×10^{-5} to 2.8×10^{-4} m/s. These values are comparable to, and in some instances approach, the upper range of permeability reported by Nzereogu et al. (2023) for erosion-prone gully soils in Nnewi and Nnobi, further supporting the high erosion susceptibility of the soils at Nguzu, Ekoli, and Ezzi.

The high permeability of these soils, in combination with their grain-size characteristics, provides favourable conditions for rapid infiltration and subsurface water movement. The predominance of coarse particles and the limited proportion of fines promote interconnected pore spaces, allowing rainfall to infiltrate and move readily through the soil mass. This enhanced water transmission may facilitate seepage and subsurface particle removal. During prolonged rainfall, continued infiltration may also progressively reduce matric suction and increase pore-water pressure, resulting in a reduction in effective stress and shear strength. These processes can promote soil particle detachment and contribute to slope instability.

In contrast, the relatively lower permeability estimated for Amaigbo and Elegu corresponds with the increased proportion of fine-grained material identified from their grain-size distribution results. Overall, the permeability pattern, particularly the high values recorded for Nguzu, Ekoli, and Ezzi, when combined with their poorly graded characteristics, confirms their high susceptibility to seepage-related erosion, rainfall-induced strength reduction, gully initiation, and continued gully expansion within the Edda area.

4.2.7 Compaction characteristics

The compaction test results are presented in Table 2, and the compaction curves shown in Fig. 9. Soil compaction significantly influences the physical properties of soil by altering the size and distribution of pore spaces, as well as increasing soil strength. A critical parameter used in assessing compaction characteristics is the maximum dry density (ρ_{dmax}), defined as the peak dry density value (in g/cm³) obtained from the compaction curve of ρ_d versus moisture content (m). Correspondingly, the optimum moisture content (m_{opt}) refers to the moisture percentage at which this ρ_{dmax} is achieved. The compaction test results, as presented in the table, indicate that only the soil

samples collected from Amaigbo and Elegu exhibit measurable ρ_{dmax}. Specifically, ρ_{dmax} for Amaigbo ranged from 1.81 to 1.89 g/cm³ at m_{opt} between 10.68 and 11.58 %, while samples from Elegu had ρ_{dmax} ranging from 1.66 to 1.69 g/cm³ at m_{opt} between 17.22 and 18.21 %. These results suggest a higher content of clay minerals in the soil matrix, which enhances particle cohesion and makes the soils more amenable to compaction. Consequently, these soils demonstrate improved structural integrity and are less prone to erosion. Conversely, soil samples from Nguzu, Ekoli, and Ezzi did not yield any meaningful compaction values. The absence of compaction test results in these samples is attributed to their predominantly loose and friable nature, with minimal clay or binding mineral content. Such soils lack sufficient cohesive strength, making them difficult to compact and highly vulnerable to erosion. This trend aligns with findings from other geotechnical investigations conducted in the area, reaffirming the spatial variability in soil properties across the study locations.

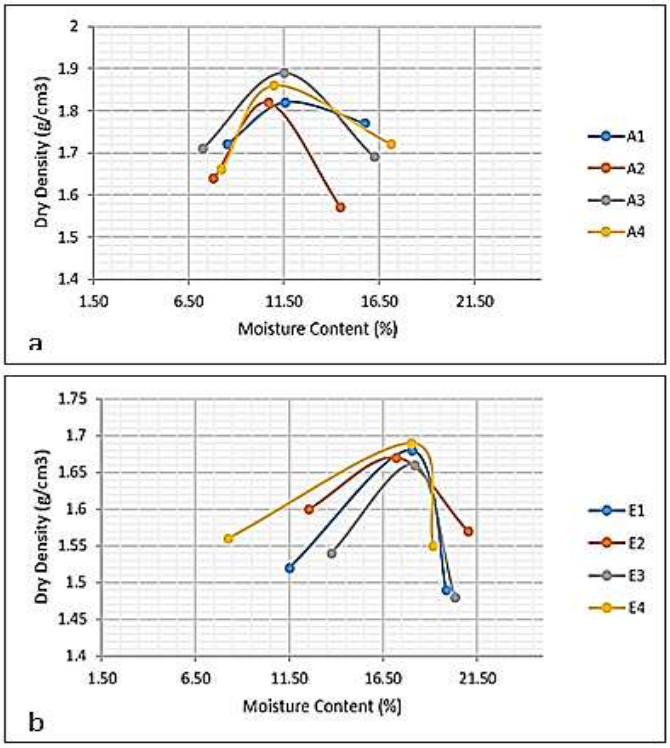


Fig. 9. Compaction curves for (a) Amaigbo gully sites and (b) Elegu Edda gully sites

4.2.8 Bulk density

Generally, the bulk density (ρ) of a soil is controlled by its level of compaction, rate of infiltration and increase in the overland flow, which enhances soil erosion. The ρ values for the soils in Edda area ranged from 1.54 – 1.96 g/cm^3, as presented in Table 2. On the average, this value is high, however, Coarse textured, sandy soils with minimal bulk density have soil particles detached by smaller, lower-energy raindrops than do heavier, clay-type soils Kort et al (1998). The high bulk density experienced in the study area can be attributed to the long intense tillage of soils in the area which depletes soil organic matter and weakens soil structure thereby making it vulnerable to the forces of erosion.

4.2.9 Slope stability analysis

The stability analysis of the twenty gully slopes within the study area was conducted to determine their factor of safety (FoS). The FoS values fall within the range of 0.60–0.92 for the saturated condition, and 0.63–1.20 for the unsaturated condition, for Nguzu, Ekoli, Ezzi, Amaigbo, and Elegu, respectively (see Fig. 10). The behaviour of these gully slopes during the dry season was represented by the unsaturated condition, while the saturated condition

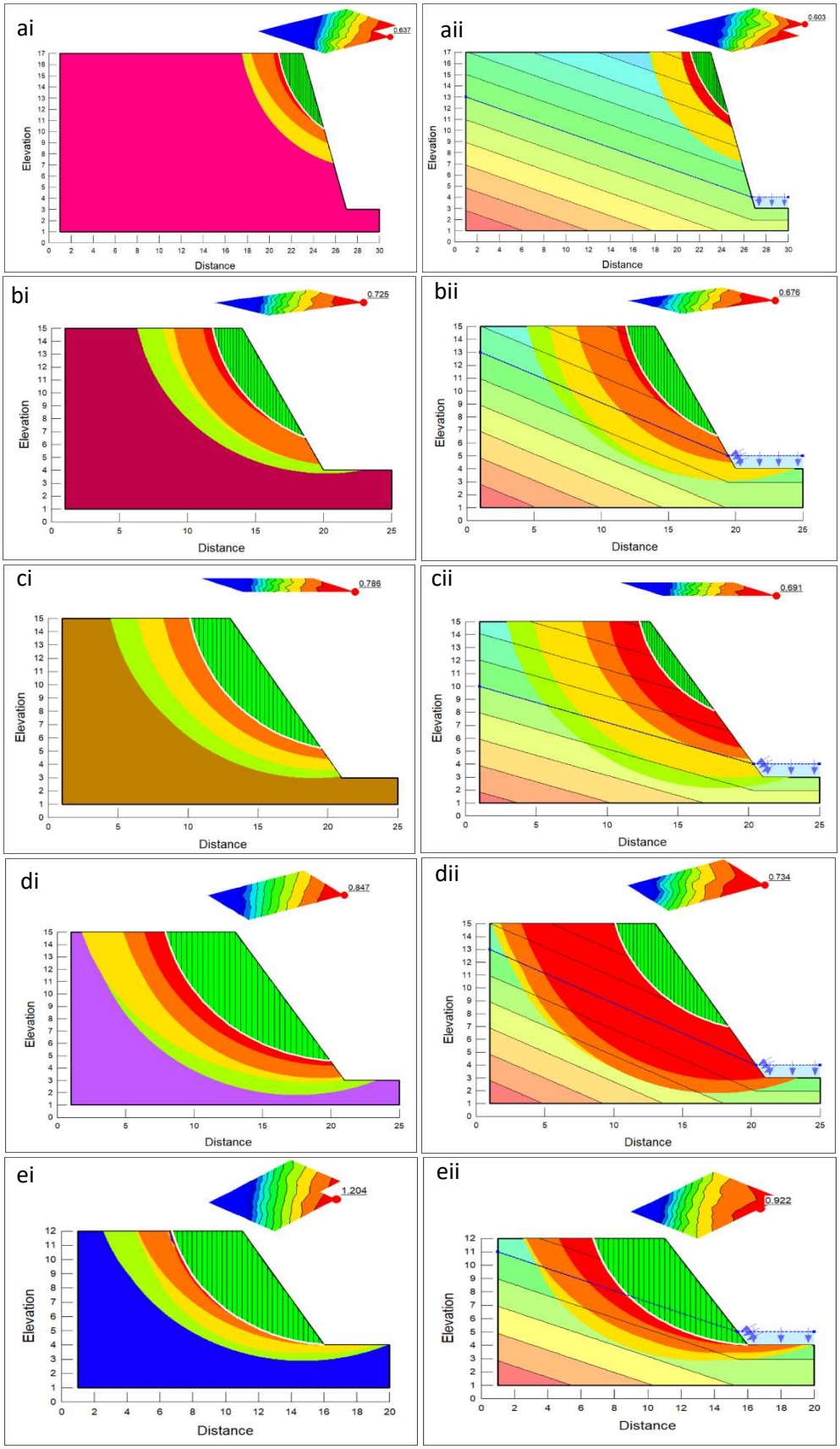


Fig. 10. Geostudio generated slope models (i – wet condition and ii – dry condition) for the factor of safety determination of the gully sites; (a) Nguzu, (b) Ekoli, (c) Ezzi, (d) Amaigbo, and (e) Elegu

represented their behaviour during the rainy season. The results of the stability analysis for both the saturated (wet condition representing rainy season) and unsaturated (dry condition representing dry season) conditions were documented in Table 2. From the analysis, all the gully slopes in the Nguzu, Ekoli, Ezzi, and Amaigbo areas of Edda were likely to be unstable, judging from FoS values, as presented in Table 2. On the other hand, the gully slopes encountered at Elegu (Fig. 10e) area were classified to be critically stable based on classification of factor of safety according to Hadmoko et al. (2010). To provide a more specific breakdown, the mean FoS value Elegu and Nguzu areas were 0.92 and 0.60, respectively, for the saturated zone, and 1.20 and 0.633 respectively, for the unsaturated zone. These values indicated occurrence of unstable slopes at Nguzu and occurrence of critically stable slopes Elegu. This highlights the heightened hazard of the gullies during the rainy season, when the slopes are either partially or fully saturated, aligning with the findings of Nzereogu et al. (2023). Additionally, findings from Wei et al (2022) in the Analysis of gully erosion susceptibility from GIS-based approach reported similar slope angle within southeastern China and reported it as very steep slopes making it susceptible to failure

The contrasting FoS values obtained for the saturated and unsaturated scenarios indicate that moisture state can substantially influence the stability of the investigated gully slopes. Under wet conditions, the loss of matric suction and the potential development of positive pore-water pressures would be expected to reduce effective stress and shear resistance, thereby increasing the likelihood of gravitational failure. Because these hydrological variables were not directly measured in the present study, they are interpreted as plausible mechanisms linking rainfall and wet-season conditions to the observed reduction in slope stability rather than as directly quantified processes.

This internal suction binds soil particles more tightly, reinforcing slope integrity and increasing FoS values, as observed in the unsaturated condition where values reached up to 1.20 in Elegu Edda. During heavy rainfall, however, the infiltration of water reduces matric suction as the soil approaches full saturation, thereby diminishing this beneficial effect.

A critical gap in the existing analysis is the limited integration of slope geometry with subsurface hydromechanical processes controlling slope stability. While slope angles and Factor of Safety (FoS) values are presented, the underlying mechanisms governing FoS reduction particularly the role of pore water pressure, effective stress variation, and matric suction loss are insufficiently addressed. This study bridges this gap by incorporating unsaturated soil mechanics and soil water interaction principles to explain the seasonal variability in shear strength and slope stability. The observed reduction in FoS is thus not only a function of slope gradient but also a consequence of rainfall-induced changes in pore pressure and effective stress, which ultimately govern gully initiation and progression. This integrated approach enhances the predictive capability of gully susceptibility assessments and provides a transferable framework for evaluating erosion risks in similar geomorphic and climatic settings.

4.2.10 Erodibility factor

The calculated erodibility factor (*K*) for the studied formation is 11.80×10^{-2}. *K* represents a quantitative measure of the inherent susceptibility of soils to detachment and transport by erosive agents, as described by Jain and Singh (2003). Within the framework of RUSLE, the *K*-factor plays a critical role in estimating soil loss, while also exhibiting clear seasonal variability. Empirical evidence indicates that *K* is not a fixed parameter but fluctuates in response to climatic conditions, attaining higher values during the rainy season than in the dry season. This seasonal increase is largely attributed to enhanced soil moisture, reduced aggregate cohesion, and intensified surface runoff during periods of sustained rainfall. The magnitude of the *K*-factor is strongly governed by a soil's

physical and chemical characteristics, which collectively determine its resistance to particle detachment. The key controlling parameters include soil texture, aggregate stability, organic matter content, and permeability, all of which influence the soil's capacity to absorb and transmit water (Benselama et al., 2018).

Soils with low cohesion, weak aggregation, and high permeability are particularly vulnerable to erosive forces. This relationship is evident in the gully-affected areas of Nguzu, Ekoli, and Ezzi areas of Edda, where the dominant soils are predominantly sandy with very low clay content. The paucity of clay minerals reduces inter-particle bonding and aggregate stability, resulting in minimal resistance to raindrop impact and surface runoff. Consequently, these sandy soils exhibit high *K*-factor values, making them highly erodible and susceptible to rapid gully initiation and expansion, especially during the peak rainy season. The combined effects of intense rainfall, poor soil cohesion, and high infiltration–runoff dynamics have therefore contributed significantly to the severity and persistence of gully erosion observed across these communities.

4.2.11 Satellite imagery analysis

The evolution and spatial progression of gully erosion within the Edda area were evaluated through a multi-temporal geomorphological assessment using high-resolution Google Earth imagery. Sequential satellite datasets were analysed across multiple gully sites to quantify changes in gully length, width, headcut migration, and catchment disturbance. This temporal comparison was undertaken to identify the principal hydrometeorological and geomorphic triggers influencing gully initiation and enlargement, with specific emphasis on rainfall intensity–duration patterns and their geomorphic responses. To contextualize the susceptibility of the study area, gully development trends at selected locations within area were compared with documented, high-magnitude gully systems in neighbouring communities such as Nguzu, with gully development within the region.

Severe gully expansion had been reported in the Ekoli and Ezzi areas by Amah et al., 2021. The comparative analysis in this study enabled the evaluation of rainfall–runoff dynamics, slope processes, lithological control, and land-use change as potential contributing factors to gully formation. The results of the sixteen-year retrospective analysis (2008–2024), as illustrated in Fig. 11, reveal clear temporal growth patterns in gully development, associated erosional behaviour, and the exceedance of critical geomorphic thresholds within the study area. These observed morphodynamic changes correspond closely with the long-term rainfall trend derived from the annual precipitation record.

4.2.11.1 Gully Expansion rate analysis

The gully exhibited a substantial longitudinal increase from 105 m in 2008 to 200 m in 2024, representing a total elongation of 95 m. Its width showed temporal fluctuations, decreasing from 99 m to 84 m in 2018 before expanding markedly to a maximum of 113 m in 2024. Using the calculation approach adopted by Nzereogu et al. (2023), the average longitudinal expansion rate was estimated at 5.94 m/yr. This indicates active and progressive gully development and is comparable to the 10.76 m/yr reported for Nnobi, although lower than the rates reported for Nnewi and Nanka. The progressive expansion corresponds with the generally increasing rainfall trend recorded in Ebonyi State, particularly from around 2016 onward. Increased rainfall enhances runoff generation, infiltration, and pore-water pressure, while reducing matric suction, effective stress, and soil shear strength. These hydromechanical processes are particularly important in Edda because the gullies occur within predominantly sandy, poorly graded, low-cohesion and relatively permeable soils. Consequently, prolonged and intense rainfall promotes headward erosion, sidewall collapse, seepage, and progressive widening and elongation of the gully system.

Table 3: Result of Edda Gully Expansion Rate

Year	Length (m)	Width (m)
2008	105	99
2014	113	87
2018	140	84
2022	182	93
2024	200	113
Expansion Rate (m/yr)	**5.94**	**1.81**

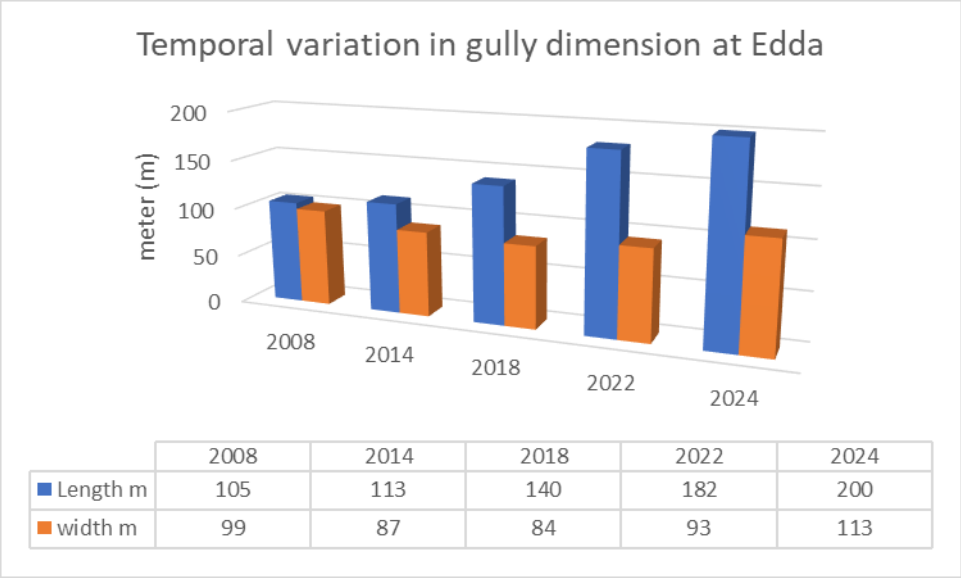


Fig. 11; Edda Gully expansion rate plot

4.2.12 Rainfall data

Figure 12 presents annual rainfall data for Ebonyi State from 2010 to 2024, demonstrating a generally increasing trend in precipitation totals, albeit with short-term inter-annual variability. The smoothed rainfall series further reveals a consistent rise in rainfall intensity and temporal persistence, particularly from around 2016 onward. With an average annual precipitation of approximately 2049 mm, this upward trend represents a significant hydroclimatic forcing mechanism driving the accelerated initiation, enlargement, and coalescence of gullies identified through aerial imagery and detailed field-based geomorphic mapping. These observations are comparable to the findings of Wei et al. in China, where gully systems were predominantly concentrated in regions receiving mean annual precipitation between 1701 and 1872 mm, highlighting the critical influence of rainfall thresholds on gully development across diverse environments. Elevated rainfall regimes enhance surface runoff production, increase antecedent soil moisture, and elevate pore-water pressures, collectively leading to a reduction in effective soil shear strength (Okogbue et al., 2020).

The correspondence between periods of elevated rainfall and marked gully expansion suggests that rainfall-induced runoff remains a dominant triggering and sustaining factor controlling gully evolution within the study area. However, while rainfall acts as the primary natural driver, anthropogenic influences cannot be overlooked. Rapid urban expansion, vegetation clearance, unregulated land-use practices, road construction, and poorly designed drainage infrastructure have significantly altered natural hydrological pathways, leading to increased runoff concentration and flow velocity. These human-induced modifications amplify the erosive impact of rainfall, effectively lowering the geomorphic threshold required for gully initiation and accelerating gully enlargement

processes. Consequently, the observed gully dynamics reflect a coupled system in which increasing rainfall trends interact synergistically with anthropogenic disturbances to intensify erosion severity across the landscape.

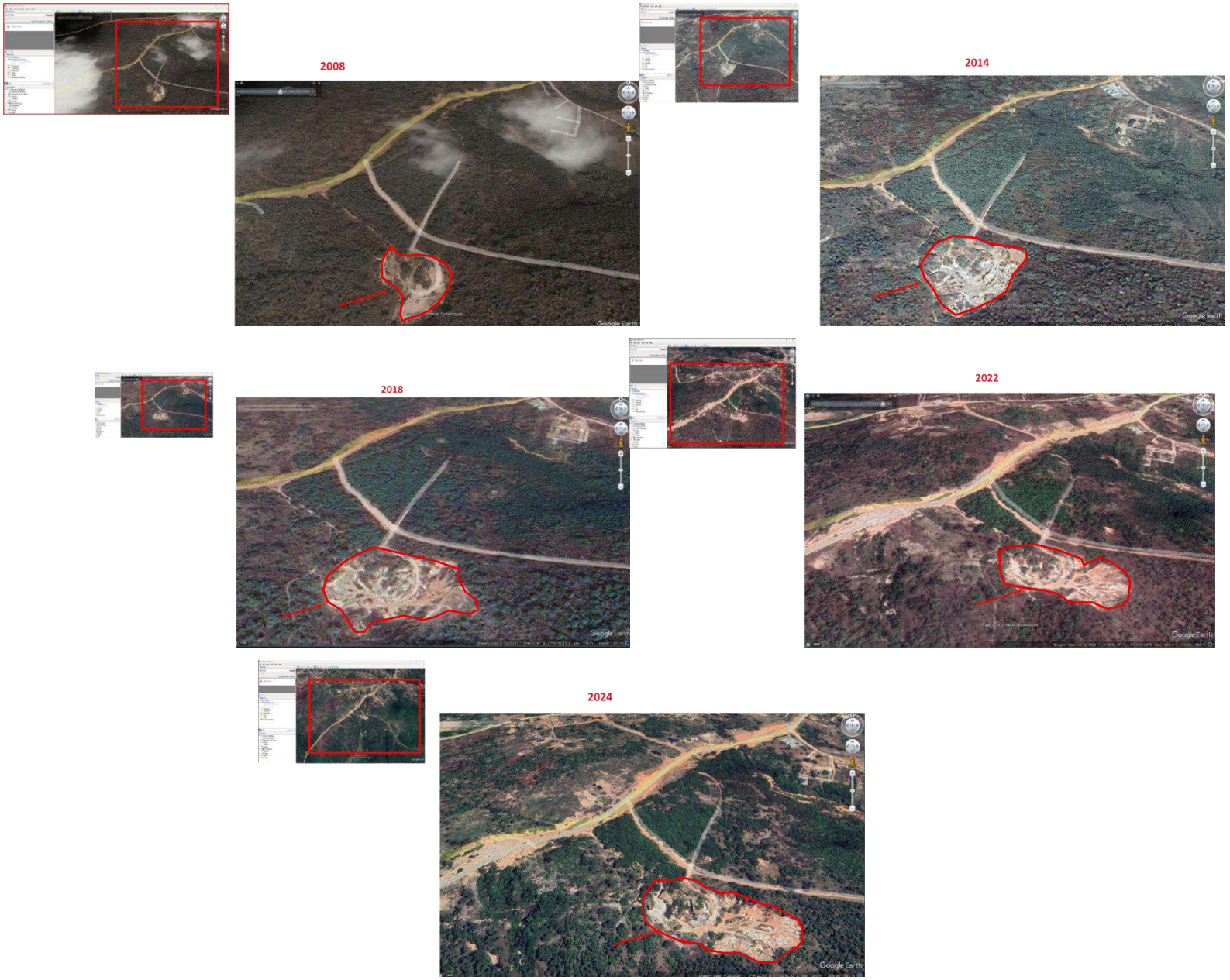


Fig. 12. Satellite imagery of gully development around Ekoli within a 16 year period (from 2008 to 2024)

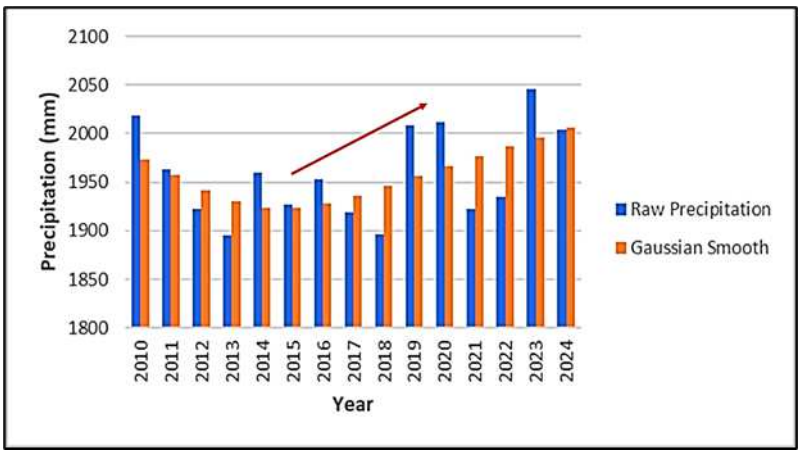


Fig. 13. Annual rainfall data for Ebonyi State, Nigeria, for the period 2012–2023. Data retrieved on 16 December 2025 from the World Bank Group Climate Change Knowledge Portal (CCKP).

4.2.13 Control Measures

Based on the findings of this study, an integrated erosion mitigation strategy is recommended for Edda and its environs. Properly engineered surface and subsurface drainage systems should be constructed to intercept and safely convey runoff away from gully heads, roads, and steep slopes, with adequate energy dissipation structures to reduce flow velocity. Unstable gully slopes should be stabilized through slope regrading, concrete or stone rip-rap, gabions, and selective grouting of highly erodible sandy units. The use of geosynthetic materials is strongly recommended. Geotextiles should be applied to reinforce weak soils, reduce particle detachment, and improve slope stability, while geomembranes can be used as impermeable barriers to control infiltration and reduce *u* Kelechi, & Okeke, (2018). Geonets should be incorporated within drainage systems to enhance subsurface water conveyance and minimize saturation-induced failures. Biological measures, including afforestation with deep-rooted vegetation, should complement structural controls to improve soil binding and surface protection. In addition, GIS and remote sensing–based monitoring should be adopted for early detection of gully expansion, while land-use activities in erosion-prone zones should be strictly regulated to ensure sustainable erosion control.

There is a consensus among geoscientist and other earth scientists working on the gullies in Southeastern Nigeria that the control of the disaster should be scientifically and systematically implemented rather than the common and general practice of channelization and embankment construction. Okagbue and Ezechi (1988) attempted a genetic classification of gullies and proposed specific control measures/method for the different classifications. Egboka and Nwankwor (1985) is of the opinion that detailed pedological, geological, hydrogeological, geotechnical and hydrogeotechnical characterization of the region threatened by gullies be done as a prerequisite for adoption and design of the most efficient control method to be employed.

Simple grouting and stabilization can arrest the progress of gullies especially when applied at a very early stage of development. Groundwater level influences the development and growth of gully, therefore controlling groundwater level by installation of well and dewatering facilities at strategic locations is necessary to check this. Extensive afforestation program can be very effective in the control of gully erosion especially when well applied but perhaps the oldest form of control measure adopted and is based on the recommendations of colonial workers. It is still used extensively in an attempt to increase the erosive resistance of the soils and to exert protection control.

The trees used are those that have deep and abundant roots which are thought to be capable of binding the soil particles together. The more common ones are Cashew trees and Bamboos. This helps to protect the soil from the direct impact of raindrops and runoff as well as maintain the moisture content of the soil at responsible level during the dry season. Gully prone areas should be delineated and human activities such as agriculture and civil works controlled as these act as gully triggers and catalyst.

At Ekoi, Edda, Ebonyi State, the gabion wall erosion control system has been implemented as a structural intervention to stabilise the gully slopes, protect the slope toes against scour and undercutting, and reduce further erosion. The system consists of rock-filled wire mesh baskets arranged to form a retaining structure, which provides resistance to soil movement while allowing water to drain through the rock voids. Its application at the Ekoi gully erosion site represents an engineering approach to mitigating erosion and limiting further gully development. The effectiveness of this intervention, however, depends on adequate drainage, foundation stability, and the geotechnical characteristics of the surrounding soil.

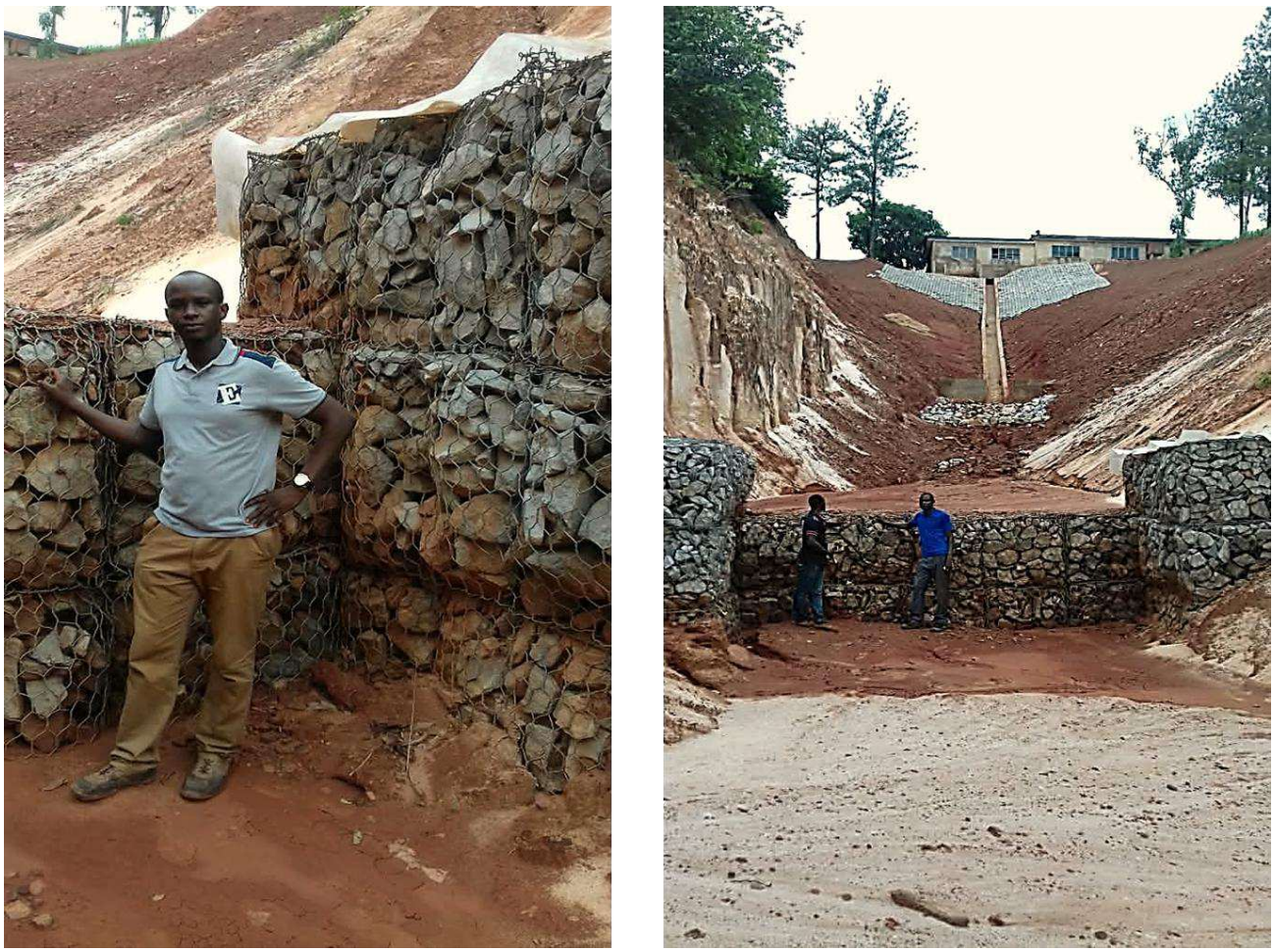


Fig. 13. Ekoli Edda (Ebonyi State, southeastern Nigeria) gully erosion control

5. CONCLUSIONS

This study has assessed that the susceptibility of Edda area to severe soil erosion and gully development. Findings showed that the gully propagation is primarily controlled by the combined influence of geological, geotechnical, geomorphic, climatic, and anthropogenic factors. The underlying Nkporo Shale and overlying Afikpo Sandstone, when subjected to intense tropical weathering, produce predominantly sandy to silty soils with weak structural integrity, low cohesion, and poor grading. Laboratory analyses revealed high sand contents, low to moderate

plasticity, elevated bulk density, and generally low shear strength, all of which predispose the soils to rapid detachment and transport under surface runoff.

Slope stability analysis further confirmed that many gully slopes within the study area are unstable to critically stable, particularly under prolonged wet conditions, when reduced matric suction and potentially increased pore-water pressures may decrease effective stress and shear resistance. Multi-temporal satellite imagery analysis revealed continuous gully elongation and lateral expansion over a sixteen-year period, closely associated with increasing rainfall intensity and persistence. Rainfall data indicate a rising trend in annual precipitation, which enhances runoff concentration, accelerates headward erosion, and promotes slope failure. The results also highlight the significant role of human activities, including road construction, excavation, vegetation removal, and poorly designed drainage systems, in amplifying natural erosion processes. These disturbances alter natural hydrological pathways, lower erosion thresholds, and accelerate gully development.

Overall, the findings underscore the urgent need for integrated and site-specific erosion control strategies in Edda. Effective mitigation should combine engineered drainage systems, slope stabilization measures, afforestation, land-use regulation, and GIS-based monitoring to reduce erosion risk, protect infrastructure and farmlands, and promote sustainable land management in the region

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Soil Sample Collection

We wish to clarify that the soil samples used in this study were collected from different communities and towns within Edda Local Government Area, Ebonyi State, Nigeria. The sampling locations were within publicly accessible areas; therefore, no private property was involved in the sample collection, and no private landowner permission was required.

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Competing financial and/or non-financial interests

We declare that the authors have no competing interest

Informed consent

We wish to clarify that the individuals appearing in the photographs are among the authors of this study and were involved in the field activities. The photographs do not include any external participants. Furthermore, all authors are aware of and have agreed to the inclusion and publication of these photographs in the manuscript**.**

Data availability

The data are subject to ownership and confidentiality restrictions; however, they can be made available upon reasonable request, subject to approval by the rightful data owners.

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