Partial Saturation as a Critical Contributing Factor to Gully Erosion and Rainfall-induced Landslides in Southeastern Nigeria

E.O. Mezie*,1, A. Tsiampousi[1], and K. Vinck[1]

[1]*Department of Civil and Environmental Engineering, Imperial College, London, United Kingdom*

**Corresponding author's email:* e.mezie23@imperial.ac.uk

Abstract: This study presents an overview of the causes behind gully erosion and landslides in Anambra State in Southeastern region of Nigeria. Anambra is a small densely populated state of significant socio-cultural, ecological, and economic value to the region, and has experienced extensive gully erosion over the past four decades, with landslides affecting over 40% of the state's landmass. Many lives, properties, agricultural lands, and fauna and flora have been lost, and many people live in fear. The literature review indicates that a combination of factors, such as the geology of the region, soil properties, rainfall events and patterns, topography, and anthropological activities, contribute to the menace. Despite not having the highest annual rainfall in the country, with an average of up to 2500 mm, the region is disproportionately affected by gully erosion. The prevalent soil types in the state are laterites and Nanka sands, characterised by sands with pockets of clay, which cover most of the unsaturated zone of the soil lithology. Further to the research plan to investigate the contribution of partial saturation on the phenomenon and to develop sustainable soil barriers as a solution, the paper presents preliminary results on numerical modelling of annual pore water pressure variations.

Keywords: Gully erosion, landslides, sustainable soil barriers, Anambra state, numerical modelling

Introduction

Rainfall-induced landslides are closely associated with gully erosion, which causes significant land degradation in Africa [1]. These problems have been linked to periods of prolonged dryness followed by intense rainfall [2]. Gully walls, acting as slopes, are particularly prone to rainfall-induced landslides when infiltrating rainfall reaches the shallow slip surfaces of these slopes [3].

Southeastern Nigeria is severely impacted by gully erosion and landslides, with Anambra state - the most affected among its five administrative states – experiencing the highest levels of degradation (see Figure 1). Over the past four decades, the extent of gully erosion and landslides in Anambra State has risen from approximately 10% to over 40% [4].

Figure 1: Common gully erosion features in Anambra State

The land degradation within Anambra State has prompted significant research and intervention efforts. However, the situation continues to deteriorate. Recent studies have unanimously emphasised that the underlying factors contributing to the issue have not been effectively investigated through an integrated approach [e.g 5]. Moreover, the influence of soil surface moisture flux balance on the stability of unsaturated soil slopes remains inadequately studied.

Therefore, the purpose of the planned research is to investigate the effect of climate on the phenomenon, while accounting for unsaturated soil behaviour for the first time. Furthermore, the use of engineered barriers from local materials to be used as capillary barrier systems (CBS) will be explored. A brief overview on the key contributory factors of the problem is given below, followed by a description of the methodology for the assessment of unsaturated properties. Finally, preliminary tests and analysis done are discussed.

Geology

Most of the southeastern region lies within Anambra Basin, a Basin that was developed during the Campanian to late Eocene age [6]. Gully erosion and landslides are most prevalent within Nanka formation in the Basin. This formation consists of three main layers: a highly weathered lateritic soil overlying Nanka sands, which overlie the Imo shale [7].

The Nanka sands, the dominant unit, are characterised by friable, medium to coarse-grained sands and siltstones that are often pebbly and lack cementation [8]. Landslides are triggered not only by the loss of suction and shear strength during rainfall infiltration [9], but also by the presence of thin moistened layers of clay and shale which weaken the structure and facilitate the sliding of saturated sand masses [10].

Soil Characteristics

Anambra state features three predominant soil types: alluvial deposits, hydromorphic soils and ferralitic soils [11]. Of these, the ferralitic soils, widely distributed across the Nanka Formation, are the most erodible and dominate areas of severe gullying within the state. Also referred to as residual soils, ferralitic soils form through intense weathering of sedimentary rocks [12]. Their reddish-brown colour is due to high aluminium and iron oxide content.

Geotechnical analysis of shallow (< 5 m) soils from gully walls highlights their susceptibility to erosion. Particle size analysis reveals a high sand content (≈ 70%), a plasticity index ranging from non-plastic to 11.4% and low cohesion (2 – 10 kPa). The angle of internal friction varies between 21^o and 36^o, indicating low to medium compaction while the coefficient of permeability (10^{-5} – 10^{-3} cm/s) signifies high permeability [11, 13].

Topography

The topography of Anambra State ranges from 30 to 340 m above mean sea level [14], forming part of interior lowlands of southeastern Nigeria. The Nanka Formation, located in the south-central part of the state, features the highest peaks interspersed with valleys. The region's topography is characterised by varying slope angles (18° – 75°), predominant V-shaped features, and average depths of approximately 50 m [15]. Steep slopes with low-cohesion soils are highly prone to erosion under intense rainfall due to rapid infiltration.

Climate - Precipitation

The region experiences an annual mean rainfall of approximately 2500 mm, occurring predominantly between March and October [16]. This is followed by a dry season with little to no rainfall from Late November to late February.

Temperatures vary seasonally, ranging from 22°C – 28°C during the rainy season to 28°C – 38°C in the dry season. Relative humidity remains high year-round, with typical values of 81% in the morning, 60 – 75% in the evening, and 85% at night. Wind speeds average less than 3 m/s but may reach 5 m/s around the beginning and end of the rainy season [17].

Evidence of Unsaturation

Significant depth of unsaturation exists during the dry season. Seasonal vegetation cycle with thick and luxuriant growth during the rainy season which dries up during the dry season is evidence of this. Furthermore, borehole tests conducted in rainy season showed water table depth of 6 – 10 m which may go down 60 – 100 m during dry season [6].

Interaction of Key Contributory Factors

Figure 3 highlights the interaction of key factors contributing to gully erosion and rainfall-induced landslides in Anambra State. The zone of intense gullying (c) aligns with areas covered by ferralitic soils (a) and changes in elevation (b).

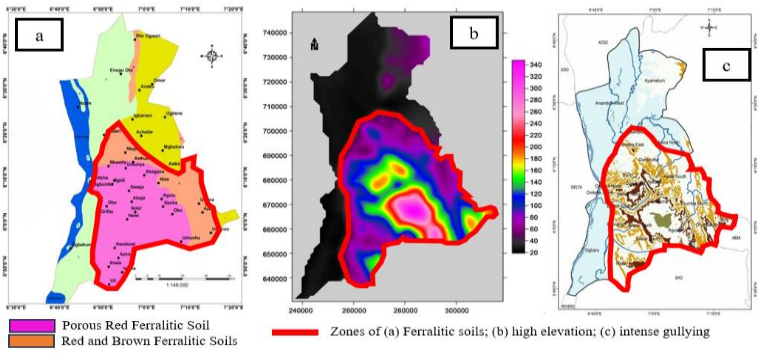

Figure 3: Interaction of contributory factors of gully erosion and rainfall-induced landslides [5, 11, 14]

From the foregoing, it can be inferred that during the dry season, gully slopes become unsaturated and exposed. Subsequent intense rainfall, particularly at the onset of rains, triggers saturated-unsaturated seepage and landslides, accelerating gully expansion.

Analysis of Rainfall-induced Landslides

Rainfall-induced landslide is a hydro-mechanical process. Rainfall infiltration into unsaturated soil reduces matric suction and shear strength, triggering slope failure. For numerical modelling, the contributory factors must be integrated into a model with realistic boundary conditions, capable of reproducing the effect of rainfall and evapotranspiration. Furthermore, suitable constitutive models comprising a mechanical model (e.g., Barcelona Basic Model (BBM, [18])) and a hydraulic model (e.g., van Genuchten model [19]) are required.

It is postulated that capillary barrier systems (CBS), comprising a fine storage layer overlying a coarse drainage layer, can offer a sustainable solution to gully erosion and rainfall-induced landslides. The hydraulic contrast between the layers creates a capillary break, as the coarse layer desaturates at low suction, while the fine layer retains water. The performance of CBS relies on these contrasting unsaturated properties [20]. To model this, laboratory tests are needed to determine the properties of slope materials and CBS. These are explained subsequently.

Methodology

The case study focuses on the Nanka gully erosion site, located within the Nanka formation in Anambra State. This site, the largest known gully erosion site in southeastern Nigeria, lies at Latitude 6° 02′ 20′′ – 6° 02′ 40′′ N and Longitude 7° 04′ 45′′ - 7° 05′ 10′′ E (WGS84), approximately 240 m above mean sea level. The gully formed in 1988 through mudslides. To date, it has expanded by about 97% through rainfall-induced landslides during the rainy season [10].

Disturbed lateritic soil was collected in mid-December 2024 from the gully wall at a depth of 1.5 m, at coordinates 6° 02′ 39′′ N and 7° 04′ 56′′ E (WGS84). Insitu density properties were measured using the sand replacement method and a speed moisture tester, yielding values of bulk unit weight of 14.244 kN/m^3, moisture content of 7.6%, corresponding dry unit weight of 13.238 kN/m^3, and insitu void ratio of 0.967.

Laboratory Analysis

Both classification tests and hydro-mechanical laboratory tests to characterise the geotechnical properties of the soils involved are currently under way. The hydro-mechanical tests comprise saturated and unsaturated hydraulic and mechanical properties tests. The classification tests are performed only for the residual soil, while the hydro-mechanical properties tests are carried out for reconstituted and re-compacted residual soils. Classification tests have been concluded, while the plan for hydro-mechanical properties tests is briefly laid out subsequently.

Grading analysis was by wet sieving and sedimentation as recommended for lateritic soils due to aggregation [21]. Compaction tests were done with British Standard Light (BSL) method to determine the approximate density to be applied for the CBS materials for field compaction on site.

The results obtained from grading analysis and plasticity tests are shown in Figure 4 (a & b). Linear shrinkage of approximately 8.41% was obtained for the soil. Organic matter content of the soil by loss on ignition (LOI) was less than 5%. The specific gravity was 2.654. The British Standard light compaction produced maximum dry unit weight and optimum moisture content of 18.367 kN/m^3 and 13.2% respectively.

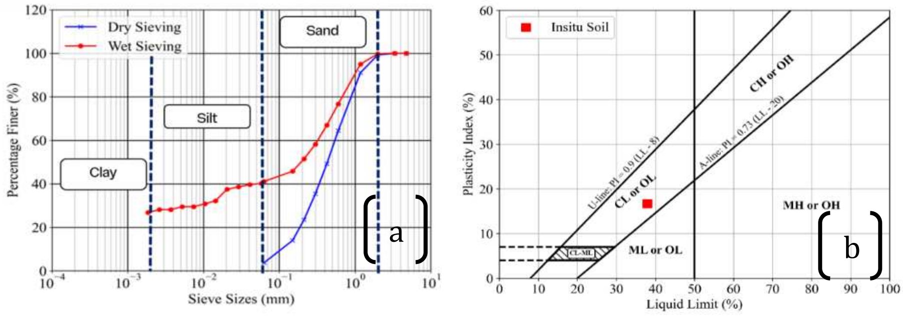

Figure 4: Soil index properties: (a) - grading analysis; (b) - plasticity characteristics

The natural soil belongs to the clayey sands (SC) class based on the Unified Soil Classification System (USCS). The soil properties correspond closely to what have previously been reported in the literature for Nanka soils. The soil is low in organic matter content. From the plasticity chart, the soil belongs to inorganic clay of low plasticity which shows a soil that can be prone to erosion. The linear shrinkage indicates that the upper lateritic soil layer has critical shrinkage behaviour [22]. This implies the tendency to form desiccation cracks during dry seasons, which can aid rapid rainwater infiltration into the lower Nanka sands predisposing slopes to failures. This is a significant observation that will be accounted for in numerical modelling. The shrinkage behaviour of the soil also predicates significant volumetric behaviour during wetting and drying which will affect variation of water content with suction and soil shear strength. This observation will also inform the need for careful volume measurements during the laboratory development of the SWRC. Generally, the class of the soil and its geotechnical properties suggests that it is feasible to characterise its unsaturated behaviour using BBM.

The mechanical properties test which will involve saturated and unsaturated triaxial tests will be conducted using a conventional triaxial apparatus and a triaxial apparatus modified to allow suction control by the axis translation technique [23], respectively. The essence of the mechanical properties tests is to calibrate the BBM rather than achieving full unsaturated characterisation of the soil. The tests outcome will allow parameters for the Isotropic Compression Line under saturated and unsaturated conditions, the yield and plastic potential surfaces, and the slope of the Critical State Line in the deviatoric stress-mean net/effective stress plane to be defined. These tests are in progress.

The soil water retention curve (SWRC) will be developed using the filter paper technique. The saturated hydraulic conductivity will be measured in the oedometer, and the soil hydraulic conductivity curve (SHCC) will be inferred from the SWRC using the Mualem approach. In addition to the standard [24], other guidelines that were developed at Imperial College London and are available in many doctoral theses [e.g 25] will be adopted. The calibration formula by [24] will be used in obtaining the corresponding suction from filter paper water contents. The obtained data will be fitted to the van Genutchen SWRC [19] equation using the Plaxis 2D equivalent.

Soil Atmosphere Interaction Analysis for CBS design

While laboratory tests to obtain saturated and unsaturated hydro-mechanical properties of the residual soil are in progress, the feasibility of designing a CBS was tested using a Mohr-Coulomb mechanical model and the van Genutchen hydraulic model available in PLAXIS 2D.

A column analysis was performed, and the performance of the CBS was judged based on its potential to minimise water infiltration into the in-situ soil. The soil column used is shown in Figure 5. It comprises of laterite, Nanka sands, fine CBS (F-CBS), and coarse CBS (C-CBS). The displacement and hydraulic boundary conditions applied to the column for the analysis are as follows: the bottom boundary was fully fixed and impermeable; the two vertical boundaries are fixed in the horizontal direction and impermeable, while infiltration was allowed only for the top boundary.

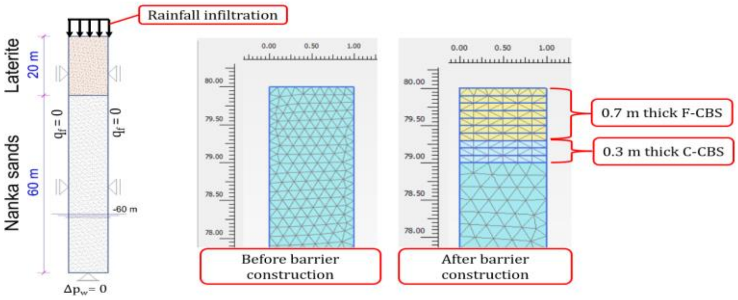

Figure 5: Model geometry

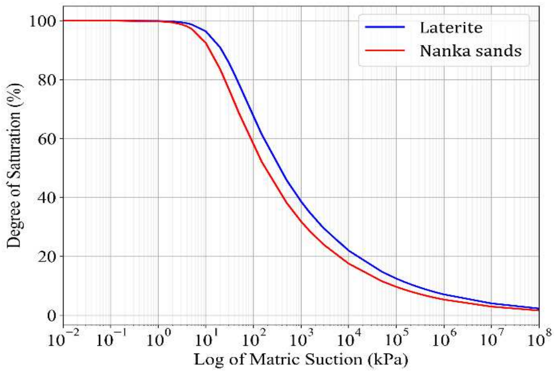

Figure 6: SWRC for the residual soils

The modelling parameters are shown in Table 1. The Mohr-Coulomb modelling parameters for laterite and Nanka sands were obtained from the existing literature within the region. The hydraulic model parameters for laterite and Nanka sands were obtained from SWRC developed based on soil grading and plasticity properties of the two soils using the fitting equation proposed by [26]. The resulting SWRCs are shown in Figure 6. The mechanical and hydraulic modelling parameters of F-CBS (silty sands) and C-CBS (coarse gravel) were obtained from the works of [27] and [28], respectively. They will be refined once the testing programme is completed.

Table 1: Modelling parameters for residual soils and CBS

Geometry materials	**Laterite**	**Nanka sands**	**F-CBS**	**C-CBS**
Geotechnical modelling parameters				
Unsaturated unit weight, γ_{unsat} (kN/m^3)	18.1	18.69	17	19
Saturated unit weight, γ_{sat} (kN/m^3)	20	20	20	20
Initial void ratio, e_{init}	0.299	0.47	0.5	0.5
Mechanical modelling parameters				
Elasticity modulus, E_{ref} (kPa)	10000	30000	8800	180000
Poisson's ratio, v	0.353	0.32	0.3	0.2

Cohesion, C_{ref} (kPa)	5.5	2	0	0
Friction angle, ϕ^o	27	32	40	60
Hydraulic modelling parameters				
S_{res}	0.01365	0.0122	0.06831	0.03
S_{sat}	1	1	1	1
g_n	1.27	1.3	1.521	2.25
g_a	0.3499	0.5678	4.3	1.5
g_l	-1	-1	0.5	10
k_x (m/day)	0.75	1.45	0.7	8640
k_y (m/day)	0.75	1.45	0.7	8640

Two analyses were conducted and compared, one with and one without a CBS, each consisting of two stages. In the analysis without the CBS, in the first stage, 10-year average net monthly inflow/outflow (see Figure 7) was cycled 10 times after initialisation of stresses to obtain a repeatable annual pore water pressure (PWP) profile, and therefore, representative of the local climate. The net monthly inflow/outflow is the difference between monthly rainfall and potential evapotranspiration (PET). The PWP profiles obtained from this stage of the analysis are shown in Figure 8. It can be observed that 10 10-year cycle is sufficient to establish repeatable PWP since the PWP of March (Year 9 & 10) and those of October (Year 9 & 10) coincided with each other.

In the second stage, one year of soil atmosphere interaction analysis based on net monthly inflow/outflow for the year 2023 was applied. At the end of March (end of dry season) and October (end of rainy season) within this year, high intensity rainfall of 0.6 m/day for 350 minutes with a return period of 10 years was applied, after which the PWP profiles were obtained.

In the analysis with the CBS, its construction was simulated at the end of December of the 10th year cycle of the first cycle, which was identical to the first cycle of the previous analysis. The barrier was constructed by removing the top 1 m of the column and replacing it with 0.3 m of C-CBS and 0.7 m of F-CBS. After the construction of the barrier, the second stage of the analysis, which was identical to the second stage of the analysis without the CBS, was repeated. Therefore, the two analyses differ only with respect to the construction of the CBS in between the first and second stages.

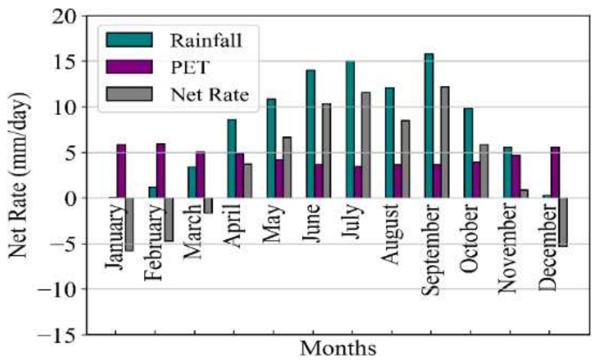

Figure 7: Climate data for Anambra state: Net inflow/outflow

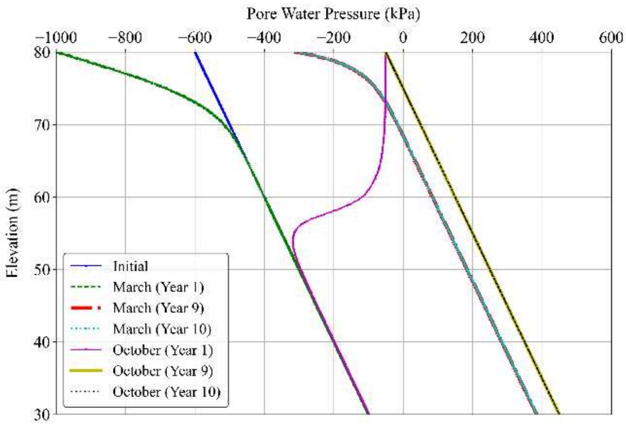

Figure 8: Stabilised PWP during long duration analysis of stage one for March and October

The results obtained in the second stages of the analyses with and without CBS for March and October 2023 are shown in Figures 9 (a & b). In each case, the PWP in December of the 10th year before barrier construction was shown. NB stands for 'no barrier' while WB stands for 'with barrier'.

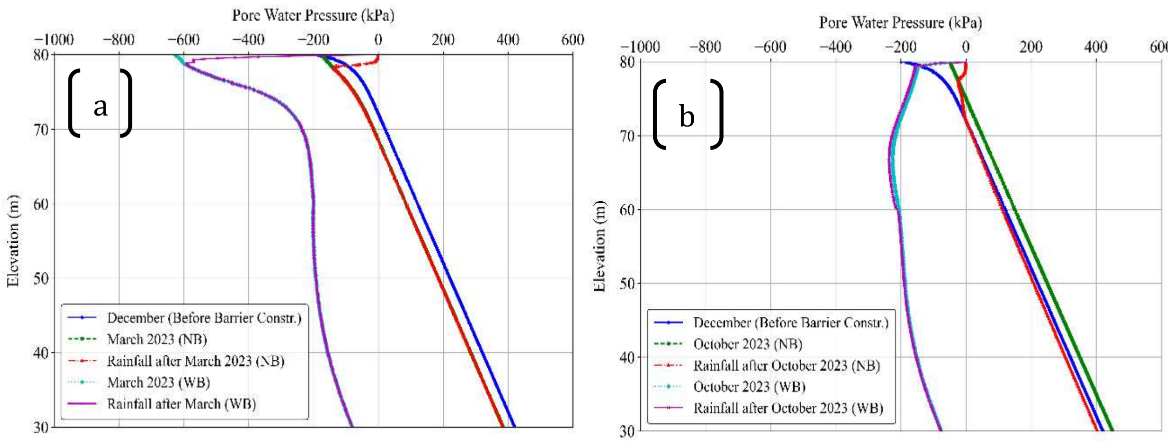

Figure 9: PWP of one year of analysis in the second and third stages: (a) – March; (b) - October

In Figure 9a and b, it can be observed that at the end of the first stage, i.e. in December, suctions were maintained in the top 9 m of the column. In the analysis without a CBS (NB), suctions penetrated the soil within the top 11 m by March 2023 (Figure 9a). When the 10-year rainfall event was then applied, suctions at the top of soil column were eliminated to a depth of about 1m within 350 minutes. In this lateritic soil, this loss of suction would contribute to erosion and deepening of the gully. By contrast, in the analysis with the CBS (WB), high suctions were maintained until the end of March 2023 and after the 10-year rainfall event, potentially protecting the soil against erosion. Similar observations can be made for October 2023, for the analyses with and without the CBS (Figure 9 b), albeit suctions at the top 10 m were generally smaller than in March 2023.

Overall, the ability of a CBS to maintain suction within this subsoil profile, and thus potentially protect it against erosion, was demonstrated. Although this study was conducted with a simple constitutive model, which has numerous limitations in simulating the mechanical unsaturated behaviour of the soil, the hydraulic modelling accounted for the effects of desaturation on the SWRC and the SHCC. It is anticipated that the use of more suitable unsaturated mechanical model and careful calibration of the hydraulic behaviour of the recompacted lateritic soil which will be used for the CBS will yield more realistic results and enable geotechnical and economical optimisation of CBS thickness.

Conclusion

A brief overview of the critical factors contributing to gully erosion and rainfall-induced landslides in southeastern Nigeria has been presented. The significant roles of geology, soil characteristics, slope properties, and rainfall in gully formation and expansion were highlighted. Previous studies have not effectively integrated these factors, nor have they adequately addressed the dynamic impact of surface moisture flux on the failure of unsaturated soil slopes in the region. This paper also summarized the methodology for determining the unsaturated properties of residual soils and CBS materials for the numerical modelling.

The results of geotechnical properties tests and soil classification were discussed. The results obtained and soil classification results for the residual soil have given confidence that it would be feasible to characterise the unsaturated soil behaviour using BBM. Additionally, preliminary numerical CBS design has shown feasibility of using CBS to maintain suction within the subsoil profile during intense rainfall and protect the natural soil against erosion. Overall, these preliminary findings reinforce confidence for the proposed plan in this study.

References

[1] G-R., Zhang, Y-J., Qian, Z-C, Wang, and B. Zhao. Analysis of Rainfall Infiltration Law in Unsaturated Soil Slope. *Scientific World Journal*, 567250, 2014.

[2] S.A., Raji, A.O. Akintuyi, E.O. Wunude, and B. Fashoto, B. A machine learning-based spatial statistical method for modelling different phases of gully development in South-Eastern Nigeria. *Ecological Informatics*, 75: 102-101, 2023.

[3] D. G. Fredlund and H. Rahardjo. *Soil mechanics for unsaturated soils*. John Wiley & Sons, 1993.

[4] C. Chinweze. Erosion and climate change challenges: Anambra state, Nigeria case study, in: IAIA17 Conference Proceedings | IA's Contribution in Addressing Climate Change in *37th Annual Conference of the International Association for Impact Assessment*, 4 – 7: 1-6, 2017.

[5] G.T. Amangabara. Gully Erosion Sites in Southeast Nigeria: Prospects for Geotourism. In: Faniran, A., Jeje, L.K., Fashae, O.A., & Olusola, A.O. (eds.) *Landscapes and landforms of Nigeria*. Springer, Cham, Switzerland, Word geomorphological landscapes, 225 – 242, 2023.

[6] O. Igwe. The Mechanisms of Enlargement and Hydrogeological Characteristics of Nanka Gully, Southeast Nigeria. *Journal Geological Society of India*, 92: 227-234, 2018.

[7] S.N. Chibuzor, E.I. Okoyeh, E.I., and B.C.E. Egboka. Geotechnical Characteristics of Regolith Derived from Nanka Formation, Southeast Nigeria. *European Journal of Engineering Research and Science*, 5 (12), 2020.

[8] N.N. Ukatu. Factors of Gully Expansion in Nanka Gully Site, Anambra State. B.Sc Project, Department of Geography, University of Nigeria, Nsukka, 2019.

[9] O. Igwe, and C.O. Una, C.O. Landslide impacts and management in Nanka area, Southeast Nigeria. *Geoenvironmental Disasters*, 6 (5), 2019.

[10] B.C.E. Egboka, A.E. Orji, and H.O. Nwankwoala. Gully Erosion and Landslides in Southeastern Nigeria : Causes , Consequences and Control Measures. *Global Journal of Engineering Sciences*, 2019.
[11] J.C. Egbueri, O. Igwe, and S.I. Ifediegwu, S.I. Erosion risk mapping of Anambra State in southeastern Nigeria: soil loss estimation by RUSLE model and geoinformatics. *Bulletin of Engineering Geology and Environment*, 81: 91, 2022.
[12] M.I. Akaegbosi. Sequence Stratigraphy of Anambra Basin. *Journal of African Earth Sciences*, 42: 394-406, 2005.
[13] C.O. Unigwe, O. Igwe, O.S. Onwuka, J.C. Egbueri, J.C. and M.E. Omeka. Roles of hydro-geotechnical and slope stability characteristics in the erosion of Ajali and Nanka geologic formations in southeastern Nigeria. *Arabian Journal of Geosciences*, 15, 1492, 2022.
[14] E.A. Udo, O.C. Ojinnaka, A.C. Chukwuocha, and U.D. Uchenna. Terrain Modeling and Analysis Using Earth Observation System Based Data: A Case Study of Anambra State, Nigeria. *Open Access Library Journal,* 8: 1-18, 2021.
[15] J.C. Egbueri, and O. Igwe. The impact of hydro geomorphological characteristics on gullying processes in erosion- prone geological units in parts of southeast Nigeria. *Geology, Ecology, and Landscapes*, 5(3): 227–240, 2021.
[16] O.D. Onafeso. The Climate of Nigeria and Its Role in Landscape Modification' In: Faniran, A., Jeje, L.K., Fashae, O.A., & Olusola, A.O. (eds.) *Landscapes and landforms of Nigeria*. Springer, Cham, Switzerland, Word geomorphological landscapes, 225 – 242, 2023.
[17] Nigeria Erosion and Watershed Management Project (NEWMAP) Environmental and Social Management plan (ESMP) for Nnewichi gully erosion site, Anambra state, 2017
[18] E.E. Alonso, A. Gens and A. Josa. A constitutive model for partially saturated soils', *Géotechnique*, 40(3), pp. 405-430, 1990.
[19] M.Th. Van Genutchen. A Closed–Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Science Society of American Journal*, 44 (5): 892-898, 1980.
[20] H. Rahardjo, Y. Kim and A. Satyanaga. Role of unsaturated soil mechanics in geotechnical engineering', *International Journal of Geo-Engineering*, 1–23, 2019.
[21] D.B. Akinniyi. Compressibility and Shear Behaviour of Saturated and Unsaturated Lateritic Clay Rich in Sesquioxide. PhD Thesis, Hong Kong University of Science and Technology, Hong kong, 2019.
[22] B. Widjaja and D. Cecilia. Correlation Between Linear Shrinkage Value and Soil Desiccation Cracking Pattern. Prosiding Seminar Nasional Riset dan Teknologi Terapan (RITEKTRA), B5-1 – B5-5, 2021.
[23] D.G. Fredlund and H. Rahardjo. Soil mechanics for unsaturated soils. New York: John Wiley & Sons Inc. ISBN: 9780471850083. 1993.
[24] ASTM D5298-16. Standard test method for measurement of soil potential (suction) using filter paper. ASTM International. 2016.
[25] M. Melgarejo-Corredor, *Laboratory and numerical investigations of soil retention curves*. PhD thesis (Imperial College, London, 2004).
[26] N. Ganjian, Y.P. Pisheh, and S.M.M.M. Hosseini. Prediction of Soil–Water Characteristic Curve Based on Soil Index Properties (2007).
[27] X. Li, M. Datcheva and T. Schanz. Fully Coupled Hydro-Mechanical Modelling of a Conceptual Slope Considering River- Level Fluctuations (ISSMGE Online Library, 'n.d.')
[28] A. Tsiampousi, C. Day and A. Petalas. Engineering soil barriers to minimise annual shrinkage/swelling in plastic clays. *Geomechanics for Energy and the Environment*, 38, 100540, 2024.