Progress in Engineering, Material Science and Industrial Systems

journal homepage: https://ojs.universityedu.org/index.php/pemsis

Engineering Geological Properties of Sandstone and Clay Formations in Tropical Sedimentary Terrains: Implications for Infrastructure Development

Charles Onyeka Nwamekwe[1*], Esomchukwu Jennifer Onyeka[2], and Ifeanyichukwu Benjamin Unigwe[3]

[1]*Industrial and Production Engineering Department, Nnamdi Azikiwe University, P.M.B. 5025 Awka, Anambra State - Nigeria.*

[2]*Department of Geology, Nnamdi Azikiwe University, P.M.B. 5025 Awka, Anambra State - Nigeria.*

[3]*Department of Engineering Management, School of School of Engineering, University of the West of England, Frenchay Campus, Coldharbour Lane, Bristol, BS16 1QY, United Kingdom.*

KEYWORDS

Engineering geology; sandstone-clay formations; geotechnical properties; tropical sedimentary terrains; infrastructure stability

ABSTRACT

Infrastructure development in tropical sedimentary terrains is increasingly constrained by weak subgrades, rapid pavement deterioration, slope instability, gully erosion, foundation settlement, and weathering-driven degradation of sandstone-clay sequences. These failures persist because engineering designs often treat lithology, geotechnics, groundwater, geomorphology, and climate as separate variables rather than interacting controls. This review addresses this limitation by evaluating how sandstone and clay formations influence infrastructure stability in tropical sedimentary environments. A structured review synthesis was conducted on studies dealing with sandstone durability, clay plasticity, grain-size distribution, Atterberg limits, ferruginization, groundwater effects, slope processes, pavement failure, quarry suitability, and sustainable geotechnical planning. The review integrated evidence from engineering geology, sedimentology, geotechnical testing, geomorphology, GIS-based hazard mapping, remote sensing, and emerging machine-learning approaches. Particular attention was given to index properties, strength behaviour, drainage response, weathering intensity, structural discontinuities, and climate-induced deterioration. The findings show that well-cemented quartz-rich sandstones can provide competent foundation and aggregate materials, whereas poorly cemented sandstone promotes infiltration, piping, erosion, and slope weakening. Clay-rich and shale-derived formations are the most critical engineering constraint because high fines, plasticity, low permeability, and moisture sensitivity reduce bearing performance and increase deformation. Reported evidence includes clay fractions of 50-70%, plasticity indices of 21-28%, soaked CBR as low as 1.03-1.60%, slope safety factors below unity, and rainfall-triggered failures after intense antecedent wetness. Ferruginization improves hardness but may redirect runoff when ferricrete restricts infiltration. The review therefore proposes integrated geological, geotechnical, hydrological, GIS, and climate-resilient assessment as the basis for safer infrastructure planning.

1. Introduction

1.1 Background on Tropical Sedimentary Terrains

Tropical sedimentary terrains rank among the most geologically complex environments for engineering practice in developing regions. These terrains are dominated by alternating sequences of sandstone, shale, clay, lateritic, and ferruginized units that show wide variation in engineering behaviour under tropical climatic conditions (Nwamekwe et al., 2025; Gomes et al., 2022). Tropical soils formed through geological and pedological processes in these regions

---

* Corresponding author's E-mail address: co.nwamekwe@unizik.edu.ng

Received April 29, 2026; Received in revised form May 19, 2026; Accepted: May 23, 2026.

possess distinct geotechnical characteristics, including lateritic and saprolitic varieties with properties that differ from soils in temperate zones (Coutinho et al., 2020; Gomes et al., 2022). Intense chemical weathering under tropical humid conditions transforms rock masses into thick residual soil profiles with abrupt contacts between weathering classes, as documented in sandstone formations where structural discontinuities and joint systems control the depth and pattern of alteration (Nwamekwe and Igbokwe, 2024). Seasonal rainfall, fluctuating groundwater levels, and rapid urbanization compound these geological challenges. Slope failures and mass movements occur frequently in areas underlain by sedimentary formations such as the Barreiras Formation, where alternating sandy and clayey layers create zones of differential permeability and strength (Coutinho et al., 2020; Paiva et al., 2020). Sandy soils in tropical terrains are prone to erosion, given their high drainage capacity and low cohesion (Santo et al., 2021), while clay-rich formations exhibit low bearing capacity, high compressibility, and plastic behaviour that pose direct risks to foundations and pavements (Gomes et al., 2022; Santos et al., 2020).

Sandstone formations in tropical settings often serve as sources of construction aggregate and provide relatively competent foundation materials due to their grain-supported framework, though their engineering properties vary with grain size, cementation, and degree of weathering (Nwamekwe et al., 2025; Nwamekwe et al., 2024). Geomechanical classification of sandstones shows that fine-grained varieties tend to be more resistant than medium to coarse-grained types (Nwamekwe et al., 2026). Clay-rich formations, by contrast, present persistent engineering difficulties. Expansive clay minerals such as illite cause volumetric changes that damage infrastructure (Igbokwe et al., 2025), and clay-dominated soils from sedimentary formations commonly show high plasticity and low permeability (Pinheiro et al., 2017; Santos et al., 2020). The engineering response of these lithologies depends on mineralogical composition, grain-size distribution, cementation, drainage conditions, and weathering intensity (Balieiro et al., 2023; Pinheiro et al., 2017). Tropical sedimentary terrains therefore experience road failure, slope collapse, pavement deformation, and gully erosion at rates that demand integrated engineering geological assessment (Paiva et al., 2020; Santo et al., 2021). The growing need for transportation infrastructure, urban expansion, and quarry materials in tropical developing regions has made it necessary to link geology, geotechnics, geomorphology, and environmental processes within a single planning framework (Balieiro et al., 2023; Gomes et al., 2022; Lautenschläger et al., 2020).

1.2 Engineering Problems in Sandstone-Clay Environments

Sandstone and clay formations present contrasting engineering challenges that frequently converge in tropical sedimentary terrains to produce widespread infrastructure damage. Clay-rich subgrade soils with low resistivity values and high moisture retention capacity represent a primary cause of road pavement failure across sedimentary regions in Nigeria and other tropical countries (Nwamekwe et al., 2025; Gomes et al., 2022). Investigations of failed highway segments in southeastern Nigeria confirmed that clay and highly weathered materials beneath road pavements trigger differential settlement, cracking, and structural collapse (Coutinho et al., 2020; Gomes et al., 2022). Expansive clay minerals, particularly illite and smectite, undergo volumetric changes with moisture fluctuation, causing foundation distress and building failure (Nwamekwe et al., 2024; Paiva et al., 2020). Geotechnical studies of failed buildings in Enugu, Nigeria, showed that foundation soils with 50 to 70 percent clay fraction and intermediate to high plasticity produced excessive consolidation and differential settlement (Paiva et al., 2020). At the sandstone-clay interface, water accumulates and lubricates contact surfaces, reducing shear strength and promoting slope instability (Santo et al., 2021; Santos et al., 2020). In mountainous tropical terrain in Sabah, Malaysia, interbedded sandstone and shale units lose strength rapidly when wet, and the absence of chemical cement in sandstone reduces resistance to sliding along sandstone-shale contacts (Igbokwe and Nwamekwe, 2025; Pinheiro et al., 2017). Rainfall-triggered landslides in Fiji demonstrated that tropical clays lose structure and cohesion once critical porewater pressures are reached, leading to rotational slides and earthflows along roads built on weathered sandstone formations (Balieiro et al., 2023; Lautenschläger et al., 2020). Gully erosion compounds these problems in areas underlain by friable, poorly cemented sandstone with low clay content, where high porosity and permeability facilitate rapid infiltration and subsurface piping (Ojo et al., 2024; Santo et al., 2021). Road failures in tropical sedimentary basins stem from a combination of incompetent clay subgrade, poor drainage, geological structures, and inadequate pre-construction site investigation (Coutinho et al., 2020; Ekwe et al., 2018; Gomes et al., 2022).

1.3 Need for Integrated Engineering Geological Assessment

The range and severity of engineering problems in sandstone-clay environments demand assessment frameworks that link geological, geotechnical, geomorphological, and environmental data within a single planning structure. Conventional site investigations often treat geology and geotechnics as separate disciplines, leading to incomplete characterization of subsurface conditions and repeated infrastructure failures (Ram et al., 2019; Roslee & Tongkul, 2018). Engineering geological mapping in Sabah, Malaysia, identified six interrelated parameters controlling slope instability: local and regional geology, hydrology and geohydrology, mineralogy and microstructures, discontinuity structures, physical and engineering properties, and geomorphological processes (Pinheiro et al., 2017). This multi-parameter approach proved essential for slope design in sedimentary terrain where sandstone and shale weather into clay-rich materials with variable strength (Igbokwe et al., 2025; Pinheiro et al., 2017). In Gombe, northeastern Nigeria, integration of remote sensing, GIS, and geological data produced a geotechnical stability model that delineated stable, moderate, and unstable zones across cretaceous sedimentary units, validated by field inspection of cracked buildings and failed bridges (Lawal et al., 2024). Geotechnical stability correlated with lithology, lineament density, elevation, and slope, confirming that no single parameter adequately predicts infrastructure performance (Lawal et al., 2024). Geological-geotechnical mapping in Ponta Grossa, Brazil, demonstrated that correlating penetration test results and laboratory characterization data with geological formations of sedimentary origin produces maps that assist in adopting solutions for regional geotechnical challenges (Okpala et al., 2025). The growing pace of urbanization and infrastructure expansion in tropical developing regions, where sedimentary formations dominate the subsurface, makes integrated engineering geological assessment a practical necessity rather than an academic exercise (Lawal et al., 2024; Paiva et al., 2020; Ram et al., 2019). Without such integration, infrastructure projects will continue to encounter preventable failures rooted in incomplete understanding of the geological controls on engineering behaviour.

1.4 Aim and Scope of the Review

This review evaluates the engineering geological properties of sandstone and clay formations in tropical sedimentary terrains and examines their implications for infrastructure development and geotechnical stability. The review specifically focuses on:

1. grain-size distribution and sediment classification;
2. Atterberg limits and plasticity behaviour;
3. sandstone durability and ferruginization;
4. foundation stability and embankment performance;
5. erosion and slope-failure mechanisms; and
6. sustainable engineering and infrastructure-planning strategies.

2. Geological and Geotechnical Controls on Infrastructure Stability

2.1 Lithological Characteristics of Sandstone and Clay Units

The engineering behaviour of sedimentary formations depends on lithological composition and textural properties. Sandstone units with quartz-rich, grain-supported frameworks and chemical cementation exhibit higher mechanical strength, as confirmed by geomechanical studies showing fine-grained sandstones resist loading better than medium to coarse-grained varieties (Rakshit, 2021). In the Crocker Formation of Sabah, Malaysia, sandstones are texturally immature with angular to subrounded quartz grains cemented by clay minerals and occasionally calcite (Roslee & Tongku, 2018). The absence of chemical cement reduces sandstone strength, especially when weathered or structurally disturbed (Roslee & Tongkul, 2018). Ferruginized sandstones gain hardness from iron oxide cementation, as documented in deeply weathered sandstones of the Marília Formation in Brazil, where hematitic concentration forms crusts under tropical conditions of high temperature and free drainage (Rosolen et al., 2017). Excessive ferruginization reduces permeability and promotes differential weathering across the profile (Rosolen et al., 2017). Clay-rich formations behave differently. Soils with 50 to 70 percent clay fraction and intermediate to high plasticity produce excessive consolidation and differential settlement beneath foundations (Uchenna et al., 2023). Expansive clay minerals such as illite and smectite cause volumetric changes with moisture fluctuation (Nzeukou et al., 2021; Ozougwu, 2025). In North Cameroon, clayey soils with montmorillonite content (2 to 6 percent) and kaolinite (6 to 12 percent) showed high compressibility and low to high plasticity characteristics ranging from 13 to 33 percent (Nzeukou et al., 2021). Shale units maintain adequate strength under dry conditions but lose this strength when wet, becoming saturated and reducing resistance to sliding (Roslee & Tongku, 2018). The mineralogical composition of clay fractions, including kaolinite, illite, chlorite, and mixed-layer phyllosilicates, controls swelling potential, permeability, and bearing capacity (Kamal et al., 2022; Scrivano et al., 2017).

2.2 Structural and Sedimentological Controls

Structural discontinuities exert strong control over engineering performance in sandstone-clay terrains. Joints, fractures, bedding planes, and faults act as preferential pathways for groundwater infiltration and weathering, reducing slope stability and increasing failure risk (Roslee & Tongku, 2018; Chidiebube et al., 2025). In the mountainous terrain of Sabah, Malaysia, the Crocker Formation shows numerous lineaments with complex structural styles developed during Tertiary tectonic activities, and these tectonic complexities directly influenced the physical and mechanical properties of the rocks, producing a high degree of weathering and instability (Okpala et al., 2025, 2018b). Kinematics analyses of rock slopes in these formations identified circular, planar, wedge, and toppling failure modes controlled by discontinuity orientation, with factors of safety ranging from 0.50 to 0.98 (Roslee & Tongku, 2018; Okpala et al., 2024). Faulted zones contain angular to subrounded sandstone fragments with fine recrystallized quartz along joint planes, poorly sorted sheared materials, and fault gouge with slicken sided surfaces (Okpala et al., 2025). Sedimentological properties including grain sorting, roundness, packing density, and grain contacts also influence mechanical strength. Rakshit (2021) demonstrated that moderate to poorly sorted grains (phi scale 0.56 to 1.5) with packing density of 54 to 77 percent and packing proximity of 32 to 70 percent control uniaxial compressive strength in sandstones. Straight and concavo-convex grain contacts contribute more to strength than point contacts (Rakshit, 2021). Poorly graded to well graded materials with high fines content, as documented in slope failure materials from Sabah with plasticity content of 9 to 28 percent, exhibit reduced drainage capacity and greater susceptibility to deformation (Roslee & Tongku, 2018; Chidiebube et al., 2025). Cross-bedding and sedimentary laminations create internal anisotropy that influences permeability contrasts and differential weathering rates within the same formation (Nzeukou et al., 2021; Rosolen et al., 2017).

2.3 Climatic and Geomorphic Influence

Tropical climatic conditions accelerate weathering, erosion, and groundwater recharge, directly affecting engineering behavior of sandstone and clay formations. Warm and moist tropical climates induce rapid weathering of lithologies, forming thick weathering profiles

(Hack, 2020; Chidiebube et al., 2025). In Sabah, high annual rainfall sustains the moist and wet nature of slopes throughout most of the day, and accumulated rainfall during prolonged periods raises pore water pressures that reduce shear strength (Roslee & Tongku, 2018; Chidiebube et al., 2025). Humid tropical climates produce deep in-situ weathered soils due to intense chemical weathering, transforming rock masses into materials of weathering grades IV, V, and VI that behave more like soil than rock from an engineering perspective (Emeka et al., 2025). At the Kasavu landslide site in Fiji, daily rainfall of 176 mm followed by 3-day antecedent rainfall of 361 mm triggered a rotational slide transitioning into an earthflow, as tropical clays rapidly lost structure and cohesion once critical porewater pressures were reached (Ram et al., 2019). Seasonal wetting and drying cycles increase shrink-swell activity in clay formations. In North Cameroon, large seasonal variations in moisture and rainfall create favourable conditions for montmorillonite swelling, damaging engineering structures including residential buildings (Nzeukou et al., 2021). Geomorphic processes compound these effects. Slope retreat, drainage incision, and gully development modify terrain stability across sedimentary terrains (Emeka et al., 2025; Stetler, 2018). Differential weathering between resistant sandstone ridges and weak shale lowlands generates unstable slopes, as documented in Badlands National Park where bulk erosion rates correlated to grain size, with silty-sandy materials producing higher mass erosion rates as a function of the silt-to-clay ratio and plastic index (Stetler, 2018). In deeply weathered sandstones of Brazil, paleoclimate, pediplanation, laterization, and dissection created complex geological, geomorphological, and pedological features across flat plateaus (Rosolen et al., 2017). The interplay of rainfall intensity, weathering depth, slope geometry, and lithological contrasts determines the spatial distribution of infrastructure failures in tropical sedimentary terrains (Kamal et al., 2022; Ram et al., 2019; Chidiebube et al., 2025).

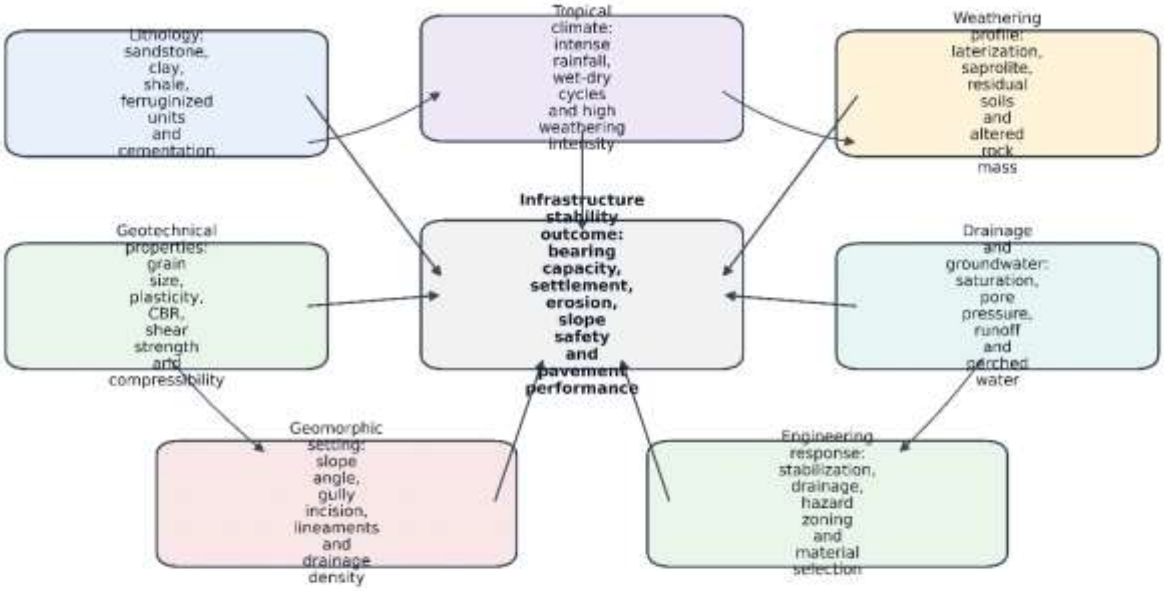


Figure 1: Conceptual interaction between lithology, climate, weathering, drainage, and infrastructure stability in tropical sedimentary terrains.

Figure 1 presents the conceptual interaction among lithology, tropical climate, weathering, drainage, geomorphic setting, and engineering response. It shows that infrastructure stability depends on combined geological and geotechnical controls rather than lithology alone. The figure supports integrated assessment for pavement, foundation, slope, erosion, and material suitability decisions.

3. Geotechnical Properties and Engineering Interpretation

3.1 Grain-Size Distribution and Sediment Classification

Grain-size distribution serves as a primary indicator of engineering behaviour in sedimentary terrains because it controls permeability, compaction response, drainage, and mechanical strength. Studies on the Bhuban sandstones of northeastern India showed that mean grain size ranged from 108 to 208 micrometres, with moderate to poor sorting (phi scale 0.56 to 1.5), and these parameters directly influenced uniaxial compressive strength (Gomes et al., 2022). In crushed sandstone waste materials from Amasiri quarries in southeastern Nigeria, sand-size fractions ranged from 46 to 60 percent while fines passing the No. 200 sieve ranged from 30 to 42 percent, and materials with less than 35 percent fines showed characteristics of good highway materials (Nwamekwe et al., 2025). Clayey soils from North Cameroon displayed grain-size distributions dominated by sand (62 to 80 percent), clay (12 to 25 percent), and silt (6 to 9 percent), classifying them as clayey sand or silty clay under the Unified Soil Classification System (Coutinho et al., 2020). In the Brazilian Amazonia, approximately 75 percent of topsoil in the region consists of fine fractions of silts and clays, creating subgrade materials with low bearing capacity that extend for tens of meters below the surface (Nwamekwe et al., 2024). Fine-grained materials with high silt-to-clay ratios produce higher mass erosion rates, as documented at Badlands National Park where bulk erosion correlated to grain size (Paiva et al., 2020). Poorly sorted materials with high fines content from slope failures in Sabah, Malaysia, consisted of poorly graded to well graded clayey loamy soils with low to intermediate plasticity (Vitalis et al., 2024). These findings confirm that grain-size distribution and sorting characteristics determine whether sedimentary materials perform adequately as subgrade, fill, or foundation materials in tropical environments.

3.2 Atterberg Limits and Plasticity Characteristics

Atterberg limits provide direct measures of soil consistency, compressibility, workability, and moisture sensitivity in sedimentary formations. Foundation soils at two failed buildings in Enugu, Nigeria, recorded liquid limits of 46 to 58 percent, plastic limits of 23 to 32 percent, and plasticity indices of 21 to 28 percent, placing them in the intermediate to high plasticity range and confirming their unsuitability for foundation purposes (Santos et al., 2020). Crushed sandstone waste materials from Amasiri quarries showed liquid limits of 32 to 38 percent and plasticity indices of 6 to 13 percent, indicating intermediate plasticity with improved engineering performance for road construction (Nwamekwe et al., 2020). Clayey soils from Boulgou in North Cameroon exhibited low plastic (13 to 22 percent) to high plastic (33 percent) characteristics, with methylene blue values of 3.3 to 5.6 confirming their silty-clayey nature (Coutinho et al., 2020). Slope failure materials from the Crocker Formation in Sabah displayed plasticity content of 9 to 28 percent with inactive to normal clay activity values of 0.34 to 1.45 (Santo et al., 2021). Residual soils from landslide sites in Cox's Bazar, Bangladesh, showed liquid limits of 25 to 48 percent and plasticity indices of 5 to 16 percent (Igbokwe et al., 2024). Expansive clay soils from Teresina, Brazil, containing illite and kaolinite minerals, demonstrated a free expansion potential of 1.9 percent classified as medium expansivity (Pinheiro et al., 2017). Residual soils from Abakaliki, Nigeria, recorded liquid and plastic limits ranging from 30 to 68 and 24 to 47 respectively, with plasticity indices between 6 and 18 (Balieiro et al., 2023). High plasticity soils undergo severe volumetric changes during moisture variation, leading to foundation distress, pavement cracking, and embankment failure, while low plasticity materials perform better under cyclic loading and seasonal moisture fluctuation.

3.3 Foundation Stability and Bearing Capacity

Foundation stability in tropical sedimentary terrains depends on soil plasticity, groundwater conditions, drainage characteristics, and lithological variability. At two failed buildings in Enugu, Nigeria, soils with 50 to 70 percent clay fraction showed high cohesion values of 29.06 to 37.62 kN/m2 and low angles of internal friction of 4.74 to 8.88 degrees, producing bearing capacity values of 241.77 to 305.2 kN/m2 (Santos et al., 2020). Despite these bearing capacity values, the soils experienced differential settlement ranging from 2.06 x 10-4 to 3.44 x 10-3 m2/yr due to high compressibility and porosity values of 25.90 to 36.15 percent that allowed water accumulation under conditions of low permeability (Santos et al., 2020). In the

Kutupalong Rohingya Camp area of Bangladesh, residual soils had undrained shear strength of only 23 to 46 kPa, while underlying silty sandstones showed friction angles of 34 to 40 degrees and cohesion of 0.5 to 13 kPa (Igbokwe et al., 2025). The geotechnical stability model developed for Gombe, Nigeria, confirmed that areas underlain by argillaceous materials of the Pindiga Formation were classified as unstable zones (17.24 percent of the study area), with field validation revealing cracked buildings and a failed bridge (Lautenschläger et al., 2020). In Sabah, Malaysia, slope stability analyses of soil and rock slopes produced factors of safety of 0.50 to 0.98, classified as unsafe, with failures occurring when materials lost shear strength due to high pore pressure and geomorphological processes (Ojo et al., 2024; Santo et al., 2021). Clay units with high moisture sensitivity experience reduced shear strength under saturated conditions, and these effects intensify where drainage systems are poor or groundwater tables fluctuate seasonally, as documented in the Barreiras Formation of Maceió, Brazil, where standard penetration test data revealed variable resistance across sandy and clayey layers (Ekwe et al., 2018).

3.4 Sandstone Durability and Quarry Suitability

Sandstone durability depends on mineral composition, cementation, porosity, ferruginization, and weathering resistance. Geomechanical classification of sandstones from the Indo-Burmese Ranges showed that the presence of angular grains and semi-angular spherical grains diminished macromechanical strength, and FETEM-EDX analysis confirmed microweathering of angular grains with deformed lattice settings (Gomes et al., 2022). Crushed sandstone waste from Amasiri quarries in southeastern Nigeria recorded high maximum dry density, low optimum moisture content, and undrained cohesion values exceeding 103 kN/m2, satisfying requirements for base course materials in road construction (Nwamekwe et al., 2025). The materials showed low swelling capacity on moisture influx, high bearing capacity, and intermediate permeability, though stabilization was recommended for long-term strength gain in high volume applications (Nwamekwe et al., 2025). Ferruginized sandstones of the Marília Formation in Brazil developed hardening hematite concentrations as layered accretions in the subparallel clayey lenses of sandstone saprolite, with iron content varying according to different soil fabrics and higher concentrations found in massive ferricrete and pisolites (Ram et al., 2019). In the Adi-Daero area of Ethiopia, iron-duricrust deposits developed from sandstone bedrock through in situ vertical transfer of iron under tropical weathering, with Fe2O3 content ranging from 6.8 to 72.93 weight percent (Roslee & Tongkul, 2018). The Macigno sandstone showed that the presence of mixed-layer phyllosilicates and microporosimetric features led to high susceptibility to relative humidity variation, with swelling minerals contributing to weathering through saline solution interaction (Lawal et al., 2024). In Sabah, Malaysia, rock samples from the Crocker Formation recorded point load strength index and uniaxial compressive strength classified as moderately weak (Santo et al., 2021). Quarry evaluation therefore requires assessment of mineralogical maturity, grain bonding, weathering resistance, fracture density, and cementation type to determine suitability for engineering applications in tropical environments

Table 1: Engineering properties of sandstone and clay formations and their infrastructure implications.

Material / formation	**Key engineering properties**	**Indicative values from reviewed studies**	**Engineering interpretation**	**Infrastructure implication**	**Recommended assessment**
Quartz-rich sandstone	Grain-supported framework, higher strength when well cemented, lower reactivity where quartz dominates	Fine-grained sandstone more resistant than medium to coarse varieties; clean	Generally competent where cementation is strong, but strength decreases with	Suitable as foundation or aggregate source after durability and fracture assessment	UCS, point-load index, petrography, grain-size analysis, porosity and

		sandstone may show high effective porosity	weathering and fractures		weathering grade
Poorly cemented sandstone	High permeability, friability, weak bonding and susceptibility to gully erosion	Sand-size fraction commonly dominates, but high fines or weak cement reduces performance	Rapid infiltration and piping can undermine slopes and pavements	Needs erosion control, drainage and careful cut-slope design	Permeability, slake durability, grain bonding, slope mapping and erosion susceptibility
Ferruginized sandstone / laterite	Iron-oxide cementation, hard crusts, variable permeability and differential weathering	Fe2O3 may rise from parent sandstone to ferricrete; ferricrete improves hardness but may restrict infiltration	Useful as construction material where quality and thickness are adequate	Improves layer strength but can redirect runoff and trigger erosion when fractured	Iron content, durability, aggregate tests, layer continuity and drainage evaluation
Clay-rich formations	High fines, moisture sensitivity, shrink-swell behaviour, low permeability and high compressibility	Clay fractions of 50-70% and plasticity indices in intermediate to high range were linked with settlement	Weak subgrade and foundation material unless improved or replaced	Promotes pavement cracking, settlement, embankment failure and foundation distress	Atterberg limits, consolidation, swelling, shear strength and mineralogical testing
Shale and sandstone-clay interfaces	Contrasting permeability, water accumulation, bedding weakness and strength loss when wet	Failure often develops along bedding, shale contacts or clay seams under high pore pressure	Critical zones for slope instability and differential settlement	Requires drainage interception, slope support and conservative foundation design	Discontinuity mapping, groundwater monitoring, shear strength and slope stability analysis
Residual tropical soils	Deep weathering profiles, lateritic/saprolitic textures, variable grading and rapid property change with moisture	Weathering grades IV-VI behave more like soil than rock under engineering loading	Performance depends on local weathering depth, fines content and compaction condition	Requires site-specific classification, not generalized lithological assumptions	SPT/CPT, index tests, compaction, CBR, permeability and seasonal moisture profiling

Table 1 summarizes engineering properties of sandstone, clay, shale interfaces, ferruginized units, and residual tropical soils. It links texture, plasticity, cementation, permeability, and weathering to bearing capacity, settlement, erosion, and aggregate suitability. The table guides field investigation, laboratory testing, material selection, and infrastructure risk interpretation.

4. Environmental and Infrastructure Failure Mechanisms

4.1 Road Failure in Tropical Sedimentary Terrains

Road failure in tropical sedimentary terrains results from the combined effects of weak subgrade materials, poor drainage, excessive moisture infiltration, and differential settlement. Along the Enugu-Onitsha expressway in southeastern Nigeria, pavement failures occurred on shale subgrade with liquid limits of 57.69 to 62.61 percent, plasticity indices of 20.32 to 24.37 percent, and soaked California bearing ratio values of only 1.03 to 1.60 percent, all falling below the Nigerian Federal Ministry of Works and Housing specification for pavement construction (Gomes et al., 2022). Subgrade soils on rural roads in Cross River State, Nigeria, showed that alignments on Cretaceous sedimentary terrain contained A-7-5 and A-7-6 soils interspersed with A-2-4 materials, while alignments on Basement Complex terrain lacked the A-7 group entirely, confirming that geology directly controls subgrade quality (Nwamekwe et al., 2025). Along the Sagamu-Papalanto highway in southwestern Nigeria, low resistivity values of 50 to 300 ohm-meters beneath failed sections indicated incompetent clay materials with high water retention capacity that expanded when wet and collapsed under imposed load (Coutinho et al., 2020). Failed sections of the Ifon-Benin highway showed plasticity indices greater than 20 percent, fines greater than 35 percent, and CBR values less than the 80 percent minimum, with cone penetration tests revealing predominant sandy silt to clayey silt topsoil over clay substratum with compressive strength of only 20 to 40 kN/m2 (Nwamekwe et al., 2024). The failure mechanism at both locations involved water ingression into the subgrade after rain eroded the earth embankment, dissolving the fill material and infiltrating the pavement layers, reducing cohesion and subgrade support (Nwamekwe et al., 2024). Along the Lagos-Ibadan expressway, natural moisture content at failed sections ranged from 13.11 to 26.89 percent compared to 11.11 to 16.40 percent at stable sections, and soils with linear shrinkage greater than 8 percent showed high susceptibility to swelling and shrinkage causing differential settlement (Paiva et al., 2020). Lateritic soils beneath failed highway sections in Akure, Nigeria, had fines exceeding 57 percent, soaked CBR of 3 to 11 percent, and percentage reduction in strength up to 79 percent upon moisture exposure (Santo et al., 2021). These findings confirm that saturated clay-rich subgrades lose strength rapidly and promote pavement cracking, rutting, and deformation across sedimentary terrains.

4.2 Erosion and Slope Instability

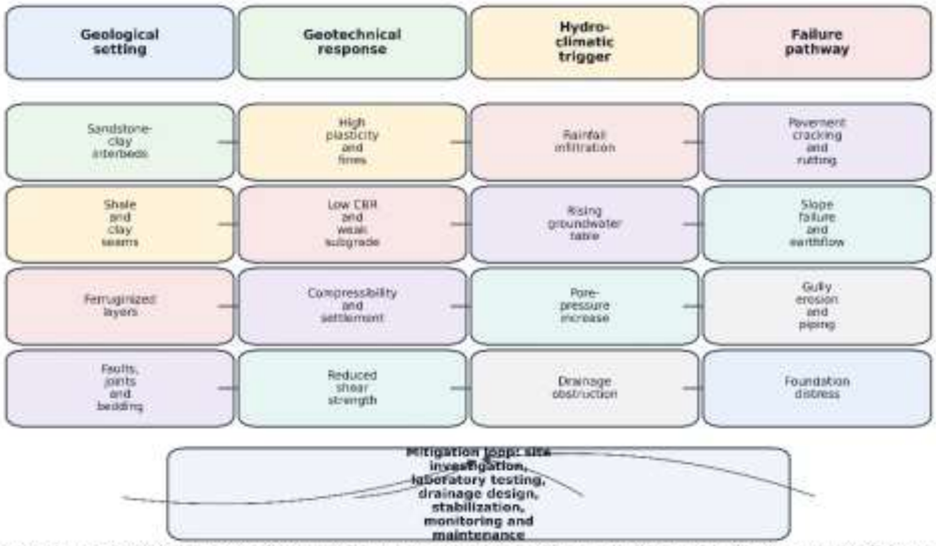
Erosion and slope instability represent severe environmental hazards in tropical sedimentary terrains where differential weathering between sandstone and clay units creates conditions for gully formation, slope retreat, and mass wasting. In the mountainous terrain of Sabah, Malaysia, the argillaceous Trusmadi Formation and the jointed sandstone and mudstone beds of the Crocker Formation produced slope failures with factors of safety of 0.56 to 0.95, with soil slope failures involving larger volumes of failed material than rock slope failures (Santos et al., 2020). Along the Penampang to Tambunan Road in Sabah, 31 critical slope failures were documented, with 67 percent occurring in soil slopes and 48 percent of all failures involving embankments, where failure materials consisted of poorly graded to well graded clayey loamy soils with cohesion values of 3.20 to 17.27 kPa and friction angles of 7.70 to 29.20 degrees (Igbokwe et al., 2025). At the Kasavu landslide site in Fiji, a shallow rotational landslide transitioned into an earthflow after daily rainfall of 176 mm, with pre-conditioning factors including steep slopes greater than 21 degrees, expansive smectite clays, and piping erosion (Pinheiro et al., 2017). Slope failures triggered by Tropical Cyclone Winston along a 35 km stretch of the Kings Road in Fiji produced approximately 61 distinct shallow failures, most of complex type including earth and debris slides with a minor flow component, triggered by 258 mm of rainfall in 24 hours after 30-day antecedent rainfall of 482 mm (Balieiro et al., 2023). In the Kutupalong Rohingya Camp area of Bangladesh, slopes of 40 to 60 degrees with numerous polygonal tension cracks failed in residual soils with undrained shear strength of only 23 to 46 kPa overlying weathered silty sandstones with cohesion of 0.5 to 13 kPa (Lautenschläger et al., 2020). At Badlands National Park, bulk erosion rates correlated to grain size, with silty-sandy materials producing higher mass erosion rates as a function of the silt-to-clay ratio and plastic index (Ojo et al., 2024). Clay-rich formations are particularly vulnerable because runoff removes weak weathered materials during intense rainfall events, and the combination of steep slopes, expansive minerals, and poor drainage accelerates erosion development across sedimentary terrains.

4.3 Engineering Implications of Ferruginization

Ferruginization modifies the engineering properties of sedimentary formations by introducing iron oxide cementation that increases hardness but alters drainage behaviour. In deeply weathered sandstones of the Marília Formation in Brazil, hardening hematite concentrations formed as layered accretions in subparallel clayey lenses of sandstone saprolite, with higher iron concentrations found in massive ferricrete and pisolites in the mottled horizon (Ekwe et al., 2018). The continuous sequence of ferricrete from saprolite to the Ferralsol indicated autochthonous regolith development through a long and intense process of laterization under tropical conditions of high temperature and free drainage (Ekwe et al., 2018). In the Adi-Daero area of northwestern Tigray, Ethiopia, iron-duricrust deposits developed from sandstone bedrock through in situ vertical transfer of iron under tropical weathering, with Fe2O3 content ranging from 6.8 to 72.93 weight percent (Ram et al., 2019). The duricrust showed a progressive increase in Fe2O3 from the parent sandstone (6.8 percent) through the mottled zone (19.5 percent) to the ferricrete (72.93 percent), with corresponding depletion of SiO2 and Al2O3 (Ram et al., 2019). In the Brazilian Amazonia, laterite deposits are geographically restricted because they require tropical heat, intense rainfall, and elevated plains on gently sloping terrain surfaces not subject to appreciable erosion (Roslee & Tongkul, 2018). These lateritic materials are widely used for structural layers of highways, but the first challenge is locating deposits with adequate quantity and quality, as they contain high clay content despite being hard and cemented (Roslee & Tongkul, 2018). Along the Ago-Iwoye/Ilishan road in Nigeria, an approximately 1 m thick lateritic topsoil cushioned anticipated severe pavement failure along the basement segment, demonstrating the protective function of ferruginized layers (Lawal et al., 2024). Restricted infiltration through impermeable ferricrete surfaces increases surface runoff and accelerates erosion development in areas where the hardpan is exposed or fractured, creating a dual engineering effect where ferruginization improves material strength but complicates drainage management.

4.4 Groundwater Influence on Soil Behaviour

Groundwater modifies engineering performance of sedimentary formations through saturation effects, reduced shear strength, and increased pore-water pressure. Along the Ado-Ikere Road in southwestern Nigeria, the rising water table within the influence zone of the pavement promoted heaving, differential settlement, and reduction in load bearing capacity of the near surface subsoil, with clay materials showing resistivity values less than 100 ohm-meters indicating incompetent saturated zones (Okpala et al., 2024). Subgrade soils on Cretaceous sedimentary terrain in Cross River State, Nigeria, showed higher moisture content values than those from Basement Complex lithology, indicating that sedimentary terrains retain more groundwater and create compaction problems where natural moisture content exceeds optimum moisture content (Nwamekwe et al., 2025). Along the Kings Road in Fiji, contemporary slope instability was caused by elevated porewater pressure during high intensity rainfall events in clay-dominated soils, with rapid increases in porewater pressures occurring at the contact of residual soils and the underlying weathered basement rock (Balieiro et al., 2023). At the Kasavu landslide site, prolonged rainfall from a tropical depression raised porewater pressures in smectite-bearing soils close to the liquid limit, triggering a rotational slide (Pinheiro et al., 2017). In Sabah, Malaysia, weathered materials experienced sliding due to high pore pressure sustained by high annual rainfall that maintained the moist and wet nature of slopes throughout most of the day (Igbokwe et al., 2024; Santos et al., 2020). Foundation soils at failed buildings in Enugu, Nigeria, had porosity values of 25.90 to 36.15 percent that allowed water accumulation under conditions of low permeability ranging from 9.99 x 10-13 to 2.12 x 10-5 cm/sec, causing waterlogging at the site (Rakshit, 2021). The TDRAMS model analysis for roads in southwestern Nigeria identified depth of water table as one of the two most significant parameters controlling pavement failure susceptibility, with an optimum weight increase of 78 percent (Roslee & Tongku, 2018). These studies confirm that high groundwater conditions destabilize slopes, weaken foundations, and reduce subgrade stiffness within clay-rich sedimentary terrains.



The framework shows how weak materials become infrastructure failures when adverse groundwater and rainfall conditions intersect with insufficient engineering control.

Figure 2: Integrated framework linking geology, geotechnical properties, groundwater, and infrastructure failure pathways.

Figure 2 links geological setting, geotechnical response, hydro-climatic triggers, and failure pathways in sandstone-clay terrains. It traces how interbeds; weak subgrades, plasticity, groundwater rise, and rainfall generate pavement cracking, slope failure, gully erosion, and foundation distress. The feedback loop emphasizes testing, drainage, stabilization, monitoring, and maintenance.

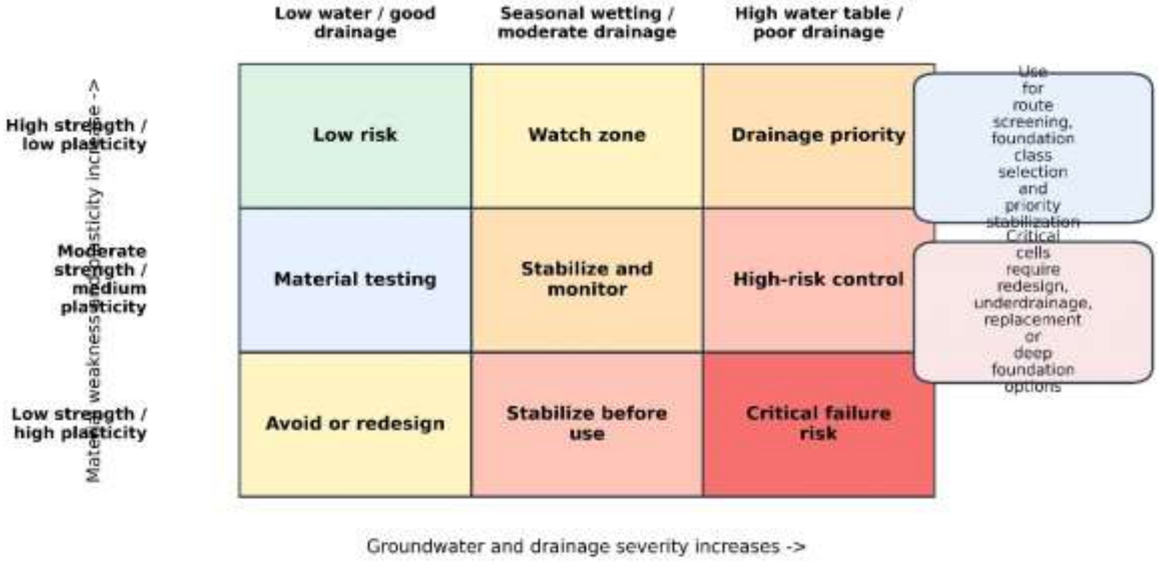
5. Engineering Applications and Sustainable Infrastructure Planning

5.1 Highway and Pavement Engineering

Effective highway construction in tropical sedimentary terrains demands careful material selection, drainage design, and subgrade stabilization based on site-specific geological conditions. Along the Enugu-Onitsha expressway in southeastern Nigeria, pavement failures occurred on shale subgrade with soaked California bearing ratio values of only 1.03 to 1.60 percent, far below the Nigerian Federal Ministry of Works and Housing specification for pavement construction (Gomes et al., 2022). Subgrade soils on rural roads in Cross River State, Nigeria, showed that alignments on Cretaceous sedimentary terrain contained A-7-5 and A-7-6 soils with poor engineering characteristics, while alignments on Basement Complex terrain lacked these problematic soil groups entirely (Nwamekwe et al., 2025). The TDRAMS model analysis for roads in southwestern Nigeria identified depth of water table and subgrade soil type as the two most significant parameters controlling pavement failure susceptibility (Coutinho et al., 2020). In the Brazilian Amazonia, approximately 75 percent of topsoil consists of fine fractions of silts and clays, creating subgrade materials with low bearing capacity that extend for tens of meters below the surface, and traditional soil classification systems such as TRB and USCS disregard the essential evaluation of mechanical and hydraulic attributes of tropical geomaterials (Campelo et al., 2022). Crushed sandstone waste from Amasiri quarries in southeastern Nigeria showed liquid limits of 32 to 38 percent, plasticity indices of 6 to 13 percent, and undrained cohesion exceeding 103 kN/m2, satisfying requirements for base course materials in road construction (Nwamekwe et al., 2024). Lateritic soils beneath failed highway sections in Akure, Nigeria, had fines exceeding 57 percent and soaked CBR of 3 to 11 percent, with percentage reduction in strength up to 79 percent upon moisture exposure (Paiva et al., 2020). These findings confirm that low-plasticity materials with good drainage characteristics perform better as pavement foundations, and engineers working in tropical sedimentary terrains need to prioritize subgrade characterization, proper drainage installation, and material stabilization to prevent the recurrent pavement failures documented across these environments.

5.2 Foundation and Embankment Design

Foundation and embankment design in tropical sedimentary terrains requires accounting for lithological variability, groundwater conditions, and plasticity behavior to minimize settlement and structural failure. At two failed buildings in Enugu, Nigeria, foundation soils with 50 to 70 percent clay fraction showed high compressibility, with coefficient of consolidation values indicating differential settlement ranging from 2.06 x 10-4 to 3.44 x 10-3 m2/yr, and porosity values of 25.90 to 36.15 percent allowed water accumulation under conditions of low permeability (Santo et al., 2021). Embankment failures dominated slope failure records in Sabah, Malaysia, where 71 percent of soil slope failures along the Penampang to Tambunan Road involved embankments, with failure materials showing cohesion values of 3.20 to 17.27 kPa and friction angles of 7.70 to 29.20 degrees (Santos et al., 2020). In the Kutupalong Rohingya Camp area of Bangladesh, residual soils had undrained shear strength of only 23 to 46 kPa overlying weathered silty sandstones with cohesion of 0.5 to 13 kPa, and slope failures occurred in slopes of 40 to 60 degrees with numerous polygonal tension cracks (Igbokwe et al., 2025). Road cut slopes in lateritic soil in Rwanda remained stable for extended periods in their natural unsaturated state but failed when weathering weakened mechanical behavior and heavy rainfall triggered rapid landslides, with stability analysis producing a minimum safety factor of 0.8 (Valentino et al., 2024). The geotechnical stability model for Gombe, Nigeria, delineated 17.24 percent of the study area as unstable zones underlain by argillaceous materials, with field validation revealing cracked buildings and a failed bridge (Pinheiro et al., 2017). Proper compaction, drainage control, and geotechnical testing are essential for minimizing settlement and embankment failure, and foundation design should incorporate site-specific data on clay mineralogy, groundwater fluctuation, and shear strength parameters rather than relying on generalized design assumptions.



	Low water / good drainage	Seasonal wetting / moderate drainage	High water table / poor drainage
High strength / low plasticity	Low risk	Watch zone	Drainage priority
Moderate strength / medium plasticity	Material testing	Stabilize and monitor	High-risk control
Low strength / high plasticity	Avoid or redesign	Stabilize before use	Critical failure risk

Use for route screening, foundation class selection and priority stabilization

Critical cells require redesign, underdrainage, replacement or deep foundation options

Figure 3: Geotechnical Risk Decision Matrix for Sandstone-Clay Infrastructure Corridos

Figure 3 is an added geotechnical risk decision matrix. It combines material strength, plasticity, groundwater condition, and drainage severity to classify infrastructure corridors from low risk to critical failure risk. The matrix helps engineers screen alignments, prioritize stabilization, decide redesign needs, and communicate geotechnical risk before construction.

5.3 Quarry Material Evaluation

Engineering suitability of sandstone aggregates requires evaluation through grain-size distribution, mineralogical composition, durability testing, and weathering assessment. Geomechanical studies of the Bhuban sandstones in northeastern India demonstrated that macro-mechanical properties including grain sorting (phi scale 0.56 to 1.5), packing density (54 to 77 percent), and grain contact types directly controlled uniaxial compressive strength (Balieiro et al., 2023). Crushed sandstone waste from Amasiri quarries in southeastern Nigeria recorded high maximum dry density, low optimum moisture content, low swelling capacity on moisture influx, high bearing capacity, and intermediate permeability, satisfying requirements for base course materials (Nwamekwe et al., 2024). The Macigno sandstone showed that the presence of mixed-layer phyllosilicates and microporosimetric features led to high susceptibility to relative humidity variation, with swelling minerals contributing to weathering through saline solution interaction (Lautenschläger et al., 2020). In Sabah, Malaysia, rock samples from the Crocker Formation recorded point load strength index and uniaxial compressive strength classified as moderately weak, with the absence of chemical cement reducing sandstone strength when weathered or structurally disturbed (Ojo et al., 2024; Santos et al., 2020). Ferruginized sandstones of the Marília Formation in Brazil developed hardening hematite concentrations as layered accretions, with iron content varying according to different soil fabrics (Ekwe et al., 2018). In the Adi-Daero area of Ethiopia, iron-duricrust deposits showed Fe2O3 content ranging from 6.8 to 72.93 weight percent, with progressive enrichment from parent sandstone through the mottled zone to the ferricrete (Ram et al., 2019). These studies confirm that quarry evaluation requires detailed assessment of mineralogical maturity, grain bonding, weathering resistance, fracture density, and cementation type to determine long-term suitability for engineering applications in tropical environments.

5.4 Sustainable Geotechnical Planning

Sustainable infrastructure development in tropical sedimentary terrains requires integrated geological mapping, erosion-control strategies, drainage management, hazard zoning, and long-term geotechnical monitoring. Engineering geological mapping in Sabah, Malaysia, identified six interrelated parameters controlling slope instability, including local and regional geology, hydrology, mineralogy, discontinuity structures, physical and engineering properties, and geomorphological processes, and recommended that development planning consider slope hazard and risk management (Ojo et al., 2024). The geotechnical stability model developed for Gombe, Nigeria, using remote sensing and GIS integration of lithology, lineament, elevation, and slope thematic maps, delineated stable, moderate, and unstable zones validated through field inspection of structures (Pinheiro et al., 2017). Geological-geotechnical mapping in Ponta Grossa, Brazil, demonstrated that correlating penetration test results and laboratory characterization data with geological formations of sedimentary origin produces maps that assist in adopting solutions for regional geotechnical challenges (Roslee & Tongkul, 2018). At the Kasavu landslide site in Fiji, future management recommendations included drainage of the ridgeline, groundwater monitoring, and provision of load support to existing slopes (Ram et al., 2019b). Road construction in tropical regions presents unique environmental challenges, and stakeholder-based prioritization models using the Analytic Hierarchy Process ranked soil and land as the most critical environmental aspect (35.0 percent), with slope failure, erosion, and peatland disturbance identified as top sub-indicators (Hafnidar, 2025). In the Brazilian Amazonia, laterite deposits used for structural layers of highways require careful location and quality assessment, as they contain high clay content despite being hard and cemented (Campelo et al., 2022). Ecohydrological studies of road impacts in tropical settings confirmed that unpaved roads contribute sediment to stream networks at rates disproportionate to the areas they occupy, and called for incorporation of transdisciplinary approaches to study road effects on tropical environments (Wemple et al., 2017). These findings confirm that sustainable geotechnical planning demands a multi-parameter, multi-disciplinary approach linking geology, geotechnics, geomorphology, hydrology, and environmental management within a single infrastructure planning framework.

Table 2: Engineering mitigation strategies for sandstone-clay terrains under tropical climatic conditions.

Hazard / engineering problem	**Main geological control**	**Triggering condition**	**Mitigation strategy**	**Expected engineering benefit**	**Best placement in project cycle**
Pavement deformation and rutting	Clay-rich or shale-derived subgrade with high plasticity and low CBR	Rainfall infiltration, poor shoulders, high groundwater and repeated traffic loading	Subgrade replacement, lime/cement stabilization, geotextile separation, adequate compaction and side drains	Improves bearing support, reduces swelling, limits moisture ingress and delays structural cracking	Route investigation, design and pre-construction material approval
Foundation settlement	Compressible clay, high porosity, low permeability and variable sandstone-clay contacts	Seasonal water accumulation and load-induced consolidation	Detailed foundation investigation, soil improvement, raft or pile foundation where required, and groundwater control	Reduces differential settlement and increases structural reliability	Foundation design and pre-excavation verification
Slope failure and earthflow	Weak weathered sandstone, clay seams, shale contacts, bedding planes and discontinuities	Intense rainfall, antecedent wetness, pore-pressure rise and toe erosion	Slope regrading, retaining structures, subsurface drainage, vegetation control and monitoring instruments	Improves shear resistance, reduces pore pressure and limits progressive failure	Route alignment, cut-slope design and maintenance planning
Gully erosion and piping	Friable sandstone, sandy-silty soils, poor cementation and concentrated runoff	Uncontrolled drainage discharge, exposed slopes and high rainfall intensity	Check dams, lined drains, energy dissipators, slope revegetation and erosion-control mats	Reduces runoff velocity, stabilizes exposed surfaces and interrupts subsurface piping	Drainage design, environmental management and post-construction maintenance
Ferricrete-related runoff concentration	Hard ferruginized crust, low infiltration zones and fractured hardpan	Surface exposure, cracking, poor drainage outlets and slope incision	Map ferricrete continuity, create controlled drainage pathways and avoid uncontrolled discharge onto erodible units	Preserves material strength while preventing runoff-driven erosion	Site characterization and drainage layout design
Climate-related deterioration	Wet-dry cycles, progressive weathering and changing rainfall intensity	Long-term moisture cycling, extreme storms and land-use change	Long-term monitoring, GIS hazard zoning, early-warning thresholds and adaptive maintenance scheduling	Supports climate-resilient infrastructure management and preventive intervention	Planning, operation and asset-management stages

Table 2 presents mitigation strategies for major infrastructure hazards in tropical sandstone-clay terrains. It relates pavement deformation, settlement, slope failure, gully erosion, ferricrete runoff, and climate deterioration to geological controls, triggers, interventions, expected benefits, and project timing. It supports practical planning from investigation to asset management.

6. Research Gaps and Emerging Directions

6.1 Limited Long-Term Geotechnical Monitoring

Most engineering geological studies in tropical sedimentary terrains rely on short-term investigations that fail to capture seasonal variability and long-term material degradation. Along the Kings Road in Fiji, slope instability recurred at the same locations over multiple rainfall seasons, yet detailed studies of factors pre-conditioning slopes to fail and slope failure mechanisms remained sparse (Ram et al., 2019). Road cut slopes in lateritic soil in Rwanda remained stable for extended periods in their natural unsaturated state but failed when weathering weakened mechanical behaviour over time and heavy rainfall triggered rapid landslides (Valentino et al., 2024). In Sabah, Malaysia, engineering geological studies of 20 to 31 critical slope failures along different road segments documented unsafe factors of safety ranging from 0.50 to 0.98, but these assessments represented single-event snapshots rather than continuous monitoring records (Igbokwe et al., 2025; Santos et al., 2020). The Barreiras Formation in Maceió, Brazil, supports major engineering works with increasing intensity since 2007, yet the formation remains deficient in studies regarding sedimentological and stratigraphic aspects (Ekwe et al., 2018). Weathering processes in tropical environments alter surface features quickly, complicating the assessment of rock strength and stability over time (Okeagu et al., 2024). Soft grounds resulting from weathering change geotechnical properties continuously, and quantities of weathered material do not need to be large to alter the properties of a ground mass, for example through weathering of discontinuity walls that reduce shear strength (Hack, 2020). These observations confirm that single-phase site investigations produce incomplete characterizations of subsurface conditions. Long-term geotechnical monitoring programs that track seasonal porewater pressure fluctuations, progressive weathering, and cumulative material degradation are needed to support reliable infrastructure design in tropical sedimentary terrains.

6.2 Weak Integration Between Geology and Civil Engineering

Geological processes remain underrepresented in engineering design despite their strong influence on infrastructure performance. Subgrade soils on rural roads in Cross River State, Nigeria, showed that alignments on Cretaceous sedimentary terrain contained A-7-5 and A-7-6 soils with poor engineering characteristics, while alignments on Basement Complex terrain lacked these problematic soil groups entirely, yet road designs did not account for these geological differences (Nwamekwe et al., 2025). Along the Ifon-Benin highway in Nigeria, pavement failures occurred where cone penetration tests revealed predominant sandy silt to clayey silt topsoil over clay substratum with compressive strength of only 20 to 40 kN/m2, conditions that pre-construction geological assessment would have identified (Nwamekwe et al., 2024). In the Brazilian Amazonia, traditional soil classification systems such as TRB and USCS disregard the essential evaluation of mechanical and hydraulic attributes of tropical geomaterials, creating a disconnect between geological reality and engineering practice (Campelo et al., 2022). The TDRAMS model analysis for roads in southwestern Nigeria demonstrated that integrating geological parameters such as depth of water table and subgrade soil type improved failure prediction, with an optimum weight increase of 78 percent for water table depth (Coutinho et al., 2020). Engineering geological mapping in Sabah identified six interrelated parameters controlling slope instability, including local and regional geology, hydrology, mineralogy, discontinuity structures, physical and engineering properties, and geomorphological processes, and recommended that engineering geological study should be prioritized as the initial step in all infrastructure programs (Roslee & Tongku, 2018). The geotechnical stability model for Gombe, Nigeria, confirmed that no single parameter adequately predicted infrastructure performance, as stability correlated with lithology, lineament density, elevation, and slope simultaneously (Pinheiro et al., 2017). These findings demonstrate that infrastructure projects in tropical sedimentary terrains require closer collaboration between geologists and civil engineers from the planning stage through construction and maintenance.

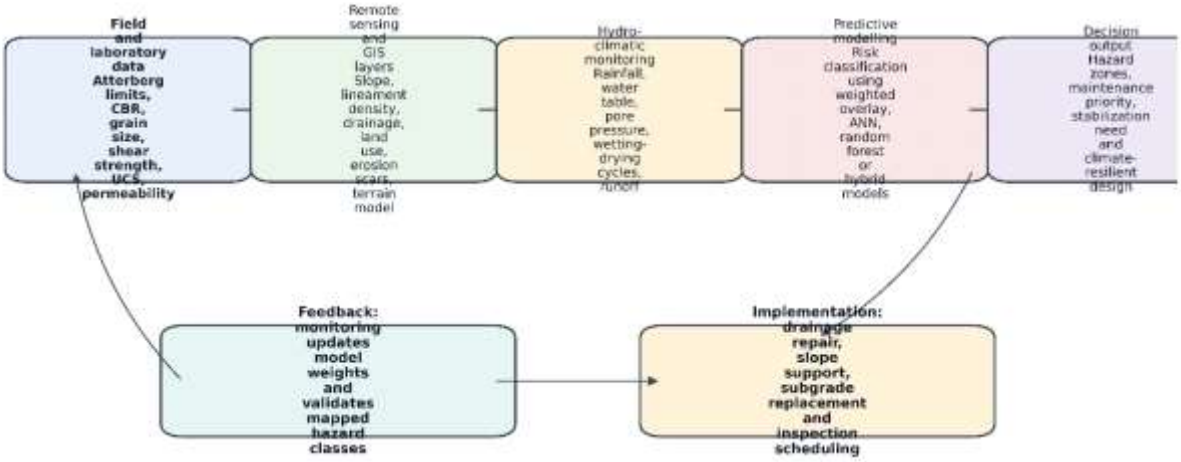
6.3 Need for GIS and Remote-Sensing Hazard Mapping

Spatial technologies improve identification of erosion-prone zones, unstable slopes, and infrastructure-risk corridors in tropical sedimentary terrains. The geotechnical stability model developed for Gombe, Nigeria, integrated four thematic maps (lithology, lineament, elevation, and slope) in a GIS environment, delineating 17.24 percent of the study area as unstable, 77.2 percent as moderate, and 4.74 percent as stable, with field validation confirming cracked buildings and a failed bridge in unstable zones (Pinheiro et al., 2017). Geospatial technologies integrating GIS, remote sensing, and GPS have been identified as effective tools for improved terrain analysis and gully erosion assessment in the humid tropics of southern Nigeria (Umo et al., 2018). In the southeast Bohol Province of the Philippines, landslide susceptibility models generated using open-sourced medium-resolution satellite data and digital elevation models processed through Analytical Hierarchy Process in GIS produced statistically significant results with a p-value of 0.031, demonstrating that medium-resolution satellite data generate accurate and compatible landslide susceptibility models (Ezeanyim et al., 2025). LiDAR technology in Malaysia's tropical climate captured terrain information at 2 cm ground sample distance using UAV platforms, revealing detailed geomorphological features including landslides through 3D terrain models that enhanced geological hazard assessment (Okeagu et al., 2024). In Sri Lanka, the combination of GIS, remote sensing, and the revised universal soil loss equation model identified areas with high landslide frequency ratios in less dense forest and cropping areas, with average annual soil erosion rates increasing from 14.56 to 15.53 t/ha/year between 2000 and 2019 (Senanayake et al., 2020). Soil erosion assessment in Kinshasa using earth observation resources and GIS determined that 2.3 percent of the total area faced high risk of soil erosion exceeding 15 t/ha/year, with urban areas showing 4.3 percent at high risk compared to 2.3 percent in rural areas (Kabantu et al., 2018). These studies confirm that GIS and remote sensing provide cost-effective, spatially comprehensive tools for hazard mapping in data-scarce tropical regions where field access is limited.

6.4 Machine Learning for Failure Prediction

Machine learning approaches offer significant potential for predicting pavement deterioration, slope instability, and settlement behaviour using geological and geotechnical datasets. Artificial neural networks have emerged as a preferred method for landslide susceptibility assessments, surpassing traditional approaches in accuracy and reliability (Nanehkaran et al., 2023). Studies from multiple countries demonstrated that ANNs provide high accuracy with low error rates, making landslide susceptibility mapping and hazard risk predictions more reliable than conventional statistical methods (Nanehkaran et al., 2023). In western Myanmar, multi-factor analysis using statistical inference identified strong correlations between rainfall intensity and landslide occurrences, with Pearson correlation coefficients of 0.806 and Spearman's rho coefficients of 0.979, providing quantitative frameworks that machine learning algorithms build upon (Shwe et al., 2024). Forest-based classification and regression analysis applied to landslide susceptibility models in the Philippines produced p-values of 2.2 x 10-16 in ordinary linear regression validation, confirming the statistical significance of prediction models derived from remote sensing data (Ezeanyim et al., 2025a). The TDRAMS model for road failure prediction in southwestern Nigeria used weighted parameter analysis to identify depth of water table and subgrade soil type as the two most significant variables, achieving optimum weight increases of 78 and 56 percent respectively

(Coutinho et al., 2020). Multi-hazard interaction approaches using simulation models, GIS, and remote sensing techniques have been applied to assess infrastructure vulnerability, with fragility curves and hazard matrices serving as tools for identifying areas exposed to multiple geological hazards (Hudaib & Ray, 2023). These developments indicate that integrating geological and geotechnical datasets with machine learning algorithms produces more accurate failure predictions than conventional deterministic methods, and future research should focus on training these models with long-term monitoring data from tropical sedimentary terrains.



This extra figure strengthens the emerging direction on GIS, remote sensing, machine learning, monitoring and climate-resilient planning.

Figure 4: GIS and Machine Learning Enabled Early-Warning Workflow for Tropical Infrastructure Risk

Figure 4 is an added early-warning workflow for GIS- and machine-learning-supported infrastructure risk management. It integrates laboratory data, remote sensing layers, hydro-climatic monitoring, predictive modelling, and decision outputs. The figure strengthens the manuscript by converting emerging research gaps into a practical framework for climate-resilient planning.

6.5 Climate-Resilient Infrastructure Design

Future infrastructure planning in tropical regions should integrate climate adaptation, hydrological variability, and geological hazard forecasting into engineering design frameworks. Toll road construction in tropical regions presents unique environmental challenges, particularly in peatland ecosystems where land subsidence, erosion, and biodiversity loss are prevalent, and traditional Environmental Management Plans often remain ineffective due to the absence of measurable indicators that guide performance-based monitoring (Hafnidar, 2025). Stakeholder-based prioritization using the Analytic Hierarchy Process ranked soil and land as the most critical environmental aspect at 35.0 percent, with slope failure, erosion, and peatland disturbance identified as top sub-indicators for toll road construction in Riau Province, Indonesia (Hafnidar, 2025). Ecohydrological studies confirmed that the magnitude of road impacts in the tropics is amplified by intense rainfall and lack of best management practices applied to road construction and maintenance, and called for incorporation of transdisciplinary approaches to study road effects on tropical environments (Wemple et al., 2017). In the Brazilian Amazonia, high annual rainfall and the hydrological regime of river flooding and ebbing induce saturation of pavement layers and loss of global geotechnical stability of compacted earth embankments, requiring climate-responsive design solutions (Campelo et al., 2022). At the Kasavu landslide site in Fiji, future management recommendations included drainage of the ridgeline, groundwater monitoring, and provision of load support to existing slopes, representing site-specific climate adaptation measures (Ram et al., 2019). Road cut slopes in lateritic soil in Rwanda demonstrated that weathering weakens mechanical behaviour progressively, and the combined effect of microstructure and mechanical behaviour must be considered in slope stability analyses under changing climatic conditions (Valentino et al., 2024). Land-use changes in Pacitan Regency, Indonesia, increased landslide hazards three-fold from 1998 to 2018, with projections showing a peak in 2030 if no intervention is made, and land capability classification strategies were proposed to reduce high-level landslide risk (Putra et al., 2021). These findings confirm that climate-resilient infrastructure design in tropical sedimentary terrains demands integration of geological hazard data, hydrological modelling, land-use planning, and adaptive engineering strategies within a unified framework.

7. Conclusion

This review demonstrates that infrastructure failure in tropical sedimentary terrains is not controlled by lithology alone, but by the combined behaviour of sandstone, clay, shale contacts, groundwater, weathering, and tropical rainfall. The evidence shows that sandstone units can provide reliable foundation and aggregate materials when they are well cemented, quartz-rich, and less weathered. However, their performance declines sharply where weak cementation, fractures, bedding anisotropy, and groundwater infiltration promote erosion, piping, and slope failure. Clay-rich and shale-derived formations represent the most critical engineering constraint. Their high fines content, plasticity, moisture sensitivity, and low drainage capacity reduce subgrade strength and increase settlement, pavement cracking, embankment instability, and foundation distress. The reviewed case studies confirm that saturated clayey subgrades, weak sandstone-clay interfaces, and poor drainage are recurrent causes of road deterioration and structural instability across tropical sedimentary basins. The study also confirms the dual engineering role of ferruginization. Iron oxide cementation may improve hardness and material durability, but continuous ferricrete horizons can restrict infiltration, concentrate runoff, and intensify erosion where drainage is poorly controlled. Therefore, ferruginized layers should not be classified automatically as suitable construction materials without durability, continuity, permeability, and drainage assessment. A major contribution of this review is the integrated engineering geological framework linking lithology, grain-size distribution, Atterberg limits, sandstone durability, groundwater behaviour, slope processes, GIS hazard mapping, and climate-resilient infrastructure planning. This framework provides a stronger basis for route selection, quarry evaluation, foundation design, pavement rehabilitation, and geotechnical risk mitigation. Future infrastructure development in tropical sedimentary terrains should prioritize site-specific geological investigation, laboratory-based geotechnical testing, groundwater monitoring, sustainable drainage design, long-term slope surveillance, and GIS or machine-learning-assisted hazard prediction. Such integrated practice will reduce preventable failures and improve the durability, safety, and sustainability of infrastructure systems.

.

References

Balieiro, N. M., Ferreira, S. R. de M., & Santos, A. C. (2023). Fundação de barragem e classificação geomecânica de maciços rochosos. Contribuciones a Las Ciencias Sociales, 16(11), 25334–25350. https://doi.org/10.55905/revconv.16n.11-034

Campelo, N. de S., Campos, A. M. L. da S., Baia, M. V. M., Almeida, D. J., Lima, R. H. C., Dias, D. K. dos R., Júnior, J. A. de A., & Filho, M. J. G. S. (2022). Challenges in the Construction of Highways in the Brazilian Amazonia Environment: Part I – Identification of Engineering Problems. https://doi.org/10.5772/intechopen.104642

Chidiebube, I. N., Nwamekwe, C. O., Chukwuemeka, G. H., and Wilfred, M. (2025). Optimization Of Overall Equipment Effectiveness Factors in a Food Manufacturing Small and Medium Enterprise. Journal of Research in Engineering and Applied Sciences, 10(1), 836-845.

Chidiebube, I.N., Onyeka, N.C., Sunday, A.P., et al. (2025a) 'A comparative analysis of machine learning models for inventory demand forecasting in a food manufacturing SME', Indonesian Journal of Innovation Science and Knowledge, 2(3), pp. 35-48.

Chidiebube, I.N., Uzochukwu, M.G., Nwamekwe, C.O., et al. (2025b) 'Evaluating machine learning models for optimizing overall equipment effectiveness in food manufacturing SMEs', Jurnal Inovasi Teknologi Dan Edukasi Teknik, 5(2). https://hal.science/hal-05149408v1/file/igbokwe-nkemakonam-chidiebube-layout-jitet.pdf

Coutinho, R. Q., MORAIS, B. D. D., & Oliveira, M. S. de. (2020). Caracterização física e mecânica de solos de encostas da Formação Barreiras localizadas no bairro Ibura (Cohab), Recife-PE. https://doi.org/10.4322/cobramseg.2022.0594

Ekwe, A. C., Opara, A. I., & Onwuka, O. S. (2018). Geoelectrical study of corrosivity and competence of soils within Uburu and Okposi areas of Ebonyi State, Southeastern Nigeria. Anti-Corrosion Methods and Materials, 65(6), 637–645. https://doi.org/10.1108/acmm-05-2018-1936

Emeka, U. C., Chikwendu, O. C., & Onyeka, N. C. (2025). Human-Centric Design Integration in Industry 5.0: A Framework for Resilient Smart Manufacturing. INTERNATIONAL JOURNAL, 3(4).

Emeka, U. C., Okpala, C., and Nwamekwe, C. O. (2025a). Circular Economy Principles'implementation in Electronics Manufacturing: Waste Reduction Strategies in Chemical Management. International journal of industrial and production engineering, 3(2), 29-42.

Ezeanyim, O. C., Ewuzie, N. V., Aguh, P. S., Nwabueze, C. V., and Nwamekwe, C. O. (2025). Effective Maintenance of Industrial 5-Stage Compressor: A Machine Learning Approach. Gazi University Journal of Science Part A: Engineering and Innovation, 12(1), 96-118. https://dergipark.org.tr/en/pub/gujsa/issue/90827/1646993

Ezeanyim, O.C., Nwabunwanne, E.C., Igbokwe, N.C. and Nwamekwe, C.O. (2025a) ‘Patient flow and service efficiency in public hospitals: data-driven approaches, strategies, challenges, and future directions’, Journal Health of Indonesian, 3(02), pp. 104–124. https://doi.org/10.58471/health.v3i02.228

Gomes, E. J. de S., Lima, I. de S., Neto, P. P. C., & Silva, F. da. (2022). A Utilização de Solos Tropicais em Obras na Engenharia. 66–79. https://doi.org/10.47879/ed.ep.2022540p66

Hack, H. R. G. K. (2020). Soft Rock Mechanics and Engineering. https://doi.org/10.1007/978-3-030-29477-9

Hafnidar, A. R. (2025). Stakeholder-Based Prioritization Model for Environmental Management Plan (EMP) in Toll Road Construction Using Analytic Hierarchy Process. Iop Conference Series Earth and Environmental Science, 1578(1), 012012. https://doi.org/10.1088/1755-1315/1578/1/012012

Hudaib, H. T. A., & Ray, R. (2023). The Methodologies and Main Challenges of Assessment the Multi-Hazard Interaction and Risk Management Associated with Roads Infrastructures and Dam Safety: A Review. International Journal of Integrated Engineering, 15(7). https://doi.org/10.30880/ijie.2023.15.07.017

Igbokwe, N. C., and Nwamekwe, C. O. (2025). Application of Machine Learning in Predicting Emergency Obstetric Cases in Sub-Saharan Africa: An Early Appraisal. International Journal of Industrial Engineering, Technology and Operations Management, 3(1), 13-22.

Igbokwe, N. C., Christiana, C., Nweke, C. O. N., and Onyeka, C. (2025). Data-Driven Solutions for Shuttle Bus Travel Time Prediction: Machine Learning Model Evaluation at Nnamdi Azikiwe University. African Journal of Computing, Data Science and Informatics (AJCDSI), 1(1), 31-55.

Igbokwe, N. C., Nwamekwe, C. O., Ono, C. G., Nwabunwanne, E. C., & Aguh, P. S. (2024). The role of digital twins in optimizing renewable energy utilization and energy efficiency in manufacturing. Siber International Journal of Digital Business, 1(4), 93-111.

Igbokwe, N. C., Okeagu, F. N., Onyeka, N. C., Onwuliri, J. B., and Godfrey, O. C. (2024a). Machine Learning-Driven Maintenance Cost Optimization: Insights from a Local Industrial Compressor Case Study. Jurnal Inovasi Teknologi dan Edukasi Teknik, 4(11), 2.

Igbokwe, N.C., Emmanuel, U.N. and Nwamekwe, C.O. (2025a) ‘Advances in post-harvest fish processing: an appraisal of traditional and modern smoking techniques for improved quality and efficiency’, Jurnal Integrasi Dan Harmoni Inovatif Ilmu-Ilmu Sosial’, 5 (9), pp. 1-13. https://philarchive.org/rec/IGBAIP

Igbokwe, N.C., Nwamekwe, C.O. and Aguh, P.S. (2025b) 'Predictive modeling of manufacturing defects using machine learning: A comparative performance study in a manufacturing SME', African Journal of Advances in Engineering and Technology (AJAET), 1(02), pp. 93-115.

Kabantu, M. T., Tshimanga, R. M., Onema, J. K., Gumindoga, W., & Beya, J. T. (2018). A GIS-based estimation of soil erosion parameters for soil loss potential and erosion hazard in the city of Kinshasa, the Democratic Republic of Congo. Proceedings of the International Association of Hydrological Sciences, 378, 51–57. https://doi.org/10.5194/piahs-378-51-2018

Kamal, A. S. M. M., Hossain, F., Rahman, Md. Z., Ahmed, B., & Sammonds, P. (2022). Geological and soil engineering properties of shallow landslides occurring in the Kutupalong Rohingya Camp in Cox's Bazar, Bangladesh. Landslides, 19(2), 465–478. https://doi.org/10.1007/s10346-021-01810-6

Lautenschläger, C. E. R., TONUS, B. P. D. A., Jula, G. F., Almeida, V. de, & Gaioski, S. R. (2020). Desenvolvimento de Mapa Geológico-Geotécnico da Cidade de Ponta Grossa (Paraná Brasil) Baseado em Resultados de Ensaios de Campo e Laboratório. https://doi.org/10.4322/cobramseg.2022.0508

Lawal, A., Yero, U. Y., & Mohammed, A. U. (2024). Application of remote sensing/GIS in the appraisal of geotechnical stability of civil engineering structures in cretaceous sedimentary units in Gombe, Northeastern, Nigeria. Dutse Journal of Pure and Applied Sciences, 10(3c), 64–80. https://doi.org/10.4314/dujopas.v10i3c.6

Nanehkaran, Y. A., Chen, B., Cemiloglu, A., Chen, J., Anwar, S., Azarafza, M., & Derakhshani, R. (2023). Riverside Landslide Susceptibility Overview: Leveraging Artificial Neural Networks and Machine Learning in Accordance with the United Nations (UN) Sustainable Development Goals. Water, 15(15), 2707. https://doi.org/10.3390/w15152707

Nwamekwe C. O., Ewuzie Nnamdi Vitalis, Igbokwe Nkemakonam Chidiebube, and Nwabueze Chibuzo Victoria. (2025a). Evaluating Advances in Machine Learning Algorithms for Predicting and Preventing Maternal and Foetal Mortality in Nigerian Healthcare: A Systematic Approach. International Journal of Industrial and Production Engineering, 3(1), 1-15. https://journals.unizik.edu.ng/ijipe/article/view/5161

Nwamekwe C. O., Ezeanyim O. C., and Igbokwe N. C. (2025b). Resilient Supply Chain Engineering in the Era of Disruption: An Appraisal. International Journal of Innovative Engineering, Technology and Science (IJIETS), 9(1), 11-23. https://hal.science/hal-05061524/

Nwamekwe, C. O., and Chikwendu, O. C. (2025). Circular economy strategies in industrial engineering: From theory to practice. International Journal of Multidisciplinary Research and Growth Evaluation, 6(1): 1773-1782. https://www.allmultidisciplinaryjournal.com/uploads/archives/20250212103754_MGE-2025-1-288.1.pdf

Nwamekwe, C. O., and Igbokwe, N. C. (2024). Supply Chain Risk Management: Leveraging AI for Risk Identification, Mitigation, and Resilience Planning. International Journal of Industrial Engineering, Technology and Operations Management, 2(2), 41–51. https://doi.org/10.62157/ijietom.v2i2.38

Nwamekwe, C. O., and Nwabunwanne, E. C. (2025). Immersive Digital Twin Integration in the Metaverse for Supply Chain Resilience and Disruption Management. Journal of Engineering Research and Applied Science, 14(1), 95-105.

Nwamekwe, C. O., Chidiebube, I. N., Godfrey, O. C., Celestine, N. E., and Sunday, A. P. (2025c). Resilience and Risk Management in Social Robot Systems: An Industrial Engineering Perspective. Culture education and technology research (Cetera), 2(2), 1-12.

Nwamekwe, C. O., Chidiebube, I. N., Godfrey, O. C., Celestine, N. E., and Aguh, P. S. (2025d). Human-Robot Collaboration in Industrial Engineering: Enhancing Productivity and Safety. Journal of Industrial Engineering and Management Research, 6(5), 1-20.

Nwamekwe, C. O., Chinwuko, C. E. and Mgbemena, C. E. (2020). Development and Implementation of a Computerised Production Planning and Control System. UNIZIK Journal of Engineering and Applied Sciences, 17(1), 168-187. https://journals.unizik.edu.ng/ujeas/article/view/1771

Nwamekwe, C. O., Edokpia, R. O., & Eboigbe, C. I. (2026). Integration of Machine Learning into Lean Six Sigma: A Systematic Review for Enhancing Predictive Analytics in the Pharmaceutical Industry. Siber Journal of Advanced Multidisciplinary, 3(4), 133-151.

Nwamekwe, C. O., Edokpia, R. O., and Igbinosa, E. C. (2025e). Exploring the Role of Artificial Intelligence in Enhancing Lean Manufacturing and Six Sigma for Smart Factories. International Journal of Industrial Engineering, Technology and Operations Management, 3(1), 1-12.

Nwamekwe, C. O., Ewuzie, N. V., Igbokwe, N. C., & Okpala, C. C. (2026). Evaluating the performances of various machine learning models for accurate production forecasting in the textile industry. International Journal of Technology, Health and Sustainability, 2(1), 138-148.

Nwamekwe, C. O., Ewuzie, N. V., Okpala, C. C., Ezeanyim, C., Nwabueze, C. V., Nwabunwanne, E. C. (2025f). Optimizing Machine Learning Models for Soil Fertility Analysis: Insights from Feature Engineering and Data Localization. Gazi University Journal of Science Part A: Engineering and Innovation, 12(1), 36-60. https://dergipark.org.tr/en/pub/gujsa/issue/90827/1605587

Nwamekwe, C. O., Ewuzie, N.V., Igbokwe, N. C., Nwabunwanne, E. C., and Ono, C. G. (2025g). Digital Twin-Driven Lean Manufacturing: Optimizing Value Stream Flow. Letters in Information Technology Education (LITE), 8 (1), pp.1-13. https://hal.science/hal-05127340/

Nwamekwe, C. O., Nwabunwanne, E. C., Okeagu, F. N., and Ono, C. G. (2025h). Lean Manufacturing Principles in the Design and Production of Social Robots. International Journal of Industrial Engineering, Technology and Operations Management, 3(1), 23-34.

Nwamekwe, C. O., Okpala, C. C., and Nwabunwanne, E. C. (2025i). Design Principles and Challenges in Achieving Zero-Energy Manufacturing Facilities. Journal of Engineering Research and Applied Science, 14(1), 1-21.

Nwamekwe, C. O., Okpala, C. C., and Okpala, S. C., (2024a). Machine Learning-Based Prediction Algorithms for the Mitigation of Maternal and Fetal Mortality in the Nigerian Tertiary Hospitals. International Journal of Engineering Inventions, 13(7), PP: 132-138. https://www.ijeijournal.com/papers/Vol13-Issue7/1307132138.pdf

Nwamekwe, C. O., Uchenna, P. C., & Onyedika, S. C. Leveraging Emerging Technologies to Enhance Business Processes in Blue Economy Sectors: A Case Study of Anambra State's Industrial Landscape. International Journal of Technology, Health and Sustainability, 2(2), pp. 559-572

Nwamekwe, C. O., Uchenna, P. C., Onyedika, S. C. (2026). Leveraging Emerging Technologies to Enhance Business Processes in Blue Economy Sectors: A Case Study of Anambra State’s Industrial Landscape. International Journal of Technology, Health and Sustainability, 2(2), pp. 559-572. https://ijths.com/wp-content/uploads/IJTHS-0202024.pdf

Nwamekwe, C., Ewuzie, N., Igbokwe, N., Okpala, C., and U-Dominic, C. (2024b). Sustainable Manufacturing Practices in Nigeria: Optimization and Implementation Appraisal. Journal of Research in Engineering and Applied Sciences, 9(3). https://qtanalytics.in/journals/index.php/JREAS/article/view/3967

Nzeukou, A. N., Tsozue, D., Pagna, B. K., Madi, A. B., Deumeni, A. F., Ngos, S., Nkoumbou, C., & Fagel, N. (2021). Clayey soils from Boulgou (North Cameroon): geotechnical, mineralogical, chemical characteristics and properties of their fired products. Sn Applied Sciences, 3(5). https://doi.org/10.1007/s42452-021-04541-4

Ojo, O. T., Chiaka, I. J., & Mark, A. I. (2024). Geophysical Subsurface Mapping Using the Electrical Resistivity Technique: A Comprehensive Study of the Petroleum Training Institute Main Campus in Effurun. Indonesian Journal of Earth Sciences, 4(1), A846. https://doi.org/10.52562/injoes.2024.846

Okeagu, F., Nwamekwe, C., and Nnamani, B. (2024). Challenges and Solutions of Industrial Development in Anambra State, Nigeria. Iconic Research and Engineering Journals, 7(11), 467-472. https://www.irejournals.com/formatedpaper/1705825.pdf

Okpala C. C., Chukwudi Emeka Udu, and Charles Onyeka Nwamekwe. (2025). Sustainable HVAC Project Management: Strategies for Green Building Certification. International Journal of Industrial and Production Engineering, 3(2), 14-28. https://journals.unizik.edu.ng/ijipe/article/view/5595.

Okpala, C. C., Ezeanyim, O. C., and Nwamekwe, C. O. (2024). The Implementation of Kaizen Principles in Manufacturing Processes: A Pathway to Continuous Improvement. International Journal of Engineering Inventions, 13(7), 116-124. https://www.ijeijournal.com/papers/Vol13-Issue7/1307116124.pdf

Okpala, C. C., Udu, C. E., and Nwamekwe, C. O. (2025a). Artificial Intelligence-Driven Total Productive Maintenance: The Future of Maintenance in Smart Factories. International Journal of Engineering Research and Development (IJERD), (21)1, 68-74. https://www.ijerd.com/paper/vol21-issue1/21016874.pdf

Okpala, C., Onyeka, C. and Igbokwe, N.C. (2024a) 'The implementation of Internet of Things in the manufacturing industry: An appraisal', International Journal of Engineering Research and Development, 20(7), pp. 510-516.

Onyeka, N. C., and Emeka, N. (2025). Circular Economy and Zero-Energy Factories: A Synergistic Approach to Sustainable Manufacturing. Journal of Research in Engineering and Applied Sciences, 10(1), 829-835.

Onyeka, N. C., Vitalis, E. N., Chidiebube, I. N., U-Dominic, C. M., and Chibuzo, N. (2024). Adoption of Smart Factories in Nigeria: Problems, Obstacles, Remedies and Opportunities. International journal of industrial and production engineering, 2(2), 68-81. https://journals.unizik.edu.ng/ijipe/article/view/4167

Ozougwu, C. (2025). Experimental Study on the Effects of Heat and Heating Duration on Expansive Soils Plasticity Determination From Parts of Southeastern Nigeria. https://doi.org/10.21203/rs.3.rs-7837526/v1

Paiva, C. F. E., Damasceno, A. D. O., & CARDOSO, A. (2020). Caracterização de fatores intrínsecos aos solos relacionados às ocorrências de deslizamentos no município de Mauá - SP. https://doi.org/10.4322/cobramseg.2022.0489

Pinheiro, R. J. B., Nummer, A. V., & Rauber, A. C. (2017). Determinação Da Condutividade Hidráulica Das Principais Unidades Geológico-Geotécnicas De Santa Maria – Rs. Geosciences = Geociências, 36(2), 347–363. https://doi.org/10.5016/geociencias.v36i2.12592

Putra, A. N., Nita, I., Jauhary, M. R. A., Nurhutami, S. R., & Ismail, M. H. (2021). Landslide Risk Analysis on Agriculture Area in Pacitan Regency in East Java Indonesia Using Geospatial Techniques. Environment and Natural Resources Journal, 19(2), 141–152. https://doi.org/10.32526/ennrj/19/2020167

Rakshit, R. (2021). Macro-mechnical charakteristics and their control on the strenght of sandstones of western Indo-Burmese Rangers, NE India. Acta Geodynamica Et Geomaterialia, 18(2), 241. https://doi.org/10.13168/agg.2021.0017

Ram, A. R., Brook, M., & Cronin, S. J. (2019). Engineering geomorphological investigation of the Kasavu landslide, Viti Levu, Fiji. Landslides, 16(7), 1341–1351. https://doi.org/10.1007/s10346-019-01191-x

Roslee, R., & Tongku, F. (2018). Engineering Geological Study on the Slope Failure Along the Kimanis to Keningau Highway, Sabah, Malaysia. Geological Behavior, 2(2), 01–09. https://doi.org/10.26480/gbr.02.2018.01.09

Rosolen, V., Bueno, G. T., Melfi, A. J., Montes, C. R., Coelho, C. V. de S., Ishida, D. A., & Govone, J. S. (2017). Evolution of iron crust and clayey Ferralsol in deeply weathered sandstones of Marília Formation (Western Minas Gerais State, Brazil). Journal of South American Earth Sciences, 79, 421–430. https://doi.org/10.1016/j.jsames.2017.09.001

Santo, C. M. do E., Guerra, A. J. T., Szlafsztein, C. F., & Costa, J. A. (2021). Análise do potencial erosivo em áreas de acesso a geomorfossítios no médio curso do rio Araguari, estado do Amapá. Revista Brasileira De Geomorfologia, 22(3). https://doi.org/10.20502/rbg.v22i3.1619

Santos, J. C. dos, Coutinho, R. Q., & Marques, J. A. F. (2020). Perfil Típico de Solos de Formação Barreiras encontrados na cidade de Maceió/AL. https://doi.org/10.4322/cobramseg.2022.0843

Scrivano, S., Gaggero, L., Santonja, J. A. G., Kock, T. D., Derluyn, H., & Cnudde, V. (2017). Texture and mineralogy influence on durability: the Macigno sandstone. Quarterly Journal of Engineering Geology and Hydrogeology, 50(4), 393–401. https://doi.org/10.1144/qjegh2016-107

Senanayake, S., Pradhan, B., Huete, A., & Brennan, J. (2020). Assessing Soil Erosion Hazards Using Land-Use Change and Landslide Frequency Ratio Method: A Case Study of Sabaragamuwa Province, Sri Lanka. Remote Sensing, 12(9), 1483. https://doi.org/10.3390/rs12091483

Shwe, M. M., Yeboah, E., Okrah, A., Sarfo, I., Oo, K. L., Moe, A. H. H., Takin, M., Prempeh, N. A., Mensah, C., Kwang, C., Bhatta, D., & Djan, M. A. (2024). Multi-Factor Analysis of Landslide and Flood Occurrences in Chin State, Western Myanmar. European Journal of Environment and Earth Sciences, 5(3), 1–11. https://doi.org/10.24018/ejgeo.2024.5.3.459

Stetler, L. D. (2018). Impacts of Material Engineering Properties on Slope Wash and Stability in Fine-Grained Bedrock Slopes at Fossil-Bearing Sites, Badlands National Park, South Dakota, USA. Geosciences, 8(7), 267. https://doi.org/10.3390/geosciences8070267

Uchenna, J. E., Igwe, O., Obinna, H. O., & Kelechi, N. E. (2023). Geotechnical Site Investigation of Two Failed Buildings in Enugu Metropolis, South East Nigeria. https://doi.org/10.21203/rs.3.rs-3713267/v1

Umo, I. S., Ibanga, O., & Ike, M. (2018). Application of Geospatial Technologies in Assessing Gully Erosion in the Humid Tropics of Eniong Offot, Uyo, Akwa Ibom State. Asian Journal of Environment & Ecology, 6(3), 1–13. https://doi.org/10.9734/ajee/2018/40224

Valentino, R., Pizzati, M., & Mizero, J. (2024). Combined Effect of the Microstructure and Mechanical Behavior of Lateritic Soils in the Instability of a Road Cut Slope in Rwanda. Geohazards, 5(2), 559–581. https://doi.org/10.3390/geohazards5020029

Vitalis, E. N., Nwamekwe, C. O., Chidiebube, I. N., Chibuzo, N., Nwabunwanne, E. C., and Ono, C. G. (2024). Application Of Machine-Learning-Based Hybrid Algorithm for Production Forecast in Textile Company. Jurnal Inovasi Teknologi dan Edukasi Teknik, 4(12), 1-9.

Wemple, B., Browning, T. N., Ziegler, A. D., Celi, J., Chun, K. P., Jaramillo, F., Leite, N. K., Ramchunder, S. J., Negishi, J. N., Palomeque, X., & Sawyer, D. E. (2017). Ecohydrological disturbances associated with roads: Current knowledge, research needs, and management concerns with reference to the tropics. Ecohydrology, 11(3). https://doi.org/10.1002/eco.1881.