
Integration of Geotechnical and Geographical Information System-Based Approaches for Investigation of Road Failure Along Bauchi – Gombe Highway in Nigeria

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ABSTRACT

This study employs an integrated approach combining geotechnical engineering methods and Geographical Information System (GIS) technology to investigate and analyze road failure mechanisms along Bauchi – Gombe Highway in Nigeria. The following laboratory tests were carry out on the soil at failure zones of the road: Moisture content test, Specific gravity test, Atterberg limits, Particle size distribution (sieve analysis) test, Compaction test, CBR test, Permeability test, CBR test and Asphalt extraction test and oxide composition tests The Natural Moisture Content across the pits varied between 2.5% and 13.2%, reflecting heterogeneous soil conditions. Specific gravity ranged between 2.45–2.68, clustered near 2.60–2.65, typical of quartz-dominated sandy/silty residual soils. Across the ten pits, Liquid limit spanned 14 – 43% and PI 0 – 23%, indicating predominantly low-to-moderate plasticity with one higher-plasticity location. Pit 3R (LL = 43%, PI = 23%) stands out as highly plastic, implying active clay minerals. Most samples were AASHTO A-2 granular soils with fines (A-2-4, A-2-6, A-2-7), while one was a high-plasticity clayey soil (A-7-6 at Pit 3R). By USCS, the profile was dominated by SM (silty sand) and SC (clayey sand), with one SW-SM (well-graded sand with silt) at Pit 8L. The Maximum Dry Density (MDD) values between 1.97–2.17 Mg/m³ and Optimum Moisture Content values 5.3–10.3% were recorded. The accepted California Bearing Ratio (CBR) values spanned 13–75%, showing a wide spread in subgrade support capacity across the corridor. By the Federal Ministry of Works criteria CBR for sub-grade should be $\geq 13\%$, sub-base should be $\geq 30\%$ and for road-base $\geq 80\%$, with $\geq 30\%$ relative compaction of 100%. Permeability values ranged from 3.08×10^{-9} to 1.01×10^{-7} m/s, indicating very low hydraulic conductivity typical of fine-grained, fines-rich sands/silts and clayey sands. The GIS analysis revealed that the major source of floodwaters damaging the Bauchi–Gombe road and associated hydraulic structures originates from the Yankari Game Reserve catchment. The findings provide a scientific basis for designing robust, region-wide mitigation measures that not only protect the Bauchi–Gombe highway but also enhance the ecological balance of the Yankari catchment.

KEYWORDS: Highways, Geographical Information System, California Bearing Ratio, Hydraulic Conductivity, Spatial Analysis

1.0 INTRODUCTION

The African region has the highest road traffic deaths in the world partly as a result of economic development which led to an increase in the number of vehicles on the road and the fact that the road infrastructures were not improved to accommodate the increases coupled with the low level of the implementation of safety measures to protect road users (Adeloye *et al.*, 2016).

Road failure is a major engineering and economic problem caused by structural, environmental, and maintenance deficiencies. Understanding these causes is essential for developing preventive strategies. Environmental and geological conditions significantly affect road stability. Weak foundation soils, discontinuities, and heavy rainfall are common causes of slope and pavement failure.

The information gathered during bridge inspections is used by engineers to plan for maintenance and rehabilitation of the bridges in order to reach or even extend their intended life span, or in a worst case scenario; the replacement of these bridges (Barritt *et al.*, 2018).

Thiesen *et al.* (2015) conducted GIS Mapping of geotechnical data of Blumenau in Brazil using a digital terrain model. The result provided information on the geographic features and urban growth. Foyer *et al.* (1996) estimated recharge using GIS that identifying possible combinations of soil type and vegetation. Antoniou *et al.* (2008) reported the application of GIS to produce thematic maps of the geotechnical, geological, seismological and geomorphological data of the area. Augusto *et al.* (2010) used GIS for geotechnical and environmental risk management of oil pipeline.

Frequent settlement and failure of embankments, culverts, and bridges along the Bauchi–Gombe road interrupt transport, inflate repair costs, and threaten public safety. Conventional analysis methods have failed to capture the complex geotechnical and hydrological interactions involved and existing studies rarely combine advanced modelling with spatial and environmental assessment.

2.0 LITERATURE REVIEW

Ademila (2017) conducted a geotechnical evaluation of lateritic subsoils from deteriorated sections of roadways in Akure, Southwestern Nigeria. The soils from the failed zones were characterized by hydro-pressure within the soil voids, which precipitated a significant reduction in strength, reaching up to 79%. This degree of structural deficiency was ascribed to suboptimal strength parameters, including, shear strength ranging from 79 to 108 kN/m², and low California Bearing Ratio (CBR) values (14–32% unsoaked and 3–11% soaked). As a result, the lateritic soils from the failed sections exhibited inadequate engineering properties, rendering them unsuitable for use as subgrade materials in road construction projects.

Odunfa *et al.* (2018) conducted a geotechnical investigation along the Lagos–Ibadan Expressway and found high moisture content (13.11–268.89%), liquidity index (33–55%), and plasticity (13–26%). These values, when compared with (FMW&H 1997) standards, indicate that subgrade soil conditions significantly contributed to pavement failure.

Adebayo and Adigun (2018) investigated the subbase and subgrade materials along the Papalanto–Sagamu route in Ogun State. The study assessed the structural properties, physical characteristics, and integrity of the soils underlying the road pavement through geotechnical methods. The result showed that the natural moisture content varied between 1% and 12%. Sieve analysis indicated that the soils were predominantly sandy clayey, with

sand content ranging from 44.7% to 93.4%. Gravel content varied from 5.6% to 51.2%, while fines ranged between 0.3% and 6.3%. The Plasticity Index values ranged from 6% to 28%, and liquid limits varied between 23% and 41%. The results further revealed that the subsurface soils were generally gap-graded, consisting of poorly graded clayey sand and gravel with high plasticity. Additionally, some soil samples exhibited low to medium plasticity clay content alongside elevated natural moisture content. Using geotechnical methods.

Abdulkarim *et al.* (2022) explores the application ArcGIS 10.1 for mapping soil properties of Abubakar Tafawa Balewa University (ATBU) Bauchi, Gubi campus for use in preliminary designs, using the kriging spatial interpolation capability. 40 trial pits distributed within the study area were used and their coordinates recorded. The samples were subjected to various laboratory tests to determine their geotechnical properties. The obtained laboratory results and corresponding recorded coordinates were used to develop mapped database in GIS software and after which, analysis-using kriging was carried out. The analysis results show maps of various soil properties. The result provides estimated data for preliminary designing and planning within the study area.

3.0 MATERIALS AND METHODS

3.1 Materials

The materials used were:

- i Soil: The soil sample used for this work was obtained at a depth of 0.5m to 1.5m below the ground level at failure points along Bauchi-Gombe road in North-East Nigeria.
- ii Water: Tap water from the borehole provided near the Geotechnical laboratory of the Abubakar Tafawa Balewa University Bauchi State was used.

3.2 Methods

3.2.1 Sample Collection

The soil samples were collected by drilling a hole into the ground with a rotating auger tool. The samples were then collected in three stages, 0.5m, 1.0m and 2.0m. The soil core was essentially extracted by twisting the auger into the ground and pulling it back up to retrieve the sample. The soil samples collected were stored in a polythene bag to maintain its natural moisture content. The samples were taken to the Civil Engineering laboratory of the Abubakar Tafawa Balewa University Bauchi State and deleterious materials such as roots were removed. All samples were taken at failure zones of road (soil material and asphalt). The soils were air-dried, pulverized with mortar and pestle and set to pass through sieve no 4 (4.75mm opening) to obtain the final soil samples for the tests.

3.2.2 Software Used

The software used were GIS, Civil3D, AutoCAD, Google Earth, Micro-Soft Excel, Microsoft PowerPoint.

3.2.3 Laboratory Tests

For the purpose of classification, checking compliance and determining the strength of the soil, the following laboratory tests were carry-out on the soil in accordance with BS 1377 (1990): Moisture content test, Specific gravity test, Atterberg limits, Particle size distribution (sieve analysis) test, Compaction test, CBR test, Permeability test, CBR test and Asphalt extraction test. Also, oxide composition tests carried out were XRD and XRF test.

4.0 RESULT AND DISCUSSION

4.1 Result of Natural Moisture Content

The result of the natural moisture content is presented in Table 1.

Table 1: Result of the Natural Moisture Content

Sample	Natural Moisture Content (%)
Pit 1L	8.1
Pit 2L	12.4
Pit 3L	13.2
Pit 4L	3.1
Pit 5L	2.5
Pit 6L	4.8
Pit 7L	3.6
Pit 8L	3.1
Pit 9L	3.4
Pit 10L	10.9

The Natural Moisture Content across the pits varied between 2.5% and 13.2%, reflecting heterogeneous soil conditions. Higher values at Pit 2L (12.4%), Pit 3R (13.2%), and Pit 10L (10.9%) indicate clayey soils with higher water retention, prone to compressibility and settlement. Lower values (2.5–4.8% in Pits 4L–9R) suggest granular soils with better drainage and stability. Localized differences, such as the higher NMC in Pit 3R compared to nearby pits, point to groundwater or drainage influences. In general, zones with high NMC may require stabilization or drainage improvements, while low-NMC zones provide more reliable subgrade support. Soils with higher NMC values (10.9–13.2%) are predominantly clayey and moisture-retentive, while those with lower values (2.5–4.8%) are more granular, well-drained, and relatively stable, as shown in Table 7. Based on the NMC values, the soils are likely of different colours, higher moisture clays typically appearing darker, while lower moisture granular soils tend to be lighter or brighter (in the reddish brown parent colour).

4.2 Atterberg Limit Results of the Soil

The Atterberg limits quantify soil consistency and plasticity: liquid limit (LL) was taken at 20 mm penetration; plastic limit (PL) is the water content at thread failure (≈ 3 mm); plasticity index (PI) = LL – PL, and the plasticity chart helps infer clay activity versus siltiness. The result is shown in Table 2.

Table 2: Atterberg Limit Result

PIT 1 L		PIT 2		PIT 3		PIT 4		PIT 5		PIT 6		PIT 7		PIT 8		PIT 9		PIT 10	
PENETR ATION (mm)	M.C (%)	PENETR ATION (mm)	M.C (%)	PENETR ATION (mm)	M.C (%)	PENETR ATION (mm)	M.C (%)	PENETR ATION (mm)	M.C (%)	PENETR ATION (mm)	M.C (%)	PENETR ATION (mm)	M.C (%)	PENETR ATION (mm)	M.C (%)	PENETR ATION (mm)	M.C (%)	PENETR ATION (mm)	M.C (%)
15.58	20.00	21.53	20.00	42.73	20.00	23.71	20.00	26.60	20.00	19.56	20.00	17.59	20.00	52.50	20.00	36.82	20.00	15.74	20.00
LL	22	LL	22	LL	43	LL	24	LL	27	LL	20	LL	18	LL	25	LL	14	LL	0
PL	13	PL	19	PL	20	PL	24	PL	27	PL	9	PL	18	PL	13	PL	7	PL	0
PI	9	PI	3	PI	23	PI	0	PI	0	PI	11	PI	0	PI	12	PI	7	PI	0

Across the ten pits, LL (excluding NP) spans 14–43% and PI 0–23%, indicating predominantly low-to-moderate plasticity with one clearly higher-plasticity location. Pit 3R (LL = 43%, PI = 23%) stands out as highly plastic, implying active clay minerals and greater

susceptibility to swelling/shrinkage, strength loss, and differential settlement under moisture variation—consistent with clayey subgrades. Moderate plasticity was observed at Pit 6R (PI = 11) and Pit 8L (PI = 12), with borderline plastic fines at Pit 1L (PI = 9) and Pit 9R (PI = 7); these zones require tighter moisture control during compaction and robust drainage to maintain stiffness. By contrast, Pits 4L, 5L, 7L, and 10L report PI = 0 (non-plastic/NP), characteristic of sands or silty sands in which volume change risk is low, though fines can soften when wet; Pit 2L (PI = 3) similarly indicates low-plastic silt/sand behaviour

4.3 Particle Size Distribution Results

The tests were conducted according to BS 1377 procedures (dry sieving to 63 µm and hydrometer for finer fractions), with results shown in Table 3.

Table 3: Summary of Particle Size Distribution Test Result

Sieve Size	Pit 1L	Pit 2L	Pit 3R	Pit 4L	Pit 5L	Pit 6R	Pit 7L	Pit 8L	Pit 9R	Pit 10L
3.35mm	0.00%	0.00%	2.80%	0.00%	0.00%	1.13%	2.47%	7.33%	9.07%	0.60%
2mm	0.07%	0.07%	4.47%	0.07%	3.67%	0.47%	0.80%	11.13%	9.87%	2.53%
1.18mm	2.93%	4.47%	6.60%	3.60%	9.53%	8.27%	5.20%	12.47%	9.13%	8.47%
600µm	17.40%	19.93%	12.33%	17.73%	17.60%	24.93%	17.93%	16.00%	13.00%	26.40%
300µm	27.93%	23.40%	14.60%	23%	22.87%	28.33%	24.47%	14.53%	14.67%	30.60%
150µm	14.93%	10.00%	9.87%	11.53%	18.93%	16.47%	19.33%	6.20%	8.20%	9.00%
63µm	11.80%	10.00%	11.87%	10.87%	7.40%	7.73%	7.60%	4.67%	33.00%	7.33%
Pan	24.93%	32.30%	36.40%	33.20%	20.00%	12.67%	22.00%	2.80%	12.07%	15.07%

The overall result showed that three textural “families” emerge: (i) coarse/clean sands (low fines), (ii) well-graded sands (strong 600–300 µm modes), and (iii) fines-rich mixes (high silt/clay fraction). Coarse/clean sands. Pit 8L shows the cleanest grading (very low *Pan* = 2.80%) with noticeable coarser fractions at 3.35–2.00 mm (7.33–11.13%)—a free-draining material likely to compact well under vibratory effort and perform reliably where drainage is maintained. Well-graded sands. Pits 10L and 6R have strong sand-size modes at 600 µm and 300 µm (e.g., 10L: 26.40% and 30.60%; 6R: 24.93% and 28.33%), indicating dense, interlocking gradations suited to higher dry densities and good bearing when moisture is controlled. These gradations align with materials commonly selected for subbase under Nigerian specifications when fines are limited. For context, Federal specs cap % passing No.200 (0.075 mm) at ≤35% for subbase/base—functionally similar to limiting the very fine fraction in this dataset (63 µm + pan).

Fines-rich mixes (moisture-sensitive). Pits 3R, 2L, and 4L carry high pan fines (36.40%, 32.30%, 33.20%, respectively), with additional retention at 63 µm—materials prone to loss of strength and increased deformability when wet; such zones typically demand stricter drainage, moisture conditioning, and, where needed, stabilization or geotextile separation to protect the base/subbase. Pit 9R is notable for 33% at 63 µm plus 12.07% pan, signaling a large near-fines mass that can drive capillary water uptake and traffic-induced softening if not well drained.

Design implications means that where fines are low (e.g., 8L, 10L, 6R), materials are strong for subgrade improvement or subbase after confirming CBR and maintaining drainage; where fines approach/exceed typical limits (e.g., 3R, 2L, 4L), aim for drainage upgrades, tight moisture control near OMC, and consider mechanical regrading/blending or light stabilization to meet layer specifications.

4.3.1 Discussion of AASHTO and USCS Classifications

Overall pattern, most samples are AASHTO A-2 granular soils with fines (A-2-4, A-2-6, A-2-7), while one is a high-plasticity clayey soil (A-7-6 at Pit 3R). By USCS, the profile is dominated by SM (silty sand) and SC (clayey sand), with one SW-SM (well-graded sand with silt) at Pit 8L.

4.3.1.1 AASHTO View (Sub-grade Performance)

- i A-2-4 (Pits 1L, 2L, 4L, 5L, 7L, 10L): Granular with non-plastic to low-plastic fines; typically, good to fair subgrade, moderate moisture sensitivity, compacts well; suitable with standard thickness base and routine drainage control.
- ii A-2-6 (Pits 6R, 9R): Granular with clayey fines (higher PI); fair subgrade, more moisture-susceptible; needs tighter moisture control, possibly a slightly thicker base or spot stabilization
- iii A-2-7 (Pit 8L): Granular with high-plasticity fines; performance between A-2-6 and A-7; drainage and fines control are important—benefits from sub-surface drainage and good separation/filter layers.
- iv A-7-6 (Pit 3R): High-plasticity clayey soil; poor subgrade in wet seasons—prone to swelling, loss of strength, and differential settlement; typically requires treatment (lime/cement), over-excavation and replacement, geosynthetic, and/or thicker pavement structure.

4.3.1.2 USCS View (Material Behavior)

- i SM (Pits 2L, 4L, 5L, 7L, 10L): Silty sands—drainable but fines can soften when wet; good compaction, moderate bearing; keep water out (surface/subsurface drainage, sealed shoulders).
- ii C (Pits 1L, 3R, 6R, 9R): Clayey sands—reduced permeability, higher plasticity and moisture sensitivity than SM; watch compaction moisture window and consider stabilization where wet.
- iii SW-SM (Pit 8L): Well-graded sand with silt—good gradation and density potential, but silt fraction still demands drainage attention.

4.3.2 Cross-Classification Insights and Design Implications

- i The problem spot is Pit 3R (A-7-6 / SC)—expect high plasticity and seasonal strength loss; prioritize stabilization (e.g., 3–6% lime or blended lime-cement after confirmatory lab tests), drainage, and possibly geotextile separation.
- ii Moderate-risk zones: Pits 6R and 9R (A-2-6 / SC) and 8L (A-2-7 / SW-SM)—manage moisture (subgrade drains, camber, sealed shoulders), consider local stabilization or increased base thickness in low-lying sections.
- iii Lower-risk zones: A-2-4 / SM (and 1L SC) generally perform well with good drainage and quality compaction; use proper moisture conditioning to hit MDD/OMC and maintain fines control to prevent pumping.

4.4 Compaction Characteristics

The Proctor compaction framework (BS 1377) used in the work targets the moisture content that yields maximum dry density, recognizing that compactive effort and water act together to rearrange particles and expel air from voids. The MDD values between 1.97–2.17 Mg/m³ and OMC values 5.3–10.3% follow the expected trend: coarser, better-drained soils compact to higher MDD at lower OMC, while finer/clayey soils need higher OMC yet achieve slightly lower MDD. Specifically, Pit 10L shows the highest MDD (2.17) at the lowest OMC (5.3%), consistent with a

dense, sand-rich matrix; at the other end, Pits 7L–8L (1.97; 9.3%) and Pits 3R (2.00; 10.1%) and 6R (2.04; 10.3%) indicate finer fractions/clayey fines controlling moisture demand and limiting achievable dry density. Practically, these zones will be more moisture-sensitive and require tighter moisture conditioning to hit OMC during field compaction, because increasing moisture above optimum rapidly reduces strength and stiffness—an effect emphasized in the thesis’ discussion of moisture on subgrade performance. Achieving compaction near OMC is critical: proper compaction increases shear strength, reduces permeability and settlement, and improves slope stability, whereas departures from OMC (too wet or too dry) will depress in-situ density and bearing. Accordingly, sections exhibiting higher OMC (≈ 9.7 – 10.3%) should be prioritized for moisture control (aeration/drying or short-term stabilization) and drainage detailing, while low-OMC/high-MDD sections can meet density targets more readily with standard effort and routine moisture control.

4.5 CBR Test Results

The accepted CBR values span 13–75%, showing a wide spread in subgrade support capacity across the corridor. By the Federal Ministry of Works criteria CBR for subgrade should be $\geq 13\%$, sub-base should be $\geq 30\%$ and for road-base $\geq 80\%$, with $\geq 30\%$ relative compaction of 100%;

- i High support ($\geq 50\%$): Pit 7L (75%), 6R (55%), 8L (57%), 3R (51%), 10L (51%)—all meet sub-base requirements comfortably; 7L (75%) is the strongest but still below the 80% road-base minimum, so it would need improvement (e.g., stabilization) to serve as base.
- ii Moderate support (30–49%): 1L (35%), 5L (31%), 9R (41%)—acceptable as sub-base, provided compaction is verified to 100% and drainage is ensured to preserve strength in service.
- iii Low support ($< 30\%$): 2L (11%) and 4L (4%)—not suitable as untreated sub-base; these locations require stabilization, blending/regrading, or replacement to bring soaked CBR up to specification. Implications for design/works planning.

Therefore, most locations meet sub-base criteria while none meets the road-base threshold.

4.6 Permeability (k) Results

Permeability values range from 3.08×10^{-9} to 1.01×10^{-7} m/s, indicating very low to low hydraulic conductivity typical of fine-grained, fines-rich sands/silts and clayey sands. Ranked by k: Pit 2L (1.01×10^{-7}) > Pit 5L (3.78×10^{-8}) > Pit 3R (8.58×10^{-9}) > Pit 1L (3.92×10^{-9}) > Pit 4L (3.08×10^{-9}). Converting to an intuitive rate, these correspond roughly to 8.7 mm/day (2L), 3.3 mm/day (5L), 0.74 mm/day (3R), 0.34 mm/day (1L) and 0.27 mm/day (4L) of potential vertical flow under unit gradient—emphasizing how slowly water migrates through most locations.

4.7 Asphalt Extraction and Gradation Tests

Gradation refers to the distribution of particle sizes in the mineral aggregate used in the asphalt mix. Proper gradation ensures optimal density, strength, and durability of the asphalt. The plotted gradation curves fit within the envelopes for all tested samples (the red upper and lower specification limits), the curves are well-graded, with a smooth S-shape, indicating a balanced aggregate distribution. No abrupt changes or flat regions in any case, which suggests good interlocking potential and load distribution for all samples tested, as shown in table 3.8 and appendix 8 (graphs).

A. Gradation Compliance:

- i All sieve sizes fall within specified limits for tested samples.
- ii A well-graded mix ensures good compatibility, resistance to deformation, and durability.

B. Bitumen Content:

- i The bitumen in all tested samples are well within the range.
- ii High enough to ensure adequate coating and flexibility, without bleeding or flushing.

C. Voids in Mix & Voids Filled with Bitumen:

- i Voids in all mix are within specifications—this helps with air voids essential for durability.
- ii Voids filled with bitumen indicate a dense, durable mix.

D. Marshall Stability and Flow:

- i Stability for all tests exceed the minimum required, indicating good load-bearing capacity.
- ii Flows are within limits, suggesting proper flexibility under traffic loading.

4.8 Oxide Composition Test

4.8.1 XRF Test Results for Pit 1 – 10

X-Ray Fluorescence (XRF) chemical analysis results (total oxides % by weight) from the ten locations were conducted in Ashaka Cement Plc and presented in Table 4.

Table 4: Oxide Composition of Natural Soil

S/N	Oxides	Pit 1	Pit 2	Pit 3	Pit 4	Pit 5	Pit 6	Pit 7	Pit 8	Pit 9	Pit 10
1	SiO ₂	87.7	82.45	79.18	75.60	70.44	62.15	56.87	49.10	42.22	38.14
2	Al ₂ O ₃	0	6.32	7.42	9.12	11.62	14.21	16.34	18.82	20.45	22.90
3	Fe ₂ O ₃	4.84	3.84	4.90	6.48	7.90	11.40	14.92	18.34	21.78	23.60
4	CaO	1.87	1.40	1.10	1.28	1.60	1.90	2.10	2.24	2.40	2.52
5	MgO	1.20	0.48	0.44	0.55	0.62	0.68	0.72	0.75	0.82	0.86
6	SO ₃	0.34	0.03	0.04	0.05	0.06	0.06	0.07	0.08	0.08	0.09
7	K ₂ O	0.02	0.29	0.31	0.38	0.41	0.45	0.48	0.52	0.55	0.58
8	Na ₂ O	0.33	0.04	0.04	0.05	0.06	0.07	0.07	0.08	0.08	0.09
9	P ₂ O ₅	0.03	0.05	0.06	0.06	0.07	0.09	0.10	0.11	0.12	0.13
10	Mn ₂ O ₃	0.03	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.20
11	TiO ₂	0.10	0.62	0.71	0.82	1.14	1.42	1.68	1.95	2.34	2.76
12	Cr ₂ O ₃	0.47	0.07	0.08	0.09	0.10	0.10	0.11	0.12	0.13	0.14
13	LOI(%)	0.05	4.50	5.60	6.90	7.40	8.10	9.30	10.40	11.60	12.40
		3.03									

4.8.2 Lateritic Classification (PIT 1–10)

The Lateritic Classification Based on Chemical Ratio (SiO₂ / (Fe₂O₃ + Al₂O₃)), classification of the soils in Pit 1 – 10 is shown in Table 5.

According to Matawal (2001; 2011) and S.Y. Umar (2008; 2012) both have written extensively on geotechnical properties of Nigerian laterites using geotechnical, index, and chemical criteria to confirm if a soil is lateritic.

For example, the first Pit,
 $\text{SiO}_2 = 87.70$,
 $\text{Fe}_2\text{O}_3 = 1.87$,
 $\text{Al}_2\text{O}_3 = 4.84$.

For Chemical tests; $(\text{SiO}_2 / (\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3))$
 $= \{(87.7)/(1.87+4.84)\}$
 Chemical test gives = 13.07 (non-lateritic)

Table 5: Classification of Soils in Pit 1 – 10

Pit	Ratio	Classification
1	13.07	Non-lateritic
2	8.04	Non-lateritic
3	6.37	Non-lateritic
4	4.09	Non-lateritic
5	3.23	Non-lateritic
6	2.08	Borderline lateritic
7	1.79	Lateritic
8	1.34	Lateritic
9	0.99	True laterite
10	0.82	True laterite

4.8.3 Discussion of XRF results for Pits 1–10

The X-Ray Fluorescence analysis conducted for the ten borrow-pits along the Bauchi–Gombe corridor provides critical insights into the geochemical evaluation, degree of laterization, and suitability of the soils for use in hydraulic structures and pavement layers (Matawal, 2011; Umar, 2012). The oxide composition trends further support the results obtained from index tests, CBR, compaction, and GIS-based spatial analysis.

The XRF results establish that soils along the Bauchi–Gombe road exhibit a strong geochemical gradient:

1. Pits 1–5: Non-lateritic, silica-dominant soils
2. Pit 6: Transitional borderline lateritic
3. Pits 7–8: Moderately lateritic soils
4. Pits 9–10: Fully matured, true laterites

These results, when viewed alongside CBR, compaction, particle size distribution, and GIS-based erosion mapping, confirm the complex geotechnical and hydrological conditions affecting the corridor. The geochemical progression directly explains the spatial distribution of road failures, settlement, and erosion, thereby contributing significantly to the integrated understanding of soil behaviour for roadway design and rehabilitation.

4.9 X-Ray Diffraction (XRD) Analysis

The XRD analysis for the ten pits along the Bauchi–Gombe corridor indicates a mineralogical progression from quartz-rich, weakly weathered soils in the north (Pits 1–4) to strongly laterized, Sesquioxide-rich profiles in the southern segment (Pits 8–10). This trend aligns with the XRF chemical results, index properties, and field observations recorded across the corridor.

i Pits 1–3: Quartz–Feldspar Dominance

Diffraction patterns for Pits 1–3 exhibit strong quartz peaks (notably at $\sim 26.6^\circ 2\theta$), with moderate feldspar reflections (albite/plagioclase in the $22\text{--}28^\circ$ range). The clay component is limited to weak kaolinite and minor illite/mica peaks. No glycol-expanding smectite reflections were detected, confirming very low swelling potential.

From an engineering perspective, these pits represent sandy to silty soils with high dry densities and low OMC, but reduced soaked CBR when drainage is poor. Their behaviour is governed by silt/clay content rather than expansive mineralogy.

ii Pits 4–6: Transitional Quartz–Kaolinite Assemblages

Pits 4–6 show increasing kaolinite intensity and slightly broadened quartz peaks, indicating progressive alteration of silicate minerals. Feldspar reflections diminish, and weak hematite/goethite peaks begin to appear, reflecting early laterization.

These transitional soils exhibit moderate plasticity, narrower compaction moisture windows, and improved cohesion compared to the northern pits. They correlate with the borderline lateritic chemical ratios from XRF and represent intermediate geotechnical behaviour.

iii Pits 7–8: Lateritic Mineral Suites

In Pits 7 and 8, the XRD patterns shift toward strong kaolinite dominance, reduced feldspar presence, and clear hematite/goethite signatures. These features indicate advanced chemical weathering and accumulation of sesquioxides typical of tropical lateritic soils.

Engineering-wise, these pits exhibit better soaked CBR values, increased natural cohesion, and reduced erodibility. Their fine-grained, kaolinitic fabric requires controlled compaction but offers strong subgrade performance.

iv Pits 9–10: True Laterite Profiles

Pits 9 and 10 display the most advanced weathering, with weakened quartz reflections and pronounced clay and Sesquioxide peaks. Kaolinite, gibbsite, hematite, and goethite are well developed, consistent with the very low silica and high Fe–Al oxides observed in XRF.

These true laterites provide excellent engineering characteristics, including high soaked CBR, minimal swelling, and strong resistance to moisture-induced degradation, making them highly suitable for subgrade, embankment, and hydraulic applications.

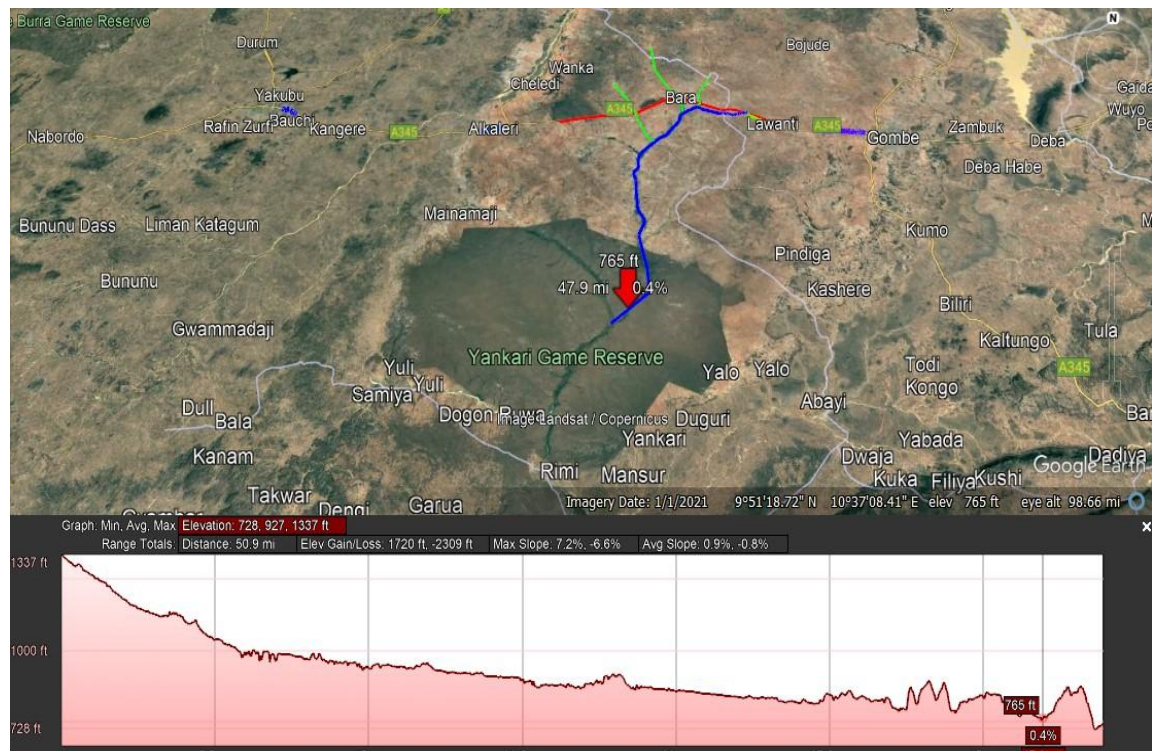
4.10 GIS Result Discussions

The GIS analysis revealed that the major source of floodwaters damaging the Bauchi–Gombe road and associated hydraulic structures originates from the Yankari Game Reserve catchment. Spatial hydrological modeling showed that the reserve’s vast watershed, with its dense network of seasonal streams and high runoff potential, directly channels large volumes of stormwater toward the highway corridor. The reserve’s topography and land cover patterns, including degraded vegetation in some zones, intensify runoff velocities and reduce infiltration, thereby accelerating downstream flood peaks.

Overlay of settlement/failure locations with hydrological layers demonstrated strong spatial correlation between flood inflows from Yankari and the sections of the road experiencing recurrent washouts, culvert overtopping, and embankment scouring. Buffer analysis further indicated that drainage structures along this corridor are undersized relative to the volume and velocity of flood discharge originating upstream. GIS mapping also highlighted that soil types in the flood-affected areas—predominantly high-plasticity clays—exacerbate the impact by undergoing significant swelling and shrinkage, which compromises embankment stability once inundated.

This result underscores the importance of integrated flood management beyond the immediate road corridor. Without upstream interventions such as watershed reforestation, controlled diversion channels, and catchment-based flood attenuation, the recurrent failures will persist. The GIS-based findings therefore provide a scientific basis for designing robust, region-wide mitigation measures that not only protect the Bauchi–Gombe highway but also enhance the ecological balance of the Yankari catchment.

i Yankari axis: The buffer GIS analysis identifies the primary flood source from the Yankari Game Reserve that is fundamentally contributing to damage along the road corridor. This spatial overlay highlights the proximity of the flood channel to the alignment, emphasizing the potential risk posed by recurrent overflows. The profile beneath the map illustrates the depth of the river (47.9m), offering critical insight into hydraulic loading and potential inundation levels. By combining the river's depth with its spatial buffer, the analysis underscores areas where the road and associated structures are most vulnerable to flood-induced erosion, settlement, and long-term instability



ii Alkaleri axis: The Alkaleri axis illustrates results of a GIS buffer analysis carried out to capture the terrain undulations within Alkaleri town. This spatial representation highlights variations in topography along the corridor, providing insight into how slope gradients and elevation changes may influence road stability and settlement trends. The blue line represents the section of the road traversing Alkaleri, serving as the key reference feature within the buffer. By integrating the road alignment with the surrounding terrain profile, the analysis makes it possible to identify critical stretches where undulating topography could predispose the pavement and associated hydraulic structures to failures.

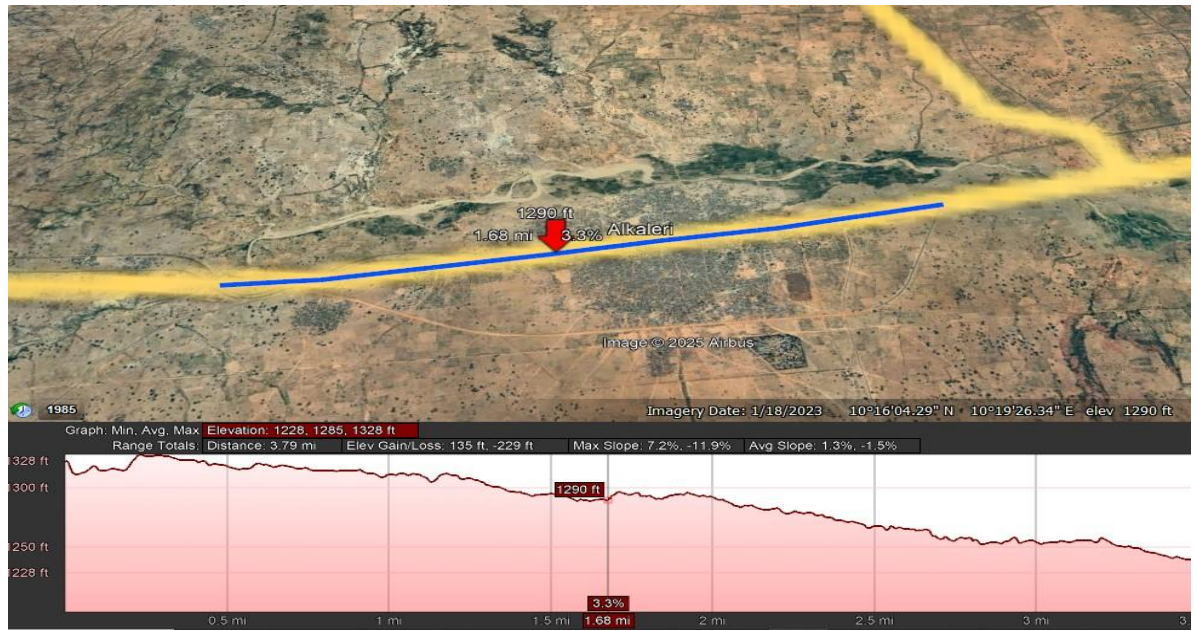


Figure 2: The Buffer GIS Analysis of Yankari Town

iii Buffer analysis: The yellow line marks the alignment of the Bauchi–Gombe road, serving as the main corridor under study. The red arrow points to the Bara bridge axis, highlighting a key structural location of damages. The road profile beneath the line shows elevation changes and gradients, helping to link soil and slope conditions with observed failures



Figure 3: The Buffer GIS Analysis of Bauchi – Gombe Road

iii Inkil–Bauchi route: The buffer analysis illustrates the blue line marking the road alignment from Inkil to Bauchi town, accompanied by the profile beneath. This section of the corridor presents a near-smooth surface, indicating relatively stable conditions and limited visible damage compared to other stretches of the Gombe–Bauchi road. The smoothness of the profile is largely attributed to the fact that this section lies on the immediate approach to Bauchi town, a location renowned for its well-maintained and higher-quality roads within the north-eastern region of Nigeria. Bauchi’s reputation for good roads reflects the combined impact of better construction practices, sustained maintenance efforts, and urban planning considerations, which help in preserving pavement integrity and reducing the recurrence of geotechnical failures.

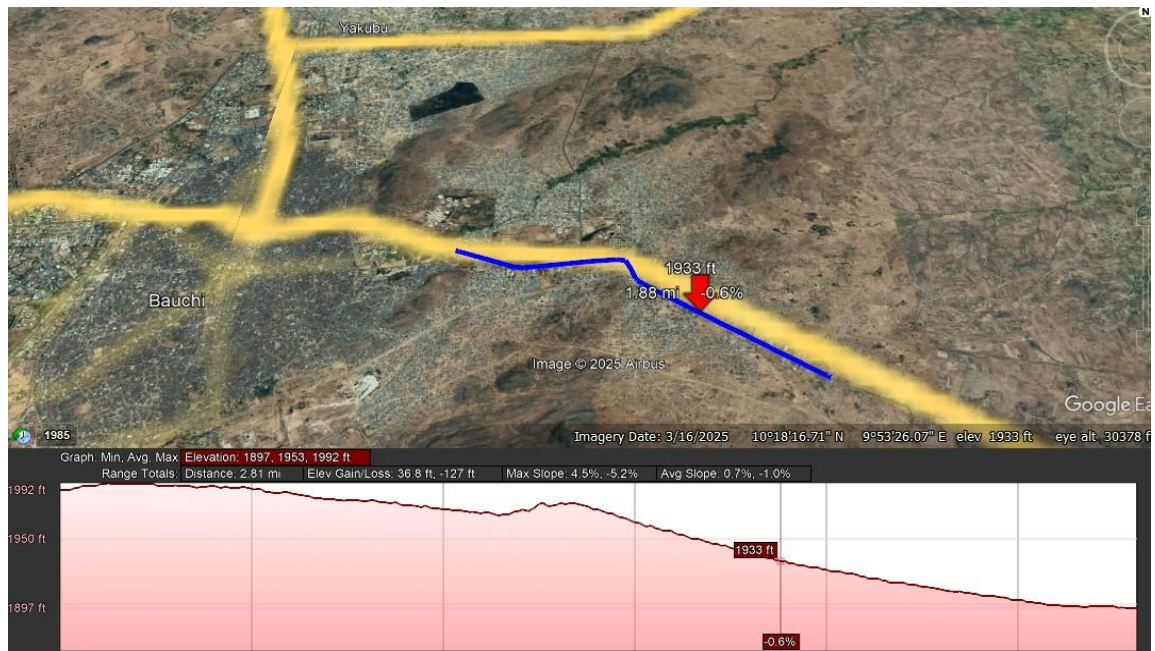


Figure 4: The Buffer GIS Analysis of Inkil–Bauchi Route

iv Dindima to Kangare route: The buffer analysis presents the blue line, which traces the Dindima to Kangare section of the Gombe–Bauchi road. Unlike other corridors marked by severe undulation and flood impacts, this stretch displays a near-smooth surface profile, reflecting improved geotechnical stability. The smoother profile is attributed to ongoing rehabilitation works currently being undertaken along this portion of the road. These interventions have helped to minimize surface irregularities, reduce susceptibility to settlement, and enhance overall riding quality.

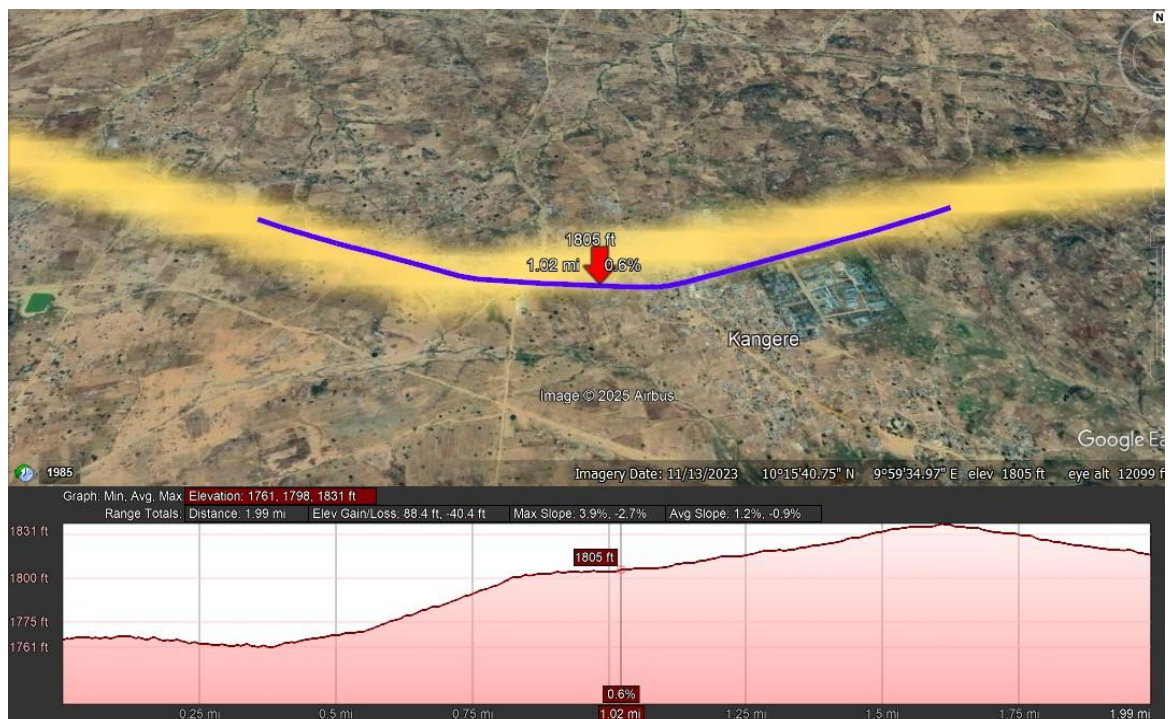
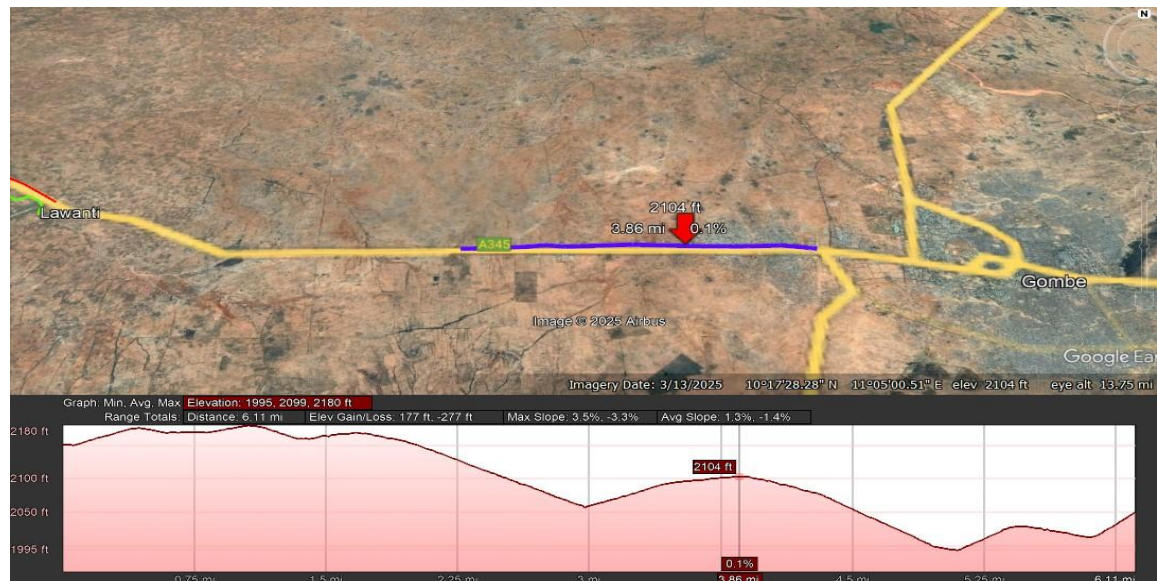


Figure 5: The Buffer GIS Analysis of Dindima to Kangare Route.

v Lawanti–Gombe route: The buffer analysis highlights the blue line representing the road stretch linking Gombe Airport (Lawanti) to Gombe town. This corridor exhibits a near-smooth surface profile, which indicates relatively minimal structural damage compared to other sections of the Gombe–Bauchi road. The stability here can be attributed to more favorable soil conditions and the absence of intense flood impacts that dominate other axes. However, the profile also reveals localized depressions in certain segments. These depressions reflect differential settlement and minor subsidence that, if not addressed, could evolve into more severe pavement failures. In the context of modern highway design, such defects are anticipated and mitigated through advanced highway design solutions



The buffer analysis highlights the three major damage locations at Kalajanga, Bara, and Tashan Tulmi, represented by green lines. These points mark critical failure zones along the Gombe–Bauchi corridor where recurrent settlement and erosion necessitated the construction of bridges as permanent engineering interventions. Beneath the map, the undulating profile illustrates the difficult landscape and topography that characterize this section. The irregular terrain reflects the combined influence of climatic variability and flood impacts emanating from the Yankari axis, which exacerbate erosion processes and geotechnical instability.

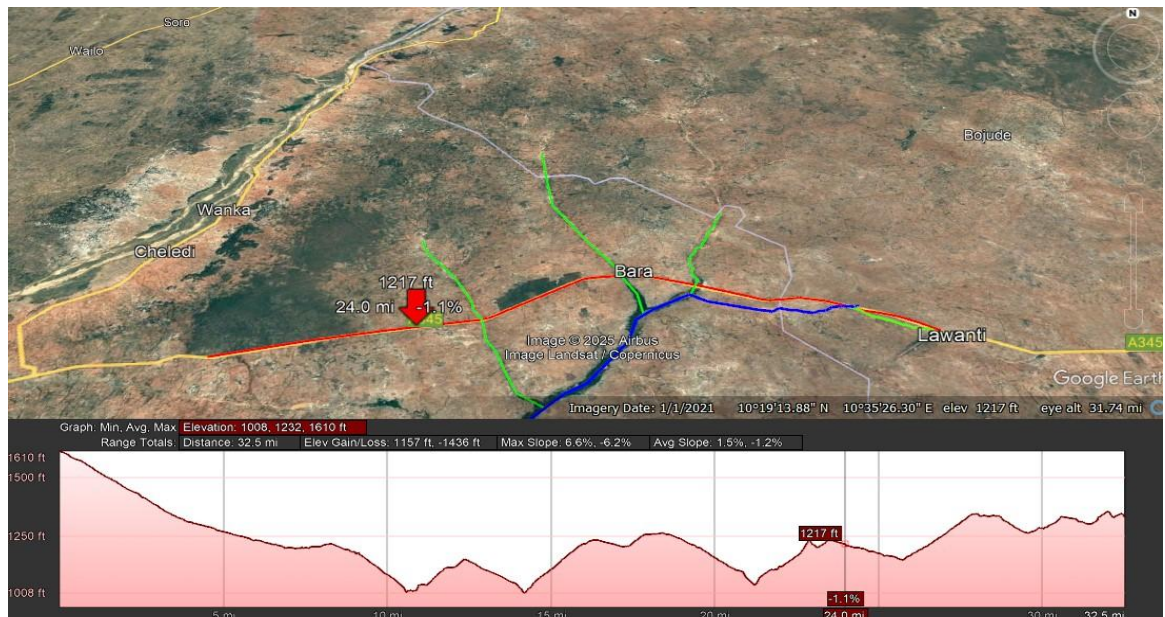


Figure 7: Damage Locations at Kalajanga, Bara, and Tashan Tulmi, Shown by Green Lines

3.11 Spatial Interpretation (Integration with GIS and Field Observations)

Combining XRF chemistry with GIS terrain analysis.

- A. Southern axis (near Yankari → Bauchi)
 - i. Dominated by true laterites
 - ii. High Al_2O_3 and Fe_2O_3
 - iii. Chemically stable soils
 - iv. Strong resistance to settlement and scour
 - v. Aligns with smoother surface profile noted in GIS
- B. Northern axis (near Gombe)
 - i. High silica, youthful alluvial soils
 - ii. More susceptible to hydrological erosion and rutting
 - iii. Matches GIS mapping of settlement-prone sections

Thus, the chemical data validates the geotechnical performance patterns observed along the corridor.

4.0 CONCLUSIONS

- i The key geotechnical and hydrological parameters contributing to road settlement and failure along the Bauchi-Gombe road were identified and characterized using numerical modeling techniques.
- ii Spatially correlate settlement patterns with soil properties, hydrological conditions, and structural data were analyzed using GIS-based analysis.
- iii The historical and current changes in topography, land use, and vegetation, and their effects on hydraulic structure stability through remote sensing techniques were identified and evaluated.

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