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# SETTLEMENT RISK ASSESSMENT OF TROPICAL BLACK CLAYS FOR SHALLOW FOUNDATIONS IN NORTH-CENTRAL NIGERIA

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**ABSTRACT:** Tropical black clays are problematic foundation materials in humid tropical environments due to their compressibility, moisture sensitivity, and stress-history effects. This study evaluated the shear strength, compressibility, and settlement susceptibility of tropical black clays from Gwagwalada, Gidigidi, Sunti, and Zungeru in North-Central Nigeria. Laboratory investigations included index property determination, soil classification, triaxial compression, and one-dimensional consolidation testing to determine cohesion (c), friction angle (ϕ), compression index ($C_c$), preconsolidation pressure ($\sigma'_p$), and coefficient of consolidation ($C_v$). The soils were predominantly classified as CL, CL–CH, and CH and exhibited moderate expansion potential. Consolidation results indicated moderate to high compressibility ($C_c$=0.167–0.221) and variable stress-history conditions ($\sigma'_p$=72–157kPa). A comparative assessment framework based on the interaction of $C_c$ and $\sigma'_p$ was developed and complemented by a preliminary Settlement Risk Index (SRI). Computed SRI values (0.00141–0.00261kPa$^{-1}$) classified the soils into moderate, high, and very high settlement-susceptibility categories, with Gidigidi deposit exhibiting the highest relative risk. The results indicate that settlement susceptibility is controlled by compressibility and stress history, while drainage characteristics influence consolidation rate. The proposed framework provides a practical basis for comparative assessment of tropical black clay deposits, although further validation using conventional settlement analyses and field-performance data is recommended.

*Keywords: Tropical black clays; Settlement Risk Index (SRI); Consolidation Behaviour; Preconsolidation Pressure; Settlement Susceptibility*

## 1. INTRODUCTION

Foundation performance in humid tropical environments is often affected by the complex behaviour of fine-grained expansive clays, which are widely distributed across Africa, Asia, and other developing regions. These soils exhibit swelling–shrinkage, high compressibility, and time-dependent deformation, resulting in excessive and differential settlement that can adversely affect foundations, pavements, embankments, railways, and hydraulic structures [1, 2]. Their engineering behaviour is controlled by mineralogy, soil fabric, moisture condition, and stress history, which influence both shear strength and consolidation response [3–5]. Previous studies have shown that soil stabilisation can improve strength and reduce compressibility [6–8], while seasonal wetting–drying cycles significantly affect settlement behaviour in tropical environments [7, 9].

It is important to distinguish between swelling–shrinkage behaviour and consolidation settlement in expansive clay deposits. Swelling and shrinkage are primarily controlled by moisture-content fluctuations, mineralogical composition, and suction changes, resulting in volume variations during wetting and drying cycles [10–12]. In contrast, consolidation settlement is governed by compressibility, stress history, and pore-water dissipation under applied loading [13–15]. Although tropical black clays may exhibit both behaviours, the present study focuses specifically on consolidation-related settlement mechanisms and their implications for foundation serviceability.

In engineering practice, tropical soils are commonly evaluated using index properties, classification systems, and California Bearing Ratio (CBR) tests. While useful for preliminary assessment, these methods do not adequately capture the mechanical processes governing foundation performance. Shear strength parameters, including cohesion (c) and friction angle (ϕ), define resistance to loading within the Mohr–Coulomb framework, whereas consolidation parameters such as compression index ($C_c$), coefficient of consolidation ($C_v$), and preconsolidation pressure ($\sigma'_p$) govern settlement magnitude and rate [13–15]. Consequently, reliance solely on index-based properties may not adequately characterise settlement susceptibility in compressible clay deposits [10, 11]. Field observations further indicate that excessive settlement may remain a critical serviceability concern even when bearing-capacity requirements are satisfied [1, 2, 12].

The interaction between strength and consolidation behaviour is influenced by soil structure, weathering, drainage conditions, and stress history [5, 13–17]. In addition, matric suction variations can significantly affect both strength and deformation characteristics in unsaturated tropical soils [18, 19]. Despite the widespread occurrence of tropical black clays in Nigeria and across sub-Saharan Africa, most previous investigations have focused on index properties, swelling behaviour, compaction characteristics, and pavement performance [20, 21]. Comparatively fewer studies have integrated shear strength and consolidation characteristics into a unified framework for settlement assessment. Consequently, engineers are often required to interpret multiple consolidation and strength parameters independently when evaluating settlement susceptibility.

Recent advances in numerical and data-driven methods have improved settlement prediction; however, their application to tropical clay deposits remains limited, particularly where high-quality datasets are scarce [22–28]. Furthermore, practical indicators capable of translating laboratory-derived consolidation parameters into comparative measures of settlement risk remain limited. Variations in compressibility and stress history can significantly influence settlement behaviour even among soils with similar classification characteristics, highlighting the need for practical assessment tools based on fundamental consolidation mechanics.

To address these limitations, this study investigates the shear strength, compressibility, and settlement susceptibility of tropical black clays from four locations in North-Central Nigeria. A comparative settlement-risk framework is proposed by integrating compression index ($C_c$) and preconsolidation pressure ($\sigma'_p$) through a Settlement Risk Index (SRI). The framework is intended to provide a practical link between consolidation behaviour and settlement susceptibility, thereby supporting geotechnical assessment of tropical clay deposits. The remainder of this paper is organised as follows: Section 2 presents the research significance; Section 3 describes the study area and experimental methods; Section 4 presents the results and discussion, including settlement-risk evaluation; and Section 5 summarises the principal findings and conclusions.

## 2. RESEARCH SIGNIFICANCE

This study addresses a gap in the geotechnical assessment of tropical black clays by emphasising settlement susceptibility alongside conventional strength-based evaluation. Unlike previous studies that largely focused on classification properties, swelling behaviour, and pavement performance, the present work integrates compressibility and stress-history effects within a comparative settlement-assessment framework. By combining compression index ($C_c$) and preconsolidation pressure ($\sigma'_p$) through a Settlement Risk Index (SRI), the study provides a practical approach for identifying relatively settlement-prone clay deposits and supporting preliminary foundation assessment in tropical environments. The findings also establish a basis for future validation and refinement of settlement-risk evaluation methods for expansive and moisture-sensitive soils.

## 3. MATERIALS AND METHODS

### 3.1 Study Locations and Sampling

Soil samples were collected from four tropical black clay deposits located in North-Central Nigeria: Gwagwalada (GW) (Federal Capital Territory) (FCT), Gidigidi (GD) (Nasarawa State), Sunti (SN) (Niger State), and Zungeru (ZG) (Niger State) (Fig. 1). The region experiences a humid tropical climate characterised by distinct wet and dry seasons that influence weathering processes, moisture regimes, and geotechnical behaviour [3,4]. Tropical black clay deposits within the region have been associated with foundation settlement, pavement distress, and seasonal moisture sensitivity [1,3,20].

The investigated locations represent contrasting geological settings. Gwagwalada (GW) is predominantly underlain by weathered Basement Complex rocks comprising migmatites, gneisses, and granites. Gidigidi (GD) is associated with sedimentary formations of the Middle Benue Trough, whereas Sunti (SN) and Zungeru (ZG) are characterised by alluvial and floodplain deposits influenced by riverine sedimentation [3,4,20]. The terrain consists mainly of gently undulating plains and low-relief floodplains with variable drainage conditions. Based on regional geological studies, the clay fractions are expected to contain varying proportions of smectite, kaolinite, and illite minerals, which influence compressibility, moisture sensitivity, and settlement behaviour [5,18–20].Five trial pits were excavated at each location, resulting in a total of twenty sampling points. Sampling depths ranged from 1.0–1.5m below ground level, corresponding to the zone commonly influenced by shallow foundations and pavement subgrades. Both disturbed and undisturbed samples were collected. Disturbed samples were used for index property determination.


Fig. 1. Location of sampling sites in North-Central Nigeria

Strength testing, while undisturbed specimens were preserved for consolidation analysis. Samples were sealed immediately after collection to minimise moisture loss and disturbance during transportation. Groundwater was not encountered within the investigated depths. Natural moisture contents were determined during laboratory characterisation, although in-situ unit weights were not measured. The adopted sampling procedures were considered representative of shallow foundation conditions within the study area [29,30]. The geographical characteristics of the sampling locations are summarised in Table 1.

Table 1: Sampling Location Characteristics and Trial Pit Information

| Location | State | Trial Pit Codes | Latitude Range (°N) | Longitude Range (°E) | Sampling Depth (m) | Number of Sampling Points |
|---|---|---|---|---|---|---|
| GW | FCT | GW-TP1 to GW-TP5 | 8.909167–8.979167 | 7.120000–7.263889 | 1.0–1.5 | 5 |
| GD | Nasarawa State | GD-TP1 to GD-TP5 | 8.469506–8.546003 | 8.446781–8.495561 | 1.0–1.5 | 5 |
| SN | Niger State | SN-TP1 to SN-TP5 | 9.102213–9.104281 | 5.231924–5.234019 | 1.0–1.5 | 5 |
| ZG | Niger State | ZG-TP1 to ZG-TP5 | 9.738153–9.746127 | 6.129702–6.136636 | 1.0–1.5 | 5 |

### 3.2 Index Properties, Soil Classification, and Expansivity Assessment

Laboratory characterisation was conducted on representative disturbed samples from the four study locations in accordance with relevant ASTM and British Standard procedures [29,30]. Natural moisture content was determined using the oven-drying method, particle-size distribution was established through combined sieve and hydrometer analyses to determine the proportions of gravel, sand, silt, and clay fractions [29,30].

Consistency characteristics were evaluated through determination of the liquid limit (LL), plastic limit (PL), and plasticity index (PI). Based on the measured grain-size distribution and Atterberg limits, the soils were classified according to the Unified Soil Classification System (USCS) and the American Association of State Highway and Transportation Officials (AASHTO) classification system [29–31].

Expansivity was assessed using swelling index measurements and activity analysis. Swelling index was used to evaluate the volume-change susceptibility of the soils upon wetting [18,19,32,33]. Soil activity was determined following the approach proposed by Skempton [34] as the ratio of plasticity index (PI) to clay fraction (% clay), providing an indication of the influence of clay mineralogy on expansive behaviour.

The combined evaluation of natural moisture content, particle-size distribution, clay fraction, Atterberg limits, swelling index, activity, and soil classification characteristics provided the basis for interpreting the strength, compressibility, and settlement behaviour of the investigated tropical black clay deposits [5,18,19,32–34].

### 3.3 Shear Strength Determination

The shear strength characteristics of the investigated tropical black clays were evaluated using triaxial compression tests performed on representative undisturbed specimens in accordance with established geotechnical laboratory procedures for fine-grained soils [29–31]. Cylindrical specimens measuring approximately 38mm in diameter and 76mm in height were prepared and enclosed in rubber membranes prior to testing.

Testing was conducted under natural moisture conditions to preserve the in-situ structure and moisture characteristics of the deposits. Confining pressures of 50, 100, and 200kPa were applied using water as the confining medium within the triaxial cell, while axial loading was progressively increased until specimen failure occurred.

The principal stresses at failure were used to construct Mohr circles and establish the Mohr–Coulomb failure envelope. Cohesion (c) and angle of internal friction (ϕ) were subsequently determined from the intercept and slope of the failure envelope, respectively [10,11,13]. The derived shear strength parameters were used to evaluate the resistance characteristics of the soils and were subsequently interpreted alongside consolidation parameters in assessing settlement susceptibility and foundation performance.

### 3.4 Consolidation and Compressibility Testing

One-dimensional consolidation tests were performed on representative undisturbed specimens using a standard oedometer apparatus in accordance with established geotechnical laboratory procedures [29,30]. Specimens measuring approximately 75mm in diameter and 20mm in height were trimmed and placed within rigid confining rings to prevent lateral deformation.

Testing was conducted under double-drainage conditions. Vertical loads of 12.5, 25, 50, 100, 200, 400, 800, and 1600kPa were applied sequentially, corresponding to a load increment ratio (LIR) of approximately 1.0. Each load increment was maintained for 24h or until primary consolidation was substantially complete. Following completion of the loading cycle, unloading was performed to evaluate recompression and swelling characteristics. Vertical deformation readings were recorded throughout the test and used to establish void ratio–effective stress relationships.

Compression index ($C_c$), recompression index ($C_r$), and swelling index ($C_e$) were determined from the respective slopes of the void ratio–log effective stress (e–logσ′) curves. Preconsolidation pressure ($\sigma'_p$) was estimated using Casagrande's graphical method [13–15], while the coefficient of consolidation ($C_v$) was determined from time-settlement data using Taylor's square-root-of-time method [15–17]. In this study, compression and rebound during unloading was recorded as positive

The derived consolidation parameters were subsequently used to evaluate compressibility behaviour, stress-history effects, and settlement susceptibility of the investigated tropical black clay deposits.

### 3.5 Settlement Risk Assessment Framework

A settlement-assessment framework was developed using compression index ($C_c$) and preconsolidation pressure ($\sigma'_p$), which respectively represent compressibility and stress-history effects on consolidation behaviour [11,15,17]. Settlement susceptibility was evaluated through a Settlement Risk Index (SRI) defined in Equ. 1 as:

$$\mathbf{SRI} = \frac{\mathbf{Cc}}{\boldsymbol{\sigma}'\mathbf{p}} \quad (1)$$

where $C_c$ is the compression index and $\sigma'_p$ is the preconsolidation pressure (kPa). Since $C_c$ is dimensionless and $\sigma'_p$ is expressed in kPa, the resulting SRI has units of $kPa^{-1}$. Higher SRI values indicate greater compressibility relative to yield stress and, consequently, increased settlement susceptibility. The proposed framework was used to compare the relative settlement risk of the investigated tropical black clay deposits.

## 4. RESULTS AND DISCUSSION

### 4.1 Natural Moisture Content

The natural moisture contents of the investigated tropical black clay deposits are presented in Table 2. Average moisture contents of 24.49, 24.46, 21.19, and 17.07% were obtained for the GW, GD, SN, and ZG deposits, respectively, indicating noticeable spatial variability in moisture condition.

Table 2: Natural Moisture Content of the Deposits

| Location | Average NMC (%) | Relative Moisture Condition |
|---|---|---|
| GW | 24.49 | High |
| GD | 24.46 | High |
| SN | 21.19 | Moderate |
| ZG | 17.07 | Low |

GW and GD deposits exhibited the highest moisture contents (>24%), indicating greater water-retention capacity typically associated with finer particles, higher clay fractions, and increased plasticity [5,18,19]. SN deposit recorded an intermediate moisture content (21.19%), whereas ZG deposit exhibited the lowest value (17.07%), suggesting comparatively drier field conditions.

Moisture content strongly influences the engineering behaviour of tropical black clays by affecting effective stress, matric suction, and interparticle bonding [6,9,18,19]. Consequently, the relatively high moisture contents observed in GW and GD deposits may contribute to increased compressibility and settlement susceptibility, whereas the lower moisture content of ZG deposit suggests comparatively greater stiffness and resistance to deformation. However, settlement behaviour remains dependent on the combined effects of moisture condition, soil structure, stress history, and compressibility characteristics [13–15].

### 4.2 Atterberg Limits and Plasticity Characteristics

The average Atterberg limits of the investigated tropical black clay deposits are presented in Table 3. The results indicate noticeable variability in consistency characteristics among the studied locations, reflecting differences in clay content, mineralogy, weathering history, and moisture-retention behaviour.

Table 3: Average Atterberg Limits of the Investigated Soils

| Location | LL (%) | PL (%) | PI (%) | SL (%) |
|---|---|---|---|---|
| GW | 56.32 | 33.45 | 22.87 | 8.40 |
| GD | 31.62 | 16.84 | 14.78 | 9.34 |
| SN | 32.87 | 16.84 | 16.02 | 8.86 |
| ZG | 37.90 | 17.44 | 20.46 | 8.98 |

Liquid limit values ranged from 31.62 to 56.32%, with GW deposit exhibiting the highest value, followed by ZG, SN, and GD deposits. Similarly, plasticity index values ranged from 14.78 to 22.87%, indicating moderate to high plasticity characteristics across the investigated deposits. The relatively high LL and PI values recorded for GW and ZG deposits suggest greater moisture sensitivity, compressibility, and potential for deformation compared with the other locations [5,18,19].

Plastic limit values varied from 16.84 to 33.45%, with GW deposit exhibiting a wider moisture range over which plastic behaviour occurs. In contrast, shrinkage limit values showed relatively little variation (8.40–9.34%), indicating broadly similar moisture contents below which further drying produces minimal volume reduction.

The Atterberg limit results confirm the fine-grained and moisture-sensitive nature of the investigated tropical black clays. The observed plasticity characteristics are consistent with previous studies that identified liquid limit and plasticity index as important indicators of compressibility, volume-change behaviour, and settlement susceptibility in expansive tropical soils [5,6,9,18,19].

### 4.3 Particle Size Distribution and Soil Gradation Characteristics

The combined particle-size distribution and sedimentation curves of the investigated tropical black clay deposits are presented in Fig. 2. The results indicate noticeable variations in particle-size composition among the studied locations, reflecting differences in depositional environment, weathering intensity, and soil-forming processes.

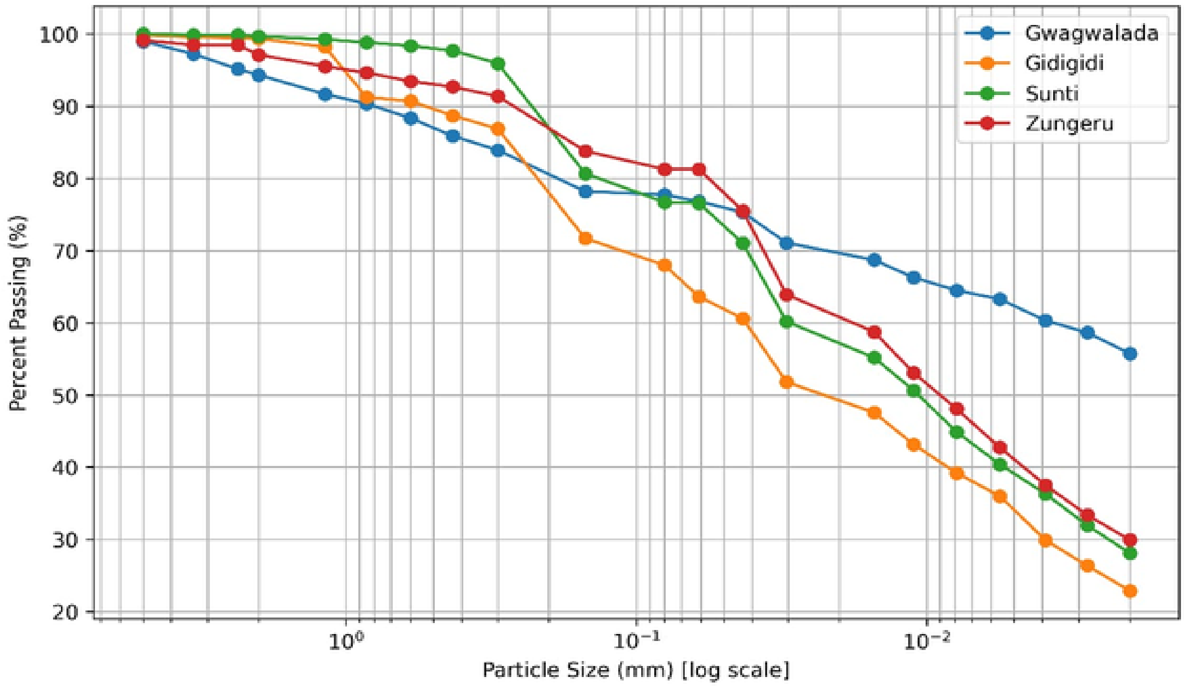


Fig. 2: Combined Particle Size Distribution and Sedimentation Curves for the Soils

GW deposit exhibited the highest proportion of fine-grained particles, with more than 55% passing within the clay-size range. This behaviour is consistent with its relatively high liquid limit and plasticity index (Table 3), indicating a greater specific surface area, higher water-retention capacity, and increased susceptibility to compressibility and settlement-related deformation [5,13–15].

GD and SN deposits displayed comparatively lower percentages of fine particles and relatively higher proportions of silt- and sand-sized fractions. Such gradation characteristics generally promote improved drainage and lower compressibility, although consolidation behaviour remains influenced by stress history and soil structure [16,17]. ZG deposit exhibited an intermediate gradation pattern.

It contains appreciable fine-grained material, consistent with its relatively high plasticity index. The sedimentation curves confirm the predominance of fine-grained material within all investigated deposits. The presence of appreciable clay fractions suggests potential sensitivity to moisture variation, consolidation, and settlement, consistent with previous studies on tropical clay soils [5,18,19].

### 4.4 Soil Classification and Expansivity Assessment

The classification and expansivity characteristics of the investigated tropical black clay deposits are summarised in Table 4. The results confirm that all deposits are predominantly fine-grained cohesive soils with varying degrees of plasticity, clay content, and moisture sensitivity.

Table 4: Soil Classification and Expansivity Characteristics of the soils

| Location | %Clay Fraction (%) | Activity | Activity Class | USCS | AASHTO | Swelling Potential | Expansion Class |
|---|---|---|---|---|---|---|---|
| GW | 55.76 | 0.41 | Inactive | CH | A-7-6 | 4.48 | Medium |
| GD | 22.90 | 0.65 | Inactive-Normal | CL | A-7-5 | 1.54 | Medium |
| SN | 28.10 | 0.57 | Inactive-Normal | CL | A-7-5 | 1.88 | Medium |
| ZG | 29.94 | 0.68 | Normal | CL–CH | A-7-6 | 3.41 | Medium |

Clay activity values ranged from 0.41 to 0.68, indicating predominantly inactive to normal clay behaviour according to Skempton's classification [34]. Although the soils exhibit appreciable clay contents, the relatively low activity values suggest that their engineering behaviour is influenced not only by clay mineralogy but also by factors such as soil structure, moisture condition, and stress history.

Particle-size data indicate that all deposits are dominated by fine-grained fractions, with GW deposit containing the highest clay content (55.76%). This observation is consistent with its relatively high liquid limit and plasticity index and supports its classification as CH under the Unified Soil Classification System. In contrast, GD and SN deposits were classified as CL, while ZG deposit exhibited intermediate CL–CH characteristics.

The AASHTO classifications placed all deposits within the A-7 group, indicating generally poor subgrade quality and confirming their susceptibility to moisture-related engineering problems. The A-7-6 classifications obtained for GW and ZG deposits reflect their comparatively higher plasticity characteristics.

Estimated swelling potential values ranged from 1.54 to 4.48, with all deposits falling within the medium expansion category. GW deposit exhibited the highest swelling potential, followed by ZG, SN, and GD deposits. The observed trend generally follows the variation in plasticity index, highlighting the influence of plasticity on expansion behaviour. Overall, the classification and expansivity results confirm the moisture-sensitive nature of the investigated tropical black clays and their potential susceptibility to deformation under changing environmental and loading conditions [5,18,19,32].

#### 4.5 Shear Strength Characteristics

The measured shear strength parameters of the investigated tropical black clays are presented in Table 5. Bulk unit weights ranged from 17.90–20.50kN/m³, indicating relatively dense fine-grained soils consistent with values reported for moderately plastic tropical clays [3–5]. Cohesion values ranged from 16.70 to 168.13kPa, while friction angles varied from 4.93 to 38.37°. The wide range of values reflects differences in soil fabric, moisture condition, stress history, and depositional environment [5,9,13].

The highest cohesion value was recorded for sample SN2 (168.13kPa), considerably exceeding the remaining SN samples. This unusually high value may indicate localised structural bonding, natural cementation, or partially overconsolidated conditions, which are commonly observed in heterogeneous tropical clay deposits [3,5,18]. Conversely, several SN samples exhibited very low friction angles (approximately 5–10°), suggesting a greater dependence on cohesive resistance than frictional interaction, a characteristic often associated with fine-grained clay matrices [6,13].

The relatively high friction angles recorded for ZG samples (22.16–38.37°) correspond with its appreciable silt and sand fractions and indicate enhanced interparticle friction and stress transfer. The results demonstrate substantial spatial variability in shear strength behaviour, highlighting the importance of site-specific geotechnical characterisation.

Table 5: Measured Shear Strength Parameters for the Investigated Soils

| Samples | Bulk unit weight ($kN/m^3$) | Cohesion ($kN/m^2$) | Angle of internal friction (°) |
|---|---|---|---|
| GW1 | 19.50 | 77.79 | 11.47 |
| GW2 | 19.80 | 71.28 | 20.79 |
| GW3 | 20.00 | 49.65 | 20.29 |
| GW4 | 20.50 | 50.54 | 27.29 |
| GW5 | 19.00 | 65.93 | 22.24 |
| GD1 | 19.90 | 80.22 | 11.53 |
| GD2 | 20.10 | 75.98 | 19.39 |
| GD3 | 20.00 | 53.95 | 19.86 |
| GD4 | 19.90 | 54.84 | 25.42 |
| GD5 | 18.80 | 61.84 | 22.23 |
| SN1 | 19.50 | 16.70 | 13.79 |
| SN2 | 18.70 | 168.13 | 18.37 |
| SN3 | 18.30 | 32.17 | 4.93 |
| SN4 | 18.30 | 34.60 | 9.78 |
| SN5 | 17.90 | 28.92 | 7.72 |
| ZG1 | 20.10 | 72.17 | 31.74 |
| ZG2 | 20.00 | 41.93 | 22.16 |
| ZG3 | 19.80 | 22.46 | 30.78 |
| ZG4 | 19.80 | 50.46 | 38.37 |
| ZG5 | 19.60 | 72.49 | 35.29 |

To quantify this variability, statistical measures including mean, standard deviation (SD), and coefficient of variation (CV) were evaluated and are summarised in Table 6. GW and GD deposits exhibited relatively consistent cohesion values, with coefficients of variation below 20%, indicating comparatively uniform strength characteristics. In contrast, SN deposits exhibited exceptionally high cohesion variability (CV=112.29%), largely attributable to the elevated cohesion recorded for sample SN2. Although this value differs markedly from the remaining SN samples, no evidence of testing or calculation errors was identified; therefore, it was retained to preserve the natural variability of the deposit.

Table 6: Summary Statistics of Shear Strength Parameters

| Location | Mean C (kPa) | SD (kPa) | CV (%) | Mean ϕ (°) | SD (°) | CV (%) |
|---|---|---|---|---|---|---|
| GW | 63.04 | 12.54 | 19.90 | 20.42 | 5.72 | 28.01 |
| GD | 65.37 | 12.11 | 18.53 | 19.69 | 5.15 | 26.15 |
| SN | 56.10 | 63.00 | 112.29 | 10.92 | 5.27 | 48.28 |
| ZG | 51.90 | 21.23 | 40.91 | 31.67 | 6.11 | 19.29 |

Similar localised increases in apparent cohesion have been reported in tropical and residual clays due to weathering, cementation, desiccation, and stress-history effects [3,5,18].ZG deposits exhibited moderate cohesion variability (CV=40.91%) but relatively consistent friction-angle values (CV=19.29%). The lower variability in friction angle suggests that frictional resistance was less sensitive to local heterogeneity than cohesion, a behaviour commonly observed in clay-rich soils [6,13]. Overall, the results confirm the heterogeneous nature of tropical black clay deposits and emphasise the importance of considering spatial variability when interpreting shear strength parameters and assessing settlement susceptibility [5,18,19].

**4.6 Consolidation Behaviour and Settlement Susceptibility**

The compressibility classification adopted in this study was based on the magnitude of the compression index ($C_c$), where values below 0.10 indicate low compressibility, values between 0.10 and 0.20 indicate moderate compressibility, and values exceeding 0.20 generally indicate highly compressible clay deposits [13–17]. Based on this classification, the investigated soils exhibit moderate to high compressibility characteristics as presented in Table 7.

Table 7: Summary of Consolidation Parameters of the Studied Soils

| Location | $C_c$ | $C_e$ | $C_r$ | $\sigma'_p$ (kPa) | $C_v$ (cm$^2$/min) |
|---|---|---|---|---|---|
| GW | 0.167 | 0.037 | 0.037 | 72 | 0.12 |
| GD | 0.201 | 0.039 | 0.039 | 77 | 0.18 |
| SN | 0.221 | 0.040 | 0.040 | 149 | 0.31 |
| ZG | 0.221 | 0.040 | 0.040 | 157 | 0.36 |

Compression indices ranged from 0.167 to 0.221, indicating moderate to high compressibility and significant settlement potential under sustained loading [14–17]. Preconsolidation pressures, determined using Casagrande's method, ranged from 72 to 157kPa and revealed substantial differences in stress-history behaviour. GW and GD deposits exhibited relatively low preconsolidation pressures (72–77kPa), indicating earlier yielding under applied loading, whereas SN and ZG deposits exhibited higher values (149–157kPa), reflecting stronger overconsolidation effects and greater resistance to initial compression. Nevertheless, their relatively high compression indices suggest that substantial deformation may still occur once the yield stress is exceeded [13–15,24].

The coefficient of consolidation ($C_v$) ranged from 0.12 to 0.36cm²/min, indicating moderate pore-pressure dissipation and time-dependent settlement behaviour. Higher $C_v$ values recorded for SN and ZG deposits suggest comparatively faster consolidation rates, although settlement magnitude remains primarily controlled by compressibility and stress history [16,17]. The reported $C_v$ values represent representative average values derived from the consolidation tests and should not be interpreted as constant properties across all stress levels.

Low recompression and swelling indices ($C_r$ and $C_e$) indicate limited elastic rebound and predominantly plastic deformation behaviour beyond the preconsolidation pressure, consistent with previous observations in fine-grained tropical soils [7,15]. To provide additional insight into the consolidation characteristics of the investigated deposits, selected structural and deformation parameters are summarised in Table 8.

Initial void ratios ranged from 0.300 to 0.305, with corresponding porosities of 23.1–23.4%, indicating broadly similar initial soil structures among the deposits. Progressive loading produced substantial reductions in specimen height and void ratio, reflecting particle rearrangement and pore-water expulsion during consolidation. The larger reductions observed in GW and GD deposits are consistent with their comparatively lower preconsolidation pressures, whereas SN and ZG deposits maintained slightly higher final void ratios due to their greater resistance to initial yielding [14,15]. The e–logσ′ relationships obtained from the consolidation tests are presented in Fig. 3

Table 8: Additional Consolidation Characteristics of the Investigated Soils

| Location | NMC (% | $H_o$ (mm) | $H_f$ (mm) | $e_o$ | $e_f$ | Porosity (%) | Loading Range (kPa) |
|---|---|---|---|---|---|---|---|
| GW | 24.49 | 20.00 | 15.51 | 0.305 | 0.012 | 23.4 | 12.49–1598.78 |
| GD | 24.46 | 20.00 | 15.37 | 0.305 | 0.003 | 23.4 | 12.49–1598.78 |
| SN | 21.19 | 20.00 | 15.83 | 0.300 | 0.030 | 23.1 | 12.49–1598.78 |
| Z G | 17.07 | 20.00 | 15.83 | 0.305 | 0.033 | 23.4 | 12.49–1598.78 |

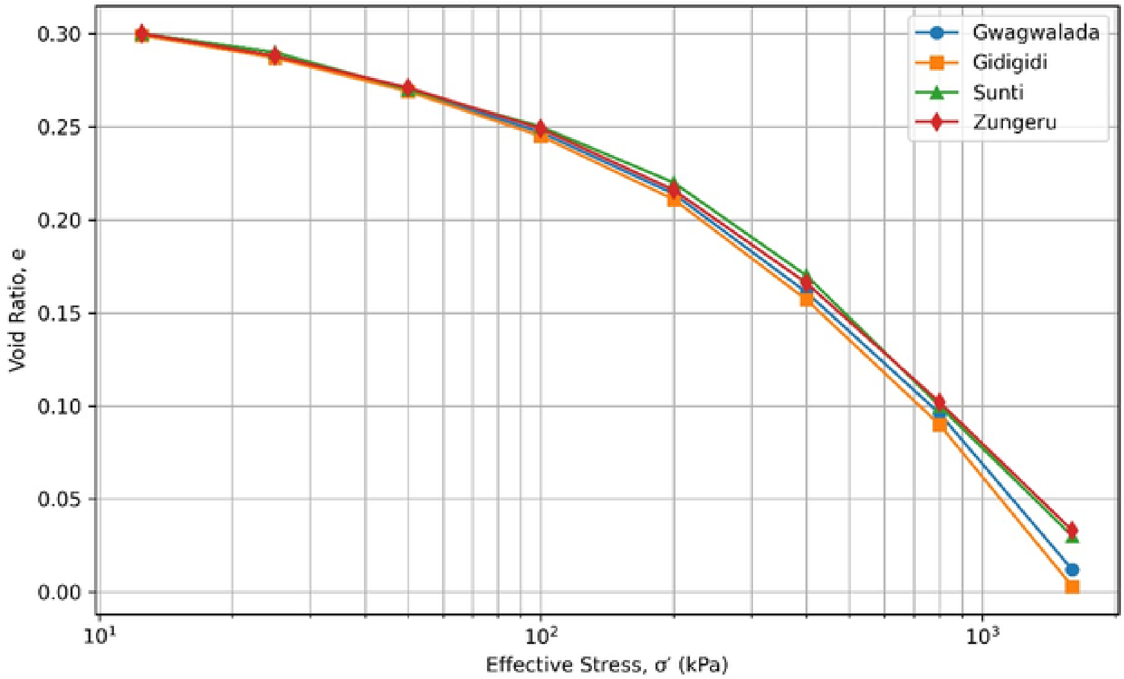


Fig. 3: Consolidation Behaviour of Investigated Soils

The e–logσ′ curves exhibit the characteristic consolidation response of fine-grained soils, comprising an initial recompression region followed by a steeper virgin compression segment. GW and GD deposits displayed earlier transitions into virgin compression, consistent with their lower preconsolidation pressures and greater settlement susceptibility. In contrast, SN and ZG deposts exhibited higher yield thresholds but steeper virgin compression slopes, indicating greater post-yield compressibility. The unloading segments exhibited comparatively gentle slopes, confirming limited elastic recovery and predominantly plastic deformation behaviour. The results demonstrate that settlement susceptibility is governed by the combined influence of compressibility, stress history, and consolidation rate, consistent with established consolidation theory and previous studies on tropical clay deposits [13–17,23,24].

### 4.7 Settlement Risk Classification and Foundation Implications

The consolidation results were interpreted using the proposed $C_c$–$\sigma'_p$ framework, which combines compressibility ($C_c$) and preconsolidation pressure ($\sigma'_p$) to evaluate relative settlement susceptibility. The framework considers both the magnitude of post-yield deformation and the stress level required to initiate significant compression.

Deposits with lower preconsolidation pressures are more susceptible to early yielding under applied loading, whereas higher compression indices indicate greater deformation once yielding occurs. Based on this interaction (Table 9), GW deposit ($C_c$=0.167; $\sigma'_p$=72kPa) and GD deposit ($C_c$=0.201; $\sigma'_p$=77kPa) exhibited comparatively higher settlement susceptibility due to their relatively low yield thresholds.

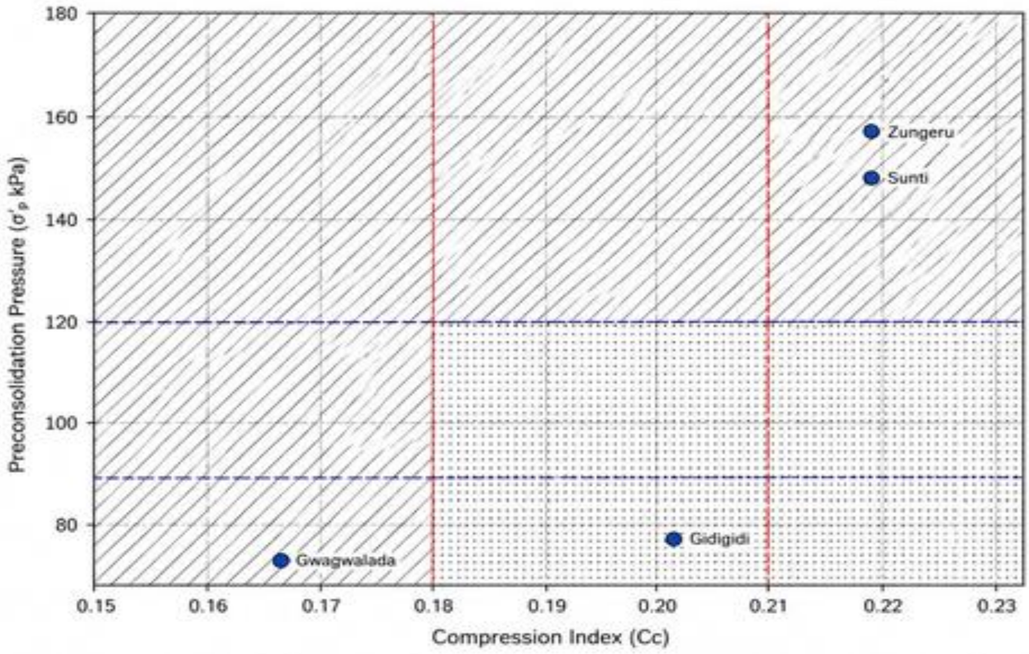


Fig. 4: Settlement Risk Plot Based on $C_c$–σ'p Interaction with Threshold Zones

In contrast, SN and ZG deposits exhibited higher preconsolidation pressures (149–157kPa), indicating greater resistance to initial compression despite their relatively high compression indices ($C_c$=0.221). Similar behaviour has been reported for structured and partially overconsolidated clays, where stress history delays yielding but does not eliminate post-yield deformation [14,15,35-38].

Table 9: Settlement Risk Classification Based on $C_c$–$\sigma'_p$ Framework

| Location | $C_c$ | $\sigma'_p$ (kPa) | Settlement Risk Class |
|---|---|---|---|
| GW | 0.167 | 72 | High settlement risk |
| GD | 0.201 | 77 | High settlement risk |
| SN | 0.221 | 149 | Moderate settlement risk |
| ZG | 0.221 | 157 | Moderate settlement risk |

The classification presented in Table 9 and the $C_c$–$\sigma'_p$ relationship shown in Fig. 4 provide a practical means of comparing the relative settlement susceptibility of the investigated deposits. The results demonstrate that settlement behaviour is influenced by both compressibility and stress history, emphasising the importance of considering these parameters together when evaluating foundation performance.

**4.8 Settlement Risk Index (SRI) and Index-Based Evaluation**

The proposed Settlement Risk Index (SRI), defined by Equ. (1), combines compressibility ($C_c$) and preconsolidation pressure ($\sigma'_p$) into a single comparative parameter for evaluating relative settlement susceptibility. Computed SRI values are presented in Table 10.

Table 10: Settlement Risk Index (SRI) and Classification of Soils

| Location | $C_c$ | σ p (kPa) | SRI ($kPa^{-1}$) | Settlement Risk Class |
|---|---|---|---|---|
| GW | 0.167 | 72 | 0.00232 | High Risk |
| GD | 0.201 | 77 | 0.00261 | Very High Risk |
| SN | 0.221 | 149 | 0.00148 | Moderate Risk |
| ZG | 0.221 | 157 | 0.00141 | Moderate Risk |

The calculated SRI values ranged from 0.00141 to 0.00261$kPa^{-1}$ and provided clear differentiation among the investigated deposits. GD deposit (0.00261$kPa^{-1}$) and GW deposit (0.00232$kPa^{-1}$) exhibited the highest settlement susceptibility due to their relatively low preconsolidation pressures, whereas SN deposit (0.00148$kPa^{-1}$) and ZG deposit (0.00141$kPa^{-1}$) exhibited moderate risk despite their comparatively high compression indices.

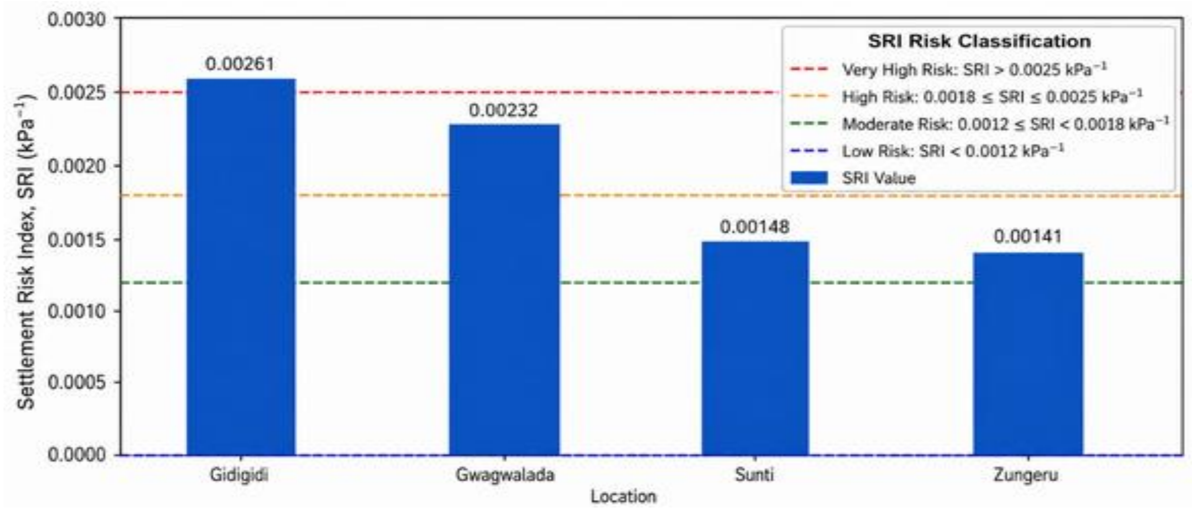


Fig. 5: Settlement Risk Index (SRI) Distribution with Classification Thresholds

These results demonstrate the combined influence of compressibility and stress history on settlement behaviour and highlight the limitations of relying on either parameter independently [23,37,38].

A preliminary SRI classification framework was developed to facilitate interpretation of the computed values (Table 11). The proposed threshold ranges were derived from the relative distribution of SRI values obtained for the investigated deposits and are intended primarily for comparative assessment rather than as universally calibrated design criteria.

Table 11: Preliminary SRI-Based Settlement Risk Classification Framework

| SRI Range ($kPa^{-1}$) | Risk Level |
|---|---|
| SRI < 0.0012 | Low risk |
| 0.0012 ≤ SRI < 0.0018 | Moderate risk |
| 0.0018 ≤ SRI ≤ 0.0025 | High risk |
| SRI > 0.0025 | Very high risk |

The SRI provides a compact numerical representation of settlement susceptibility and complements the graphical $C_c$–$\sigma'_p$ framework presented in Section 4.7. Soils classified within the high and very high SRI categories may warrant detailed settlement evaluation and possible ground-improvement measures, whereas moderate-risk soils may be suitable for lightly loaded structures subject to conventional settlement assessment [2,12,36]. The SRI distribution with classification thresholds are illustrated in Fig. 5. Although the proposed index successfully differentiates the investigated deposits according to their relative settlement susceptibility, the classification framework should be regarded as preliminary because it has not been calibrated against calculated foundation settlements, field measurements, or full-scale performance data. Consequently, the SRI is intended as a comparative screening tool rather than a substitute for conventional settlement analysis.

### 4.9 Integrated Foundation Performance and Design Implications

The combined evaluation of shear strength, consolidation behaviour, and the Settlement Risk Index (SRI) provided a basis for assessing the relative foundation behaviour of the investigated tropical black clay deposits. While cohesion (c) and friction angle (ϕ) describe shear resistance, consolidation parameters and SRI values provide insight into compressibility, stress history, and settlement susceptibility. The results indicate that shear strength alone may not provide a complete assessment of foundation performance in fine-grained tropical soils where consolidation-related deformation can be significant [1,2,12,39].

The observed behaviour reflects the interaction between compressibility ($C_c$) and preconsolidation pressure ($\sigma'_p$). GW and GD deposits exhibited higher settlement susceptibility due to their relatively low preconsolidation pressures and corresponding higher SRI values, whereas SN and ZG deposits exhibited lower SRI values because of their greater resistance to initial yielding despite comparatively high compression indices. These findings support previous observations that preconsolidation pressure influences the onset of yielding, while compression index governs the magnitude of post-yield deformation [22–24,37-39].

The coefficient of consolidation ($C_v$) provided additional information regarding the rate of settlement development. Higher $C_v$ values recorded for SN and ZG deposits indicate comparatively faster pore-pressure dissipation, whereas lower values for GW and GD suggest slower consolidation rates [16,17]. However, the magnitude of settlement remains primarily controlled by compressibility and stress history.

From an engineering perspective, the proposed framework may serve as a preliminary screening tool for identifying deposits that warrant detailed settlement evaluation. However, the present study did not include conventional settlement calculations, bearing-capacity analyses, or field-performance validation. Consequently, the findings should be interpreted as indicators of relative settlement susceptibility rather than predictions of actual foundation performance.

Deposits exhibiting comparatively higher settlement susceptibility, such as GW and GD, may require detailed settlement analyses and consideration of mitigation measures including preloading, soil replacement, lime or cement stabilisation, moisture-control systems, and geosynthetic reinforcement. In contrast, SN and ZG may be more suitable for conventional shallow foundations, subject to project-specific verification of settlement and bearing-capacity requirements. Where heavy structural loads are anticipated, raft or deep foundation systems may be considered to reduce differential settlement and improve load transfer.

The integration of $C_c$, $\sigma'_p$, $C_v$, and SRI provides a practical basis for comparing the relative settlement susceptibility of tropical black clay deposits and identifying locations where additional geotechnical investigation or ground-improvement measures may be warranted. Nevertheless, further validation using conventional settlement analyses, field observations, and broader tropical clay datasets is recommended.

## 5. CONCLUSIONS

This study evaluated the shear strength, compressibility, and settlement susceptibility of tropical black clay deposits from Gwagwalada, Gidigidi, Sunti, and Zungeru in North-Central Nigeria using laboratory-based geotechnical characterisation, triaxial compression testing, and one-dimensional consolidation analysis. The investigation integrated strength and consolidation parameters to develop a comparative framework for assessing settlement susceptibility in tropical black clays.

The investigated soils were predominantly fine-grained, moisture-sensitive clays classified as CL, CL–CH, and CH under the Unified Soil Classification System and A-7-5 to A-7-6 under the AASHTO classification system. The deposits exhibited moderate expansion potential and generally poor engineering quality for subgrade applications.

Shear strength parameters displayed substantial spatial variability, particularly within the SN deposit, where cohesion values ranged from 16.70 to 168.13kPa. Coefficients of variation ranging from 18.53 to 112.29% confirmed the heterogeneous nature of the deposits and highlighted the importance of site-specific geotechnical characterisation.

Consolidation testing indicated moderate to high compressibility, with compression indices ranging from 0.167 to 0.221 and preconsolidation pressures ranging from 72 to 157kPa. GW and GD deposits exhibited lower preconsolidation pressures and greater susceptibility to yielding, whereas SN and ZG deposits exhibited stronger stress-history effects and greater resistance to initial compression. The coefficient of consolidation ranged from 0.12 to 0.36cm²/min, indicating differences in the rate of consolidation among the deposits.

A preliminary Settlement Risk Index (SRI) was proposed to integrate compressibility and stress-history effects into a single comparative parameter. Computed SRI values ranged from 0.00141 to 0.00261kPa$^{-1}$, with GD and GW exhibiting the highest relative settlement susceptibility. The combined use of the $C_c$–$\sigma'_p$ framework and SRI provided a practical basis for comparing the relative settlement susceptibility of the investigated deposits.

The findings indicate that compressibility, stress history, and consolidation characteristics are key factors controlling the relative settlement behaviour of tropical black clays. However, the proposed SRI should be regarded as a preliminary screening tool because it was not calibrated against calculated settlements or documented field performance.

The study is limited by the number of investigated locations, the absence of mineralogical characterisation, limited swelling assessment, and the lack of field or analytical validation of the proposed SRI thresholds. Future studies should incorporate mineralogical analyses, expanded datasets, detailed swelling characterisation, conventional settlement calculations, numerical modelling, and field-performance observations to refine and validate the proposed framework.

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