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ENGINEERING GEOTECHNICAL CHARACTERIZATION FOR PIPELINE INFRASTRUCTURE: A CASE STUDY OF THE ESCRAVOS–ODIDI CORRIDOR IN NIGER DELTA, NIGERIA

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ABSTRACT

Laying of Pipeline infrastructure in swampy deltaic terrain is often constrained by weak soils, shallow groundwater, and corrosive environments, yet few site-specific datasets exist for tropical deltas. This study presents a comprehensive geotechnical investigation along the 40-inch × 30 km Escravos–Odidi gas pipeline corridor in the Niger Delta, Nigeria. Thirty boreholes were advanced to 5.0 m depth, with systematic sampling and laboratory testing conducted to determine stratigraphy, index properties, moisture content, and soil chemistry. Results revealed a predominance of soft marine clays interbedded with occasional sand lenses. These soils exhibit high compressibility and plasticity (PI = 27–38%) and very high natural moisture contents exceeding 80%. Groundwater was consistently encountered at shallow depths (0–0.8 m), increasing the risks of trench instability and buoyancy effects. Soil pH values ranged from 5.8 to 6.8, indicating slightly corrosive to non-corrosive conditions with implications for cathodic protection. Based on the findings, the study recommends a minimum pipeline burial depth of 3.0m to mitigate settlement and uplift risks. Additionally, appropriate cathodic protection systems and soil improvement measures should be incorporated into design and construction. The study provides essential baseline data for pipeline engineering in swampy terrains and offers a framework for improving resilience, corrosion control and sustainable energy delivery in the Niger Delta and similar environments worldwide.

key words: Engineering; Geotechnical; Characterization; Pipeline; Infrastructure

1. INTRODUCTION

Pipeline infrastructure is a critical component of global energy and resource distribution, enabling the safe and efficient transport of oil, gas, and water across diverse terrains (Oyedele *et al.,* 2019). The design and construction of such linear systems require a comprehensive understanding of subsurface conditions, as geotechnical variability directly influences structural integrity, safety, and long-term performance (Jomata *et al.,* 2022; Kennedy, 2024). In tropical deltaic environments such as the Niger Delta, rapid lateral and vertical changes in soil properties present unique engineering challenges, including differential settlement, soil liquefaction, and slope instability (Butchibabu *et al.,* 2021; Vincent and Mallo, 2023). Subsurface exploration, comprising borehole drilling, soil sampling, topographic and right of way survey and in-situ testing, remains the cornerstone of geotechnical investigation for pipeline corridors (Ashioba and Udom, 2023). Borehole spacing in linear corridors is mathematically defined to ensure representative coverage, balancing economic feasibility with engineering reliability (Kinde *et al.,* 2024). Complementary geophysical methods, particularly geoelectrical resistivity surveys, enhance understanding of subsurface heterogeneity and groundwater conditions (Tiwari and Ajmera, 2023). The integration of geotechnical and geophysical datasets strengthens subsurface models, enabling engineers to anticipate potential constraints and design mitigation strategies (Barman and Dash, 2022). Despite advances in geotechnical and geophysical techniques, pipeline failures remain a recurring issue in tropical deltaic regions due to inadequate subsurface characterization (Blayi *et al.,* 2024). Conventional investigations often fail to capture the full variability of soils across swamp terrain, depressions, and elevated ridges, leading to underestimation of risks such as settlement, erosion, and lateral spreading (Abdulmumini *et al.,* 2024). The absence of integrated datasets further limits predictive modeling, reducing the reliability of engineering designs (Muhammad *et al.,* 2022). Hence the study aim to assess the engineering geotechnical characterization for pipeline infrastructure of Escravos–Odidi corridor in Niger Delta, Nigeria.

2.0. METHODOLOGY

2.1 Study Area

The study area is located within Warri South Local Government Area (LGA) of Delta State, Nigeria as shown in Fig1. The proposed development is a 30 km, 40-inch width onshore gas pipeline that will serve as a spur line connecting the Escravos Node to the Odidi Manifold. The pipeline Right-of-Way (ROW) extends approximately 30 km in length and 25 m in width, traversing predominantly swampy terrain within the Niger Delta creeks and wetlands. The Niger Delta climate is characterized by two main seasons: i. Dry Season: November to March (approximately 5 months). ii. Wet Season: April to October (approximately 7 months). The average annual rainfall is about 2,400 mm, making it one of the wettest regions in Nigeria. Vegetation is primarily composed of mangrove swamp forest, interspersed with freshwater swamp forest species such as raffia palms, bamboos, and dense hardwood trees. Topographically, the terrain is flat to gently undulating and dominated by marshy depressions. The soil is predominantly soft, peaty marine clay, which presents challenges for construction activities and requires careful geotechnical consideration for pipeline stability and support.

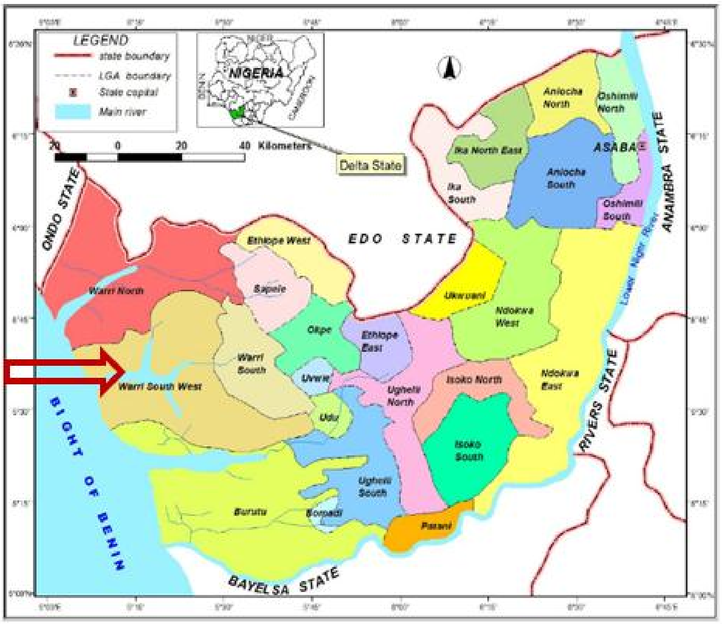

Fig 1: Map showing the study area marked with red arrow in Delta state Nigeria.

2.2 Site Geology

The project area lies within the Niger Delta Basin (Miocene–Recent), a prolific hydrocarbon province in Southern Nigeria that borders the Atlantic Ocean. The site geology is primarily that of the Niger Delta basin which forms the southern or bottom extension of the Nigerian sedimentary basin (See Figure 2a). The geology is composed of sediments which are characteristic of several depositional environments as the Benin River empties her load into the Atlantic Ocean. As the Benin River approaches the Atlantic Ocean, it leaves a surface deposit of marine clay which is commonly seen within the site. Geographically, the area covers a low-lying tropical rain forest with the whole of the Escravos to Odidi getting a heavy rainfall of approximately 2400mm or more per year. Stratigraphically, the Niger Delta is divided into three main lithostratigraphic units:

i. Akata Formation (Lower Unit): Marine shales with minor sand beds (deep subsurface). The Akata Formation consists mainly of thick marine shales deposited in a deep offshore environment.These fine-grained sediments were laid down under low-energy conditions and often contain high organic matter, making them the primary source rocks for hydrocarbons in the Niger Delta. Due to their depth and composition, they are typically overpressured and play a key role in hydrocarbon generation and migration.

ii. Agbada Formation (Middle Unit): This is characterized by alternating layers of sandstones and shales deposited in deltaic environment. The sandstones serve as excellent reservoir rocks, while the shales act as source rocks and seals. The unit hosts most of the oil and gas accumulations in the Niger Delta due to its favourable porosity, permeability and trapping structures.

iii. Benin Formation (Upper Unit): The Benin formation is composed ppredominantly of coarse-grained, unconsolidated sands with occasional clay interbeds, deposited in a continental environment. It forms the surface layer of the Niger Delta and its highly permeable, making it an important aquifer for groundwater supply. Its loose nature can lead to geotechnical challenges such as settlement and erosion.

Weathering processes, particularly intense tropical weathering and cyclical wetting and drying, have altered the near-surface clays, resulting in soils with variable strength and compressibility characteristics. The general topography is low-lying and flat, except at depressions that define creeks, tidal channels, and seasonal floodplains. The site soils consist mainly of very soft marine clays with occasional peat, which are of low bearing capacity and high compressibility, necessitating careful geotechnical evaluation.

During Quaternary age (last few million years) recent sediments were deposited and reworked from Tertiary sediments during sea-level transgressions and regressions. The area falls within the saltwater or mangrove swamps and coastal beaches (sand bars-beaches and bars) geomorphic subdivision of the Niger Delta, comprising Pleistocene and Recent sediments deposited by fluvial and shallow continental shelf hydrodynamic processes (see Figure 2b). Structurally, the terrain is flat and muddy and devoid of rocks of any form. The site is tectonically inactive with no incidence of tremor ever recorded.

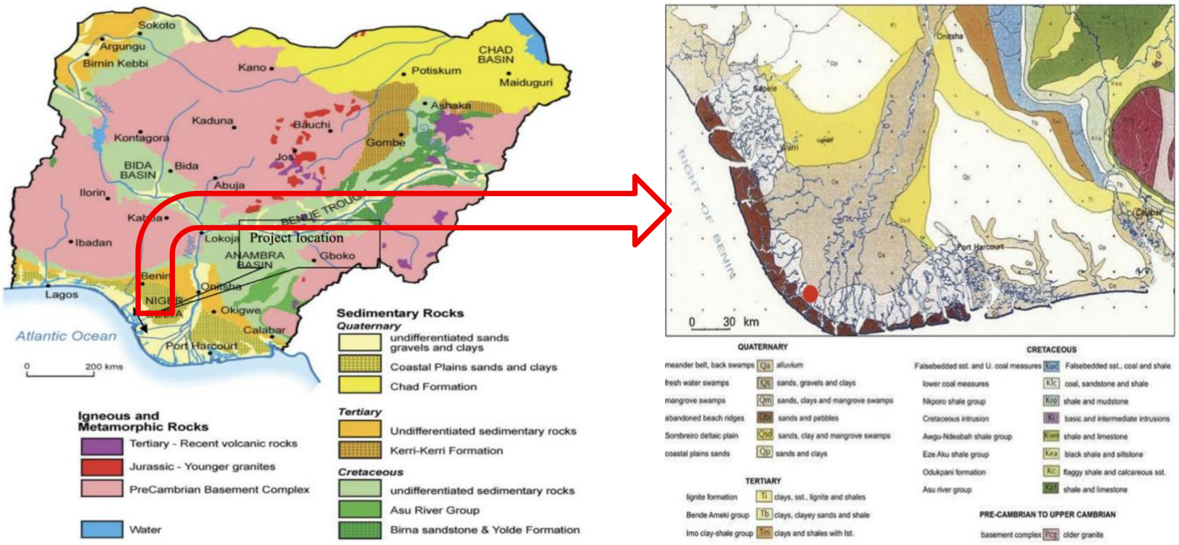

Fig 2: Map showing (a) Geological Map of Nigeria, (b) Regional Geology of the Niger Delta Area

2.3 Field Investigation

As shown in Figure 3, the field investigation comprised borehole drilling, topographic surveying of the pipeline corridor, and soil resistivity testing. Thirty boreholes, designated BH-1 to BH-30, were drilled using a hand auger rig. Soil samples were collected at 1.0 m intervals for visual assessment, laboratory analysis, and classification, particularly at locations exhibiting notable changes in soil lithology. During the August 2025 field campaign, the groundwater level at the site was typically 0 to 0.7 m below ground level. This level is subject to seasonal variation.

2.3.1 Borehole Drilling

The field investigation along the proposed pipeline route comprised a combination of subsurface exploration and in-situ testing to establish the geotechnical and geoelectrical characteristics of the Right of Way (RoW). The geotechnical investigation comprised mainly exploring thirty (30) number boreholes with soil sampling to 5.0m depth. The field work was carried out at the site between 14 August and 9 September 2025. A total of thirty boreholes were advanced to a depth of 5.0 m along the 30 km pipeline Right of Way (RoW). The boreholes were strategically distributed to capture representative subsurface conditions across swamp terrain, depressions, and elevated sections. This is done according to the borehole spacing in a linear corridor condition, which is mathematically given as;

$$S_{Avg} = \frac{L}{N} \quad 2.1$$

Where N is the number of boreholes, L is the length of the corridor and S_{Avg} is the average spacing. Cable percussive rigs were employed in areas of higher soil resistance, while hand augers were used in softer deposits to minimize disturbance. This dual approach ensured reliable penetration and accurate recovery of soil samples across variable stratigraphy (Akpokodje, 1987; Nwankwoala & Amadi, 2015). Representative disturbed samples were taken from the boreholes at 1.0m intervals on both cohesive and cohesionless soils encountered within the boreholes. The samples were for a systematic description of the soil encountered in the investigation.

2.4 Topographic Survey

Differential GPS (DGPS) Hi-Target Receivers operated in Real-Time Kinematic (RTK) mode to establish highly accurate geospatial coordinates for each borehole along the proposed pipeline corridor. The RTK technique corrected satellite positional errors in real time, achieving centimeter-level precision. This approach ensured that each borehole was referenced to a consistent geodetic framework. Such accuracy was critical for correlating subsurface geotechnical data with surface topographic features. A Leica Total Station, employing the ray method, captured terrain data across the 25-meter-wide Right of Way (ROW). This facilitated systematic documentation of both natural and man-made features, ensuring precise horizontal alignment of the pipeline corridor. The ray method radiated measurements from control points, efficiently acquiring data and minimizing cumulative survey errors. Complementing these instruments, Leica automatic levels were utilized to determine elevations at each borehole position. By conducting precise levelling loops tied to established benchmarks, vertical control was maintained throughout the survey. This ensured that borehole depths and stratigraphic profiles could be accurately referenced to a common datum, enabling reliable integration of geotechnical data with engineering design models. The combined use of DGPS, Total Station, and automatic levels provided a robust geospatial framework for the project. High positional accuracy along the pipeline corridor enabled detailed geotechnical profiling, while the integration of topographic and elevation data allowed for comprehensive characterization of the terrain. This facilitated the identification of soil variability, slope gradients, and potential geotechnical constraints that could influence pipeline design and construction. Moreover, the adoption of DGPS in RTK mode significantly minimized spatial error compared to conventional GPS methods, thereby enhancing the reliability of mapping soil heterogeneity across the ROW. Such precision is indispensable in pipeline engineering, where minor deviations in alignment or elevation can have substantial implications for structural integrity, safety, and long-term performance. The methodology ensured that the survey outputs were not only accurate but also compatible with advanced engineering design software, supporting seamless integration into the broader pipeline development workflow (Kennedy, 2024).

2.5 Soil resistivity test

The soil resistivity test is a geophysical method that measures the ground's electrical resistance, indicating its ability to conduct or resist electric current. This test was conducted using an ABEM SAS 300 Terrameter with a Schlumberger array electrode configuration. Current is introduced into the ground, and the resulting potential difference is measured across the electrodes. The resistivity values, influenced by factors such as soil type, moisture content, porosity, degree of saturation, and the presence of dissolved salts or organic matter, are compared with the standard table in Table 1. Results from selected test stations are presented in Figure 5. The Schlumberger array uses four electrodes, with the potential electrodes (M and N) positioned closer together than the current electrodes (A and B). For deeper readings, only the outer current electrodes are moved, while the potential electrodes typically remain fixed. The resistivity formula is as follows:

$$\rho = \frac{\pi}{L} \cdot \left(\frac{a^2 - b^2}{b}\right) \cdot R$$

where $a$is half the distance between current electrodes, $b$is half the distance between potential electrodes, and $L$is the electrode spacing factor.

3.0 RESULTS

Table 1 presents the soil resistivity values and corresponding corrosivity ratings of five soil samples (A–E), alongside their implications for buried metallic structures. Soil resistivity is a critical parameter in corrosion studies, as it reflects the soil's ability to conduct electrical current. Generally, low resistivity values indicate high ionic conductivity, which enhances electrochemical reactions and accelerates corrosion of buried metals. Sample A exhibited a soil resistivity of less than 500 Ohm·cm and was classified as very severely corrosive. This indicates extremely high electrical conductivity, likely due to elevated moisture content, dissolved salts, or high concentrations of ions such as chlorides and sulfates. Soils within this resistivity range pose a significant corrosion threat to underground metallic structures such as pipelines, storage tanks, and cables. The implication for buried metals is a high corrosion risk, necessitating aggressive protection strategies such as high-quality protective coatings, cathodic protection systems, and routine monitoring. Sample B recorded resistivity values between 500 and 1,000 Ohm·cm and was rated as severely corrosive. Although slightly less aggressive than Sample A, this soil still presents a substantial corrosion hazard. The moderately low resistivity suggests significant ionic mobility, which can facilitate corrosion processes. Protective coatings and cathodic protection are strongly recommended to prevent premature structural failure. Sample C had resistivity values between 1,000 and 2,000 Ohm·cm and was classified as moderately corrosive. This indicates a moderate risk environment where corrosion is possible but may occur at a slower rate compared to Samples A and B. Periodic inspection and selective application of protective measures would be appropriate in this case. The soil conditions suggest moderate moisture and electrolyte presence. Sample D exhibited resistivity values ranging from 2,000 to 10,000 Ohm·cm and was categorized as mildly corrosive. Higher resistivity reflects reduced electrical conductivity and lower availability of corrosive ions. Consequently, the corrosion risk to buried metals is relatively low. Basic protective measures, such as standard coatings, may suffice to ensure long-term structural integrity. Sample E showed resistivity values greater than 10,000 Ohm·cm and was classified as essentially non-corrosive. Such high resistivity indicates low ionic concentration and limited moisture content, conditions that are generally unfavorable for electrochemical corrosion processes. Buried metallic structures in this soil type are expected to have minimal corrosion risk and extended service life, requiring only minimal protective intervention. The results demonstrate a clear inverse relationship between soil resistivity and corrosivity: as resistivity increases from Sample A to Sample E, the corrosive potential decreases correspondingly. This trend aligns with established corrosion principles, where soils with low resistivity promote higher corrosion rates due to enhanced electrochemical activity. From an engineering perspective, the findings highlight the necessity of site-specific corrosion risk assessment before installation of underground metallic infrastructure. Samples A and B require immediate and comprehensive corrosion control strategies, while Samples D and E present more favorable conditions for buried metal durability.

Table 1: Soil resistivity and corrosivity ratings of soil samples

Soil sample	**Soil Resistivity (Ohm·cm)**	**Corrosivity Rating**	**Implication for Buried Metals**
A	**< 500**	Very severely corrosive	High corrosion risk: aggressive protection needed
B	**500 – 1,000**	Severely corrosive	Protective coatings and cathodic protection advised
C	**1,000 – 2,000**	Moderately corrosive	Monitor and apply protective measures as needed
D	**2,000 – 10,000**	Mildly corrosive	Low risk; basic protection may suffice
E	**> 10,000**	Essentially non-corrosive	Minimal corrosion risk; long service life expected

Table 2 presents the spatial coordinates, drilling depth, groundwater depth, and top-layer soil characteristics of five boreholes (BH-01 to BH-05) along the study alignment. These parameters provide important insight into subsurface conditions, groundwater occurrence, and geotechnical behavior of the study area. All boreholes were drilled to a uniform depth of 5.0 m. The consistency in drilling depth ensures comparability of subsurface conditions across locations and suggests that the investigation was designed to assess shallow subsurface characteristics relevant to foundation design or pipeline installation. Since corrosion and geotechnical stability are significantly influenced by near-surface soil conditions, a 5 m depth is appropriate for preliminary engineering assessment. Groundwater levels ranged from 5 m to 8 m. BH-01 and BH-04 recorded groundwater at 5 m, indicating relatively shallow water tables. BH-03 showed groundwater at 6 m, while BH-02 and BH-05 recorded deeper groundwater levels at 8 m. Shallow groundwater (5–6 m) suggests higher soil moisture content, which can significantly influence soil strength and corrosion potential. Moist soils enhance ionic mobility and may increase the risk of corrosion in buried metallic structures. Conversely, slightly deeper groundwater levels (8 m) may indicate comparatively drier near-surface conditions, although peaty soils can still retain substantial moisture even above the water table. The topsoil across the boreholes consisted primarily of soft clay (BH-01, BH-03, BH-04) and peaty clay (BH-02, BH-05). Soft clay is typically characterized by high compressibility, low shear strength, and high water content. These properties can lead to settlement issues and may create favorable conditions for corrosion due to moisture retention. Peaty clay contains significant organic matter, which increases soil acidity and moisture-holding capacity. Organic-rich soils often exhibit higher corrosivity because decomposition processes can produce organic acids and reduce soil resistivity. The occurrence of peaty clay in BH-02 and BH-05 suggests potentially more aggressive chemical environments compared to the predominantly soft clay locations. The boreholes are located at chainages 0+000 and 1+000 km, indicating two main alignment sections. Both sections exhibit similar shallow subsurface conditions dominated by clayey soils. The prevalence of cohesive soils (soft clay and peaty clay) indicates: Poor drainage conditions, High water retention capacity, Potential for differential settlement, Increased likelihood of corrosion for buried metallic installations. Areas with soft clay and shallow groundwater (e.g., BH-01 and BH-04) may require enhanced ground improvement techniques and corrosion protection measures. Meanwhile, locations with peaty clay (BH-02 and BH-05) may require careful chemical evaluation due to potential acidity and organic content.

Table 2: Borehole characteristics and depth

Borehole ID	Chainage (km)	Latitude	Longitude	Depth (m)	Groundwater Depth (m)	Soil Type (Top Layer)
BH-01	0+000	769746.544	615198.312	5.0	5	Soft clay
BH-02	1+000	744759.16	617700.967	5.0	8	Peaty clay
BH-03	0+000	772237.192	615442.411	5.0	6	Soft clay
BH-04	1+000	761312.524	615190.255	5.0	5	Soft clay
BH-05	0+000	767178.427	15167.119	5.0	8	Peaty clay

Table 3 presents the geotechnical and chemical characteristics of soils obtained from selected boreholes (BH-01, BH-02, BH-10, BH-20, and BH-30). The parameters evaluated include moisture content, Atterberg limits (Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI), soil pH, and the Unified Soil Classification System (USCS) classification.

These parameters are critical in determining soil behavior, strength, compressibility, and potential corrosivity. The natural moisture content ranged from 74% to 85%, with BH-20 recording the highest value (85%) and BH-10 the lowest (74%). These values are relatively high and indicate that the soils are water-saturated or near saturation. High moisture content is typical of clayey soils and significantly affects engineering performance by reducing shear strength and increasing compressibility. Elevated moisture also enhances electrical conductivity, which may increase corrosion risk for buried metallic structures. The Liquid Limit (LL) ranged between 55% and 70%, while the Plastic Limit (PL) ranged from 28% to 33%. The resulting Plasticity Index (PI) varied from 27% to 38%. Boreholes BH-02 and BH-20 exhibited the highest LL (70% and 68%) and PI (38% and 35%), indicating highly plastic soils. BH-10 recorded the lowest LL (55%) and PI (27%), suggesting comparatively lower plasticity. Plasticity Index values above 20% generally indicate highly plastic clay with significant volume change potential. The PI values (27–38%) observed in this study confirm that the soils are highly plastic and prone to shrink-swell behavior. Such soils may undergo considerable deformation under load or moisture variation, posing challenges for foundation stability and underground installations. The pH values ranged from 5.8 to 6.8, indicating slightly acidic to nearly neutral soil conditions. BH-02 (5.9) and BH-20 (5.8) were more acidic. BH-10 (6.8) was closest to neutral. Slightly acidic soils can contribute to corrosion of buried metals, particularly when combined with high moisture content and clayey texture. The relatively lower pH in CH soils (BH-02 and BH-20) suggests a potentially more aggressive chemical environment compared to CL soils. According to the Unified Soil Classification System: BH-01, BH-10, and BH-30 were classified as CL (Lean Clay). BH-02 and BH-20 were classified as CH (Fat Clay). Lean clays (CL) are inorganic clays of medium plasticity, generally exhibiting moderate compressibility and strength. Fat clays (CH) are highly plastic clays with high compressibility, low permeability, and significant swelling potential. The presence of CH soils in BH-02 and BH-20 indicates more problematic ground conditions due to their high plasticity and moisture retention capacity.

Table 3: Borehole soil characteristics

Borehole ID	Moisture Content (%)	LL (%)	PL (%)	PI (%)	pH	USCS Classification
BH-01	82	65	30	35	6.2	CL (Lean Clay)
BH-02	78	70	32	38	5.9	CH (Fat Clay)
BH-10	74	55	28	27	6.8	CL (Lean Clay)
BH-20	85	68	33	35	5.8	CH (Fat Clay)
BH-30	80	62	29	33	6.4	CL (Lean Clay)

Figure 1 presents a generalized soil and rock resistivity chart illustrating the typical resistivity ranges (in Ohm·m) of various geological materials, sediments, and groundwater types. The chart provides a comparative framework for interpreting measured soil resistivity values and assessing their implications for corrosion potential and subsurface characterization. The figure demonstrates that resistivity varies widely depending on mineral composition, moisture content, porosity, degree of weathering, and electrolyte concentration. Materials such as **massive sulfides**, **graphite**, and **salt water** occupy the lowest resistivity range (<1 Ohm·m), reflecting their high electrical conductivity. These materials are typically associated with aggressive corrosion environments due to enhanced ionic mobility. Conversely, **igneous and metamorphic rocks**, especially unweathered shield rocks, show very high resistivity values (often exceeding 1,000–10,000 Ohm·m). These materials are generally dry, compact, and low in pore water content, thereby limiting electrochemical activity and reducing corrosion risk. Clays are shown within the low to moderate resistivity range. Their relatively low resistivity is attributable to: High surface area and cation exchange capacity, Significant moisture retention, Presence of dissolved salts. This confirms that clay-rich soils such as those identified in the borehole analysis (CL and CH soils) are likely to exhibit moderate to high corrosivity. High plasticity clays (CH) are especially prone to lower resistivity due to greater water and ion retention. Wet gravel and sand occupy intermediate resistivity ranges. Although sandy soils generally have higher resistivity due to lower surface area and reduced water retention, saturation significantly lowers resistivity values. Therefore, groundwater presence is a critical factor influencing corrosion potential in sandy formations. The chart clearly distinguishes between salt water and fresh water: **Salt water** exhibits extremely low resistivity due to high ionic concentration, making it highly corrosive. **Fresh water** has moderate resistivity, indicating lower but still significant conductivity. This reinforces the importance of groundwater chemistry in corrosion assessment. Areas with shallow groundwater and dissolved salts may show substantially reduced resistivity values.

The chart also illustrates the distinction between unweathered bedrock and weathered layers (saprolite, mottled zones, duricrust). Weathered materials generally show lower resistivity than intact bedrock because weathering increases porosity, moisture infiltration, and ionic mobility. Thus, near-surface soils and weathered zones are typically more corrosive than deeper, intact rock formations. When interpreted alongside the soil resistivity classifications in Table 1, Figure 1 provides a geological explanation for corrosivity ratings: Very low resistivity soils (<1,000 Ohm·cm) likely correspond to clayey, saturated, or saline environments. Moderate resistivity soils (1,000–10,000 Ohm·cm) may reflect sandy-clayey mixtures or moderately weathered materials. High resistivity soils (>10,000 Ohm·cm) suggest dry, coarse-grained soils or intact bedrock with minimal corrosion risk. The dominance of clayey soils and high moisture content in the borehole data suggests that the study area likely falls within the low to moderate resistivity range of the chart, supporting earlier conclusions regarding potential corrosion susceptibility.

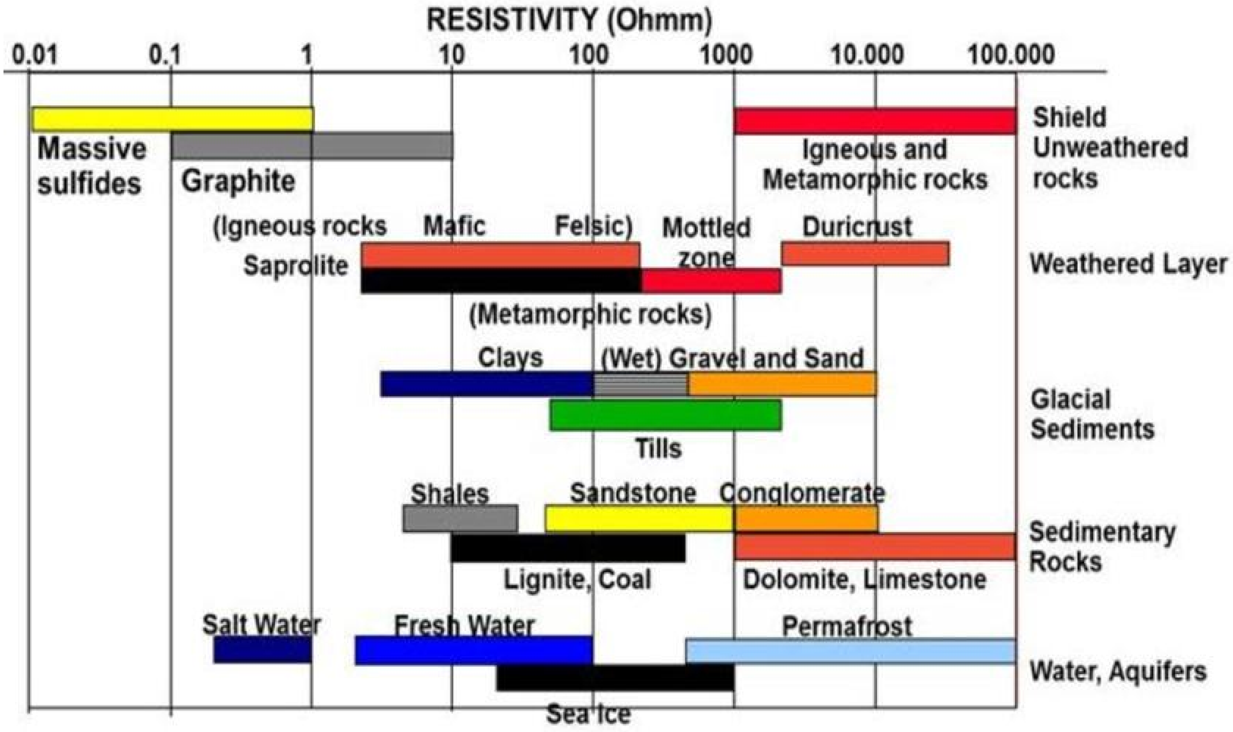

Figure 1: Soil resistivity chart

Table 4 presents the field resistivity measurements obtained using the electrical resistivity method (likely Schlumberger array configuration), showing electrode spacing (AB/2 and MN/2), measured resistance (R), and calculated apparent resistivity (ρ) in Ohm·m. These results provide insight into subsurface layering, lithological variations, and potential corrosivity of the soil profile. The AB/2 values increase progressively from 1 m to 120 m, indicating increasing depth of investigation. As electrode spacing increases, the current penetrates deeper layers, thereby reflecting vertical changes in subsurface materials. At shallow depths (1a–1c; AB/2 = 1–5 m), resistivity values range from 4.08 to 25.59 Ohm·m. The very low value of 4.08 Ohm·m (1a) suggests a highly conductive near-surface layer, likely composed of clayey, water-saturated, or organic-rich soil. Such low resistivity indicates high corrosivity potential. At moderate spacings (2a–2c; AB/2 = 10–30 m), resistivity values range from 17.60 to 77.08 Ohm·m. These values suggest a transition from highly conductive clay-rich soils to slightly less conductive materials. The variability may reflect heterogeneity in soil composition, such as alternating clay and sandy clay layers or variations in moisture content. Further increases in spacing (3a–3c; AB/2 = 40–60 m) show a substantial rise in resistivity, ranging from 138.29 to 273.81 Ohm·m. This sharp increase indicates the presence of a more resistive subsurface layer, possibly sandy clay, lateritic material, or partially weathered bedrock. Higher resistivity at this depth suggests reduced moisture content or lower ionic concentration. At greater spacings (4a–4c and 5a–5c; AB/2 = 70–120 m), resistivity values fluctuate between 110.00 and 297.26 Ohm·m. These values remain relatively high compared to the shallow layers, indicating that deeper subsurface materials are significantly less conductive. The slight variations may represent stratified formations with alternating clayey and sandy units. From a corrosion perspective: Resistivity values below 50 Ohm·m (e.g., 4.08, 12.53, 17.60 Ohm·m) indicate highly aggressive soil conditions for buried metallic structures. Values between 50–200 Ohm·m suggest moderate corrosion risk. Values above 200 Ohm·m indicate relatively low corrosivity. Therefore, shallow installations are at higher corrosion risk compared to deeper placements. Protective coatings and cathodic protection systems would be particularly necessary in the upper soil horizons.

Table 4: Soil samples resistivity values

Soil sample	**AB/2[m]**	**Mn/2[m]**	**R[Ω]**	**ρ (Ohmm)**
1a	1	0.2	0.520	4.08
1b	2.5	0.2	0.521	25.59
1c	5	0.2	0.0653	12.53
2a	10	2.0	0.303	25.59
2b	20	2.0	0.056	17.60
2c	30	2.0	0.109	77.08
3a	40	5.0	0.340	170.97
3b	50	5.0	138.29	138.29
3c	60	5.0	273.81	273.81
4a	70	8.0	0.309	297.26
4b	80	8.0	214.97	214.97
4c	90	8.0	160.70	160.70
5a	100	10.0	0.070	110.00
5b	110	10.0	220.57	220.57
5c	120	10.0	273.81	273.81

4.0 DISCUSSION

The resistivity values obtained in Table 4 show very low resistivity at shallow depths (4.08–25.59 Ωm), moderate resistivity at intermediate depths (17.60–77.08 Ωm), and higher resistivity at deeper layers (110–297 Ωm). This vertical trend suggests a conductive, clay-rich, moisture-saturated surface layer overlying relatively more resistive formations. This pattern is consistent with the findings of Wijewickreme and Weerasekara (2019), who reported that clayey and waterlogged soils typically exhibit resistivity values below 50 Ωm and are highly aggressive toward buried metallic structures. Similarly, Oyedele *et al.* (2019) emphasized that soil resistivity below 100 Ωm significantly increases corrosion rate due to enhanced ionic mobility. The extremely low resistivity value of 4.08 Ωm observed in the shallow layer agrees with the classification by NACE International (2013), which identifies soils with resistivity below 1,000 Ωcm (10 Ωm) as severely corrosive. Comparable studies by Jomata *et al.* (2022) in southwestern Nigeria reported shallow resistivity values ranging from 5–30 Ωm in clay-dominated terrains, which were associated with high corrosion susceptibility of buried pipelines. The progressive increase in resistivity with depth observed in this study aligns with the general geoelectrical model described by Kennedy (2024), where deeper layers often show higher resistivity due to reduced moisture content and increased compaction or transition to weathered bedrock.

The borehole results showed high moisture contents (74–85%), high liquid limits (55–70%), and plasticity indices (27–38%), classifying the soils predominantly as CL (lean clay) and CH (fat clay). These results indicate highly plastic, compressible soils with strong water retention capacity. According to Khan *et al.* (2021), clays with PI values above 20% exhibit high shrink–swell potential and significant moisture retention, which lowers resistivity and enhances corrosive activity. The findings also agree with Butchibabu *et al.* (2021), who reported that CH soils in the Niger Delta region showed lower resistivity and higher corrosion rates compared to sandy formations. The slightly acidic pH values (5.8–6.8) further support corrosion susceptibility. John *et al.* (2023) noted that acidic soils accelerate electrochemical reactions by increasing hydrogen ion concentration, thereby increasing metal dissolution rates. Similar observations were made by Olofinyo *et al.* (2019) who stated that corrosion rate increases as soil pH decreases below neutral conditions. Groundwater depths ranging from 5–8 m indicate relatively shallow water tables in some locations. The presence of shallow groundwater enhances soil moisture and electrolyte concentration, thereby reducing resistivity and increasing corrosion risk. This observation is consistent with findings by Vincent and Mallo (2023), who reported that corrosion rates are significantly higher in saturated soils compared to unsaturated soils due to continuous ionic conduction. Likewise, Khahro (2022) observed that areas with shallow groundwater in southeastern Nigeria exhibited lower resistivity and higher pipeline deterioration rates.

The resistivity values recorded in this study fall within the range typically associated with clay, wet sand, and weathered materials, as shown in standard resistivity charts (Ashioba and Udom, 2023). The shallow low-resistivity zone corresponds to clay-rich, conductive materials, while deeper higher-resistivity layers likely represent sandy clay or partially weathered bedrock. Similar vertical resistivity trends were documented by Kinde *et al.* (2024), who identified a three-layer geoelectric structure in clay-dominated terrains: Conductive topsoil, transitional weathered layer, more resistive substratum. The present findings strongly conform to this model. The dominance of clayey soils, high moisture content, shallow groundwater, and low resistivity at near-surface levels collectively indicate moderate to severe corrosion potential in the study area. This aligns with the corrosion severity classifications reported by Tiwari and Ajmera (2023). Studies by Barman and Dash (2022) also showed that pipelines installed in clayey terrains with resistivity below 50 Ωm experienced accelerated deterioration unless cathodic protection systems were applied. The present study therefore supports existing recommendations that protective coatings and cathodic protection are essential in low-resistivity environments. The results of this study are consistent with established geotechnical and corrosion research. Specifically: Low resistivity correlates with clay-rich, moisture-saturated soils. High plasticity soils exhibit greater corrosion potential. Slightly acidic pH enhances electrochemical activity. Shallow groundwater reduces soil resistivity and increases aggressiveness. The findings align closely with previous studies of Abdulmumini *et al.* (2024);

Blayi *et al.* (2024); Xiao *et al.* (2024); Muhammad, *et al.* (2022); de Lima and Keller (2021). conducted in similar tropical and clay-dominated environments. Therefore, the study confirms established theoretical relationships between soil resistivity, moisture content, soil plasticity, and corrosion potential, while providing localized baseline data for infrastructure design and corrosion management within the study area.

5.0 CONCLUSION

This study evaluated the geotechnical and geoelectrical characteristics of soils within the study area with the aim of assessing their corrosion potential and implications for buried metallic infrastructure. The integration of soil resistivity measurements, borehole lithological data, Atterberg limits, moisture content, pH, and USCS classification provided a comprehensive understanding of subsurface conditions. The results revealed that the study area is predominantly underlain by clayey soils classified as CL (lean clay) and CH (fat clay), characterized by high moisture content (74–85%), high liquid limits (55–70%), and high plasticity indices (27–38%). These properties indicate highly plastic, compressible soils with strong water retention capacity and low permeability. Such soils are generally associated with low electrical resistivity and increased corrosion susceptibility. Resistivity measurements showed very low values at shallow depths (as low as 4.08 Ωm), indicating highly conductive and potentially aggressive environments. Resistivity generally increased with depth, suggesting a transition from conductive clay-rich surface layers to more resistive subsurface formations. Based on standard corrosion classification systems, the shallow subsurface environment ranges from moderately to severely corrosive, posing significant risk to buried metallic structures. The slightly acidic to near-neutral pH values (5.8–6.8), combined with shallow groundwater levels (5–8 m), further enhance the electrochemical conditions favorable for corrosion processes. The overall geoelectric profile suggests a three-layer model comprising a conductive topsoil, a transitional weathered zone, and a more resistive deeper layer. The study area exhibits moderate to high corrosion potential, particularly within shallow clayey horizons. Without adequate protective measures such as high-quality coatings and cathodic protection systems, buried metallic infrastructure may experience accelerated deterioration. The findings provide essential baseline data for geotechnical design, corrosion risk assessment, and long-term infrastructure management within the study area.

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