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Evaluation of Factors of Soil Resistivity in the Niger Delta

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Abstract

Soil conductivity is responsible for its aggressive behavior to metallic objects either in contact or buried in the ground. Rapid deterioration and eventual rupture of pipelines leading ultimately to crude oil spillages have been of economic as well as environmental concern. Although many factors contribute to soil resistivity, these relationships have hardly been quantitatively expressed. This paper explores the factors affecting soil resistivity firstly by matching the spatial regional distribution with each of the identified factors of influence, including ground elevation soil type, depth to water table and undrained strength. 183 Vertical Electrical Sounding VES with the ABEM SAS 1000, using Schlumberger electrode configuration were carried out along a pipeline route to generate resistivity distribution across a linear alignment that traverses three geomorphic sub-environments in the Niger Delta Region. The apparent resistivity values averaged over depths of 3 m and 10 m were plotted against the co-ordinates using Surfer-16 and overlaid on Google earth Pro to produce a spatial distribution with enhanced location visibility. The results show that apparent resistivity is influenced by depth to water table with lower values in areas of shallow water table occurrence. Furthermore, it is shown that changes in resistivity below the water table are more due to variation in soil type. Within a soil type above the water table, soil resistivity increases monotonically with depth until the depth of probe extends to a different soil horizon. Results of this study provide guidance as to what ground resistivity to expect in different part of the delta as well as provide valuable information to assess the risks to assets either as a means of prioritizing maintenance or of improving design for new installations in the Niger Delta Region.

Keywords

Factors, Resistivity, Aggressivity, VES, Environment of Deposition

1. Introduction

The purpose of this study is to explore the influence of depositional environment on the measured resistivity by analyzing soil and environmental factors contributing to soil resistivity in different geomorphic zone of the Niger Delta Region. An extensive and intricate network of pipelines have been developed in the more than 60 years of exploration, production and transportation of crude in the region associated with a history of frequent crude oil leakages often attributed to corrosion. According to Ordinioha and Brisibe (2013) over 7000 oil spill incidents were recorded between 1958 and 2012 which gives a yearly average of about 240,000 barrels with significant health exposures and impact. In their studies, Obida et al. (2017) generated a spatial distribution of pipeline spills between 2007 and 2015. Whanda et al. (2016) performed a geospatial analysis of oil spill distribution and susceptibility in the Niger Delta Region of Nigeria in which they identified locations of repeated oil spill events which he associated with close proximity to communities. This support the fact it is difficult to link the distribution or even frequency of these spills to the environment of deposition, since pipeline spills can be caused by a multitude of factors and are subject to route and length. What is evident, however, is that corrosion of pipeline is hastened by soil conductivity which is the inverse of resistivity.

Previous studies have linked the variation in the spatial distribution of the subsurface resistivity to a combination of influencing factors such as elevation above mean sea level, depth to water level and soil and groundwater quality, soil type and physical property (Corcoran et al., 1977; Agunloye, 1984; Khare & Nahar, 1997; Norhazilan et al., 2012; Afa & Anaele, 2010), but without empirical evidence. Water is essential for the corrosion reaction to take place, and soils with a moisture content above 20% are thought to be particularly corrosive (Khare & Nahar, 1997). Soil acidity: The dissolution of metals is facilitated by acidic conditions. Consequently, the lower the pH, the higher the corrosion rate. Soil aeration on the other hand is considered to promote corrosion, especially if they contain soluble sulphates. Bacteria reduce sulphates to sulphides, and the corresponding oxidation of elemental hydrogen is the reaction which involves them in corrosion mechanisms (Okiongbo et al., 2021). By far the most important factor, soil resistivity provides a measure of the concentration of soil electrolyte, which is essential in the corrosion process. Soils with low resistivity will encourage corrosion, i.e. the lower the resistivity of the soil, the higher the corrosion rate.

The overwhelming significance of resistivity was emphasized by Palacky (1987) when he described the relationship between environmental factors and the corrosive nature of soil, and reported that the soil resistivity has the most profound effect on soil corrosivity. In addition to being a valuable aid when interpreting the severity of corrosive areas, the determination of an appropriate ground-bed location for optimum cathodic protection system, and the design of the cathodic protection are essentially based on shallow *in-situ* soil resistivity (Peabody, 1967).

Keller and Frischknecht (1996) suggested that evidence concerning a subsurface soil type, its moisture content and aggressivity can be revealed from surface resistivity measurements. The soil electrical resistivity indicates the relative capability of the soil to carry electrical current. It is a main indicator of the corrosiviness of soils, as the rate of corrosiveness is a function of the electrical conductivity. Khare and Nahar (1997) reported that the electrical resistivity is closely related to the soil properties, such as water content, salinity, soil texture, etc., as the rate of corrosion is a function of the electrical conductivity. The objective of the paper therefore is to explore the presence and intensity of these factors of influence within the environments of deposition and analyze their contribution to aggregate soil resistivity. Understanding the factors of influence should provide tools to better assess the risks to assets either as a means of prioritizing maintenance or liability or of improving design for new installation.

2. Methodology

Spatial distribution of resistivity within the Niger Delta Region was generated using 350 VES performed at different geo-referenced locations. All pertinent field precautions were observed to ensure good VES data quality, including electrode installation in firm ground, checking for current leaks and creeps to avoid spurious measurements, avoiding existing pipeline alignments to avoid conductivity interference with the pipeline. The ABEM Terameter, Model SAS 1000, was used for fieldwork to acquire all the data. These VES were performed with either Wenner or Schlumberger electrode configurations. The apparent resistivity for each depth of probe was computed for the data sets for each electrode configuration. Apparent resistivity for depth windows 0 - 3 m and 0 - 10 m were averaged to represent shallow underground use in line with current practice and potential design depths for possible future pipeline infrastructure. The geospatial distribution of each set of apparent resistivity was generated user Surfer-16 and overlain on Google-Earth Pro for enhanced location visualization. Furthermore, boreholes lithologs and undrained strength derived from Cone Penetration Tests (CPT) points proximal VES points were correlated with apparent resistivity.

3. Geology and Geomorphology of the Study Area

The Niger Delta was formed in the Tertiary (Ekweozor & Daukoru, 1984) and remains an active area of sedimentation. The present-day delta is a complex of individual fluviomarine systems that have succeeded one another in a stepwise fashion as the delta prograded towards the southwest (Doustt, 1987). The area slopes gently from north to the south where it grades into the Continental shelf.

Elevation varies from about 50 m in the north to 0 m above mean sea level in the coastal fringes. The geology of the region is dominated by three lithostratigraphic units, Akata, Agbada and Benin Formations, overlain by various types of Quaternary deposits (Short & Stauble, 1967; Allen, 1965), all of which are of no direct engineering significance to pipeline construction. The Quaternary sediments overlying the Benin Formation consist of six geomorphic sub-environments (**Figure 1**), namely: Meander belt with back swamps which consists of alluvium, Fresh water swamps comprising of sands, gravels and clay, Mangrove swamps, Abandoned beach ridges also called Barrier Islands, Sombreiro-Warri Deltain Plain and the Coastal Plain sands. The network of pipelines described earlier is usually embedded in these units, which comprise alluvial and hydromorphic soils and lacustrine sediments of Pleistocene age and which sediments thickness vary from 0 - 30 m.

4. Results and Discussions

Results of the spatial distribution of apparent resistivity averaged across 0 - 3 m

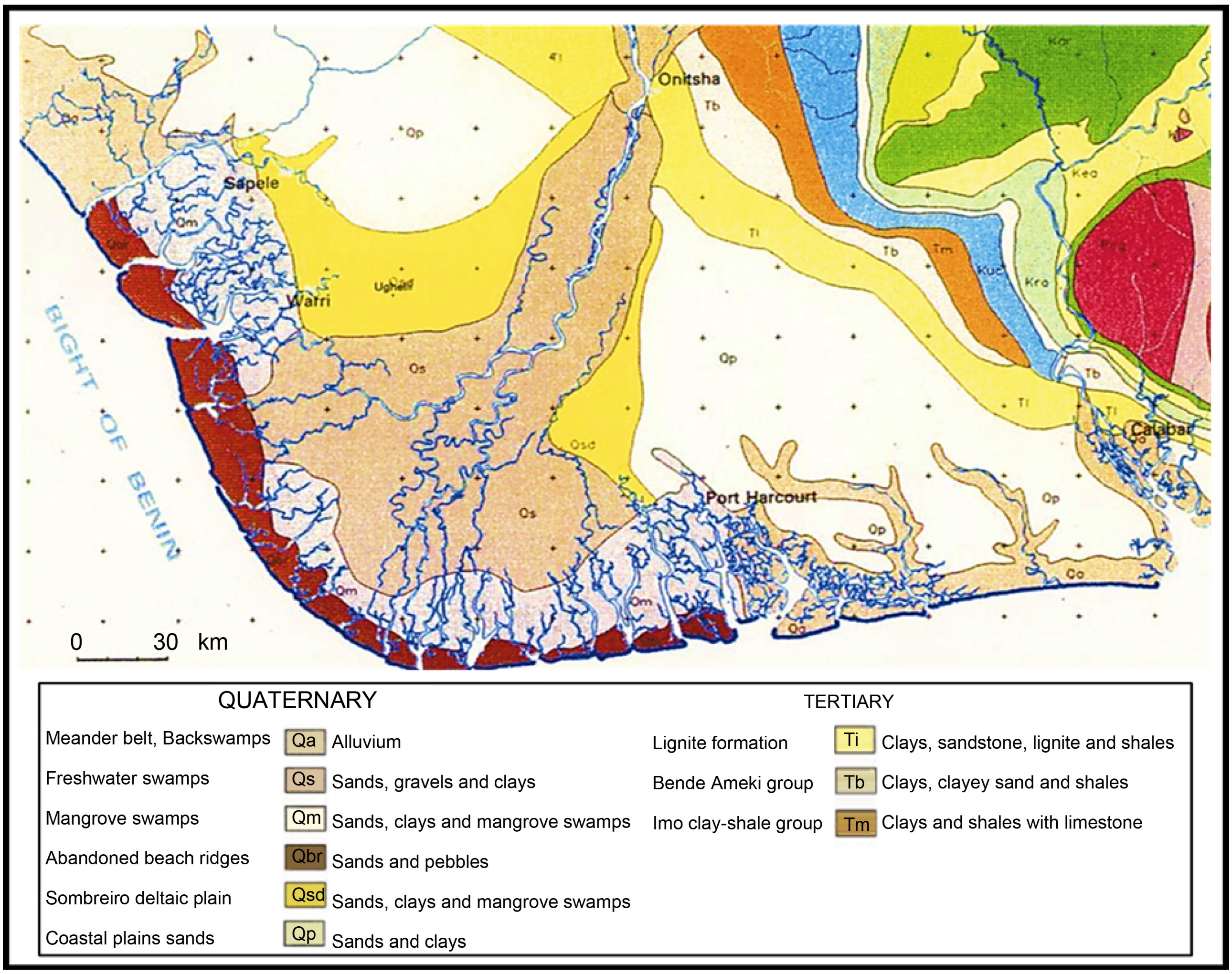

Figure 1. Distribution of Quaternary sediments in the Niger delta (Reijers, 2011).

and 0 - 10 m below ground surface are presented in Figures 2-5. Figure 2 covers the entire Niger Delta with the apparent resistivity ranging from 0 - 3500 ohm-m. This wide range in apparent resistivity is accounted for by the presence of very diverse soil types and conditions. Due to the large scale of this map, many sub-classes of resistivity are indistinguishable.

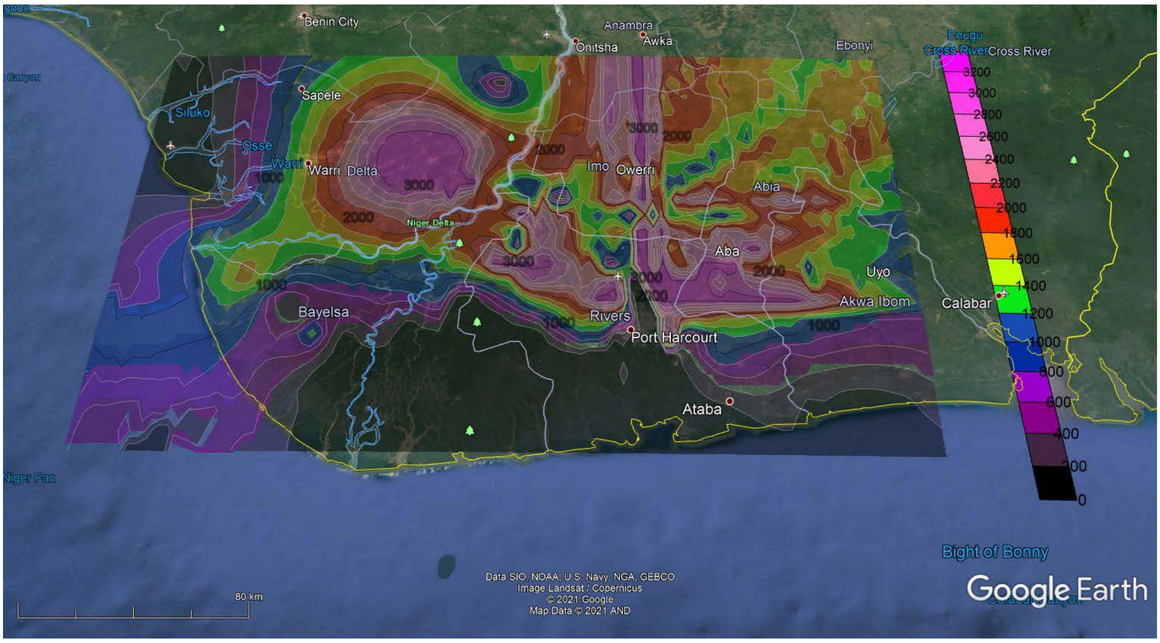

Figure 2. Spatial variation of apparent resistivity averaged over (0 - 3 m) for 0 - 3400 ohm-m.

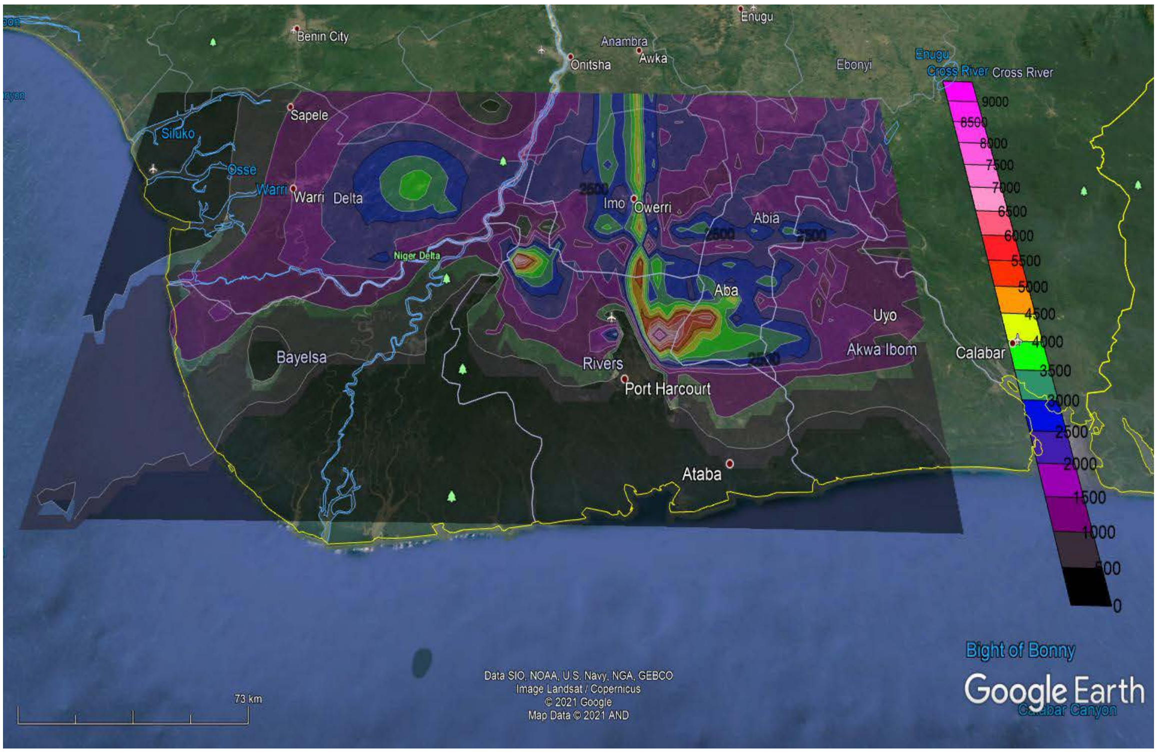

Figure 3. Spatial variation of Apparent Resistivity averaged over (0 - 10 m) for 0 - 9000 ohm-m.

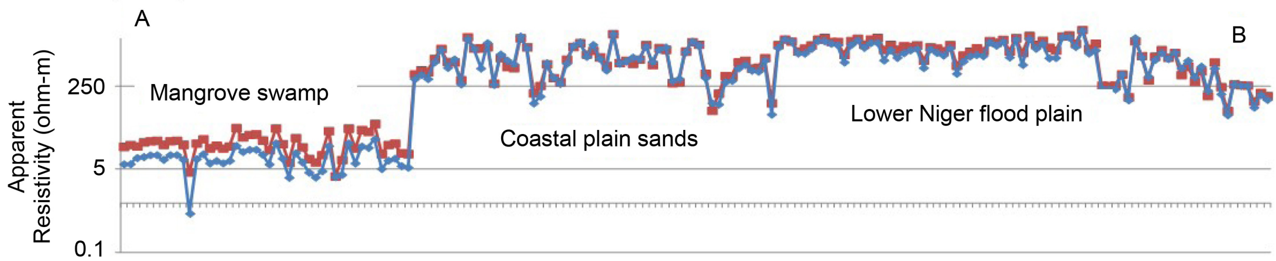

Figure 4. Apparent Resistivity of surface layers (0 - 3 m and 0 - 10 m) along the traverse in the Eastern Niger Delta.

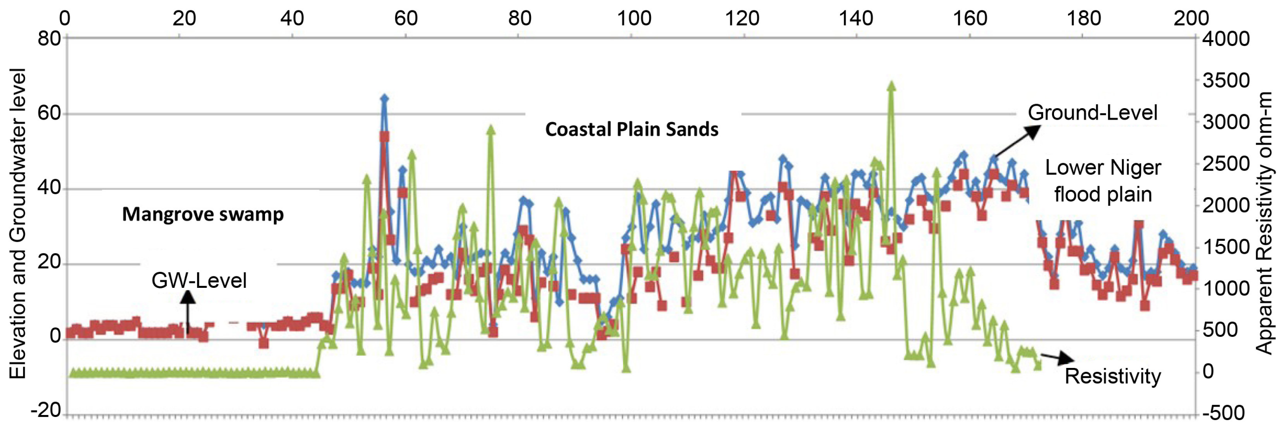

Figure 5. Groundwater surface elevation and apparent resistivity along the traverse in the Eastern Niger Delta.

A smaller scale on the other hand can capture ground resistivity variations in line with the BS-1377 classification scheme as described by Abam et al. (2021). Results of the spatial distribution of apparent resistivity averaged over 0-10m depth below ground surface are presented in **Figure 3**. This figure showed that average resistivity increased with depth in the soil horizons above the water table.

To further explore the variation of resistivity with depth, a linear profile of soil resistivity across the Nigger delta from Cawthorne Channel to Obrikom reference is made to the work by Abam (2016) in which averaged soil resistivity for 0 - 3 ohm-m and 0 - 10 ohm-m were effectively compared (**Figure 4**). Fortunately, this profile also traversed different geomorphic zones, and established typical values for each geomorphic zone. As expected, the lowest resistivities were recorded in the mangrove swamps with the combination of high salinity, high water level and preponderance of silty and organic clay, confirming earlier findings of Osakuni and Abam (2004). There is also a distinctive increase with depth as shown by the difference in apparent resistivity between the 0 - 3 m and that of 0 - 10 m depth profiles. This difference is nonexistent in the other areas because of the near homogeneous composition of the soil and fairly consistent groundwater level.

The results of this study show that areas with higher elevation tend to have higher resistivity values as the ground is generally drier. The variation of both surface elevation and groundwater level along a traverse from Cawthorne Channel to Obrikom, a distance of 183 km and cutting across three geomorphic sub-environments in the Eastern Niger Delta is presented in Figure 2. The maximum depths to groundwater (7 - 10 m) are recorded in the more elevated areas which comprise freshwater forest. This is followed by the floodplain areas which recorded 0 - 5 m, the Beach ridges 0 - 1.5 m and the mangrove swamp areas with depth to groundwater between 0 - 0.5 m with the lower limits representing the wet season scenarios.

A plot of depth to water table and apparent resistivity (Figure 6) show that they are generally correlated although with significant scatter due to the other factors of interest.

Figure 5 further shows approximate ground elevation above mean sea level captured from a GPS in a gradual decent to the Atlantic coastline. This gradual decent in elevation towards the sea cuts across the region as shown by (Figure 7).

Furthermore, results show that the most severe sub-environments with the least resistivity and by extension most corrosive are at low elevations in poorly drained soils which in this case are the salt water and mangrove swamp estuary complex, coastal creeks, meander belts and wooded back swamps and coastal beaches and Islands) such as clays and tidal marshes and in this respect are consistent with the findings of Schwerdtfeger (1965), Afa and Ngobia (2013).

There is also a degree of season dependence of resistivity. This is evidenced by recording of consistently higher resistivity values during the dry season at three locations in Brass, Amassoma and Ogbia by Afa and Ngobia (2013). These ranges of groundwater level fluctuation due to seasonal changes in rainfall intensity coincide with the depths of interest to pipeline placement. The season dependence of groundwater level is manifested as a degree of full column saturation. Thicker unsaturated and discontinuous water columns are developed in the topsoil horizon in the dry season with less rainfall in comparison with the wet

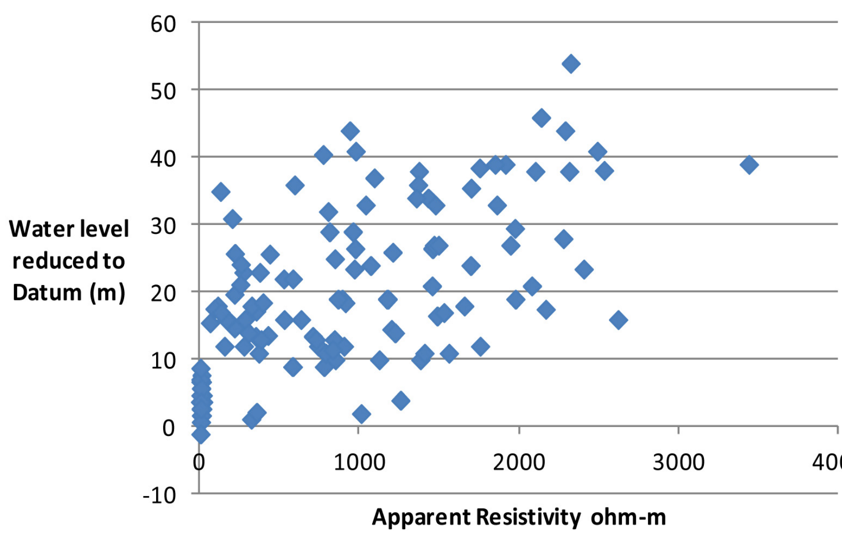

Figure 6. Correlation groundwater level and resistivity along Cawthorne Channel-Obrikom.

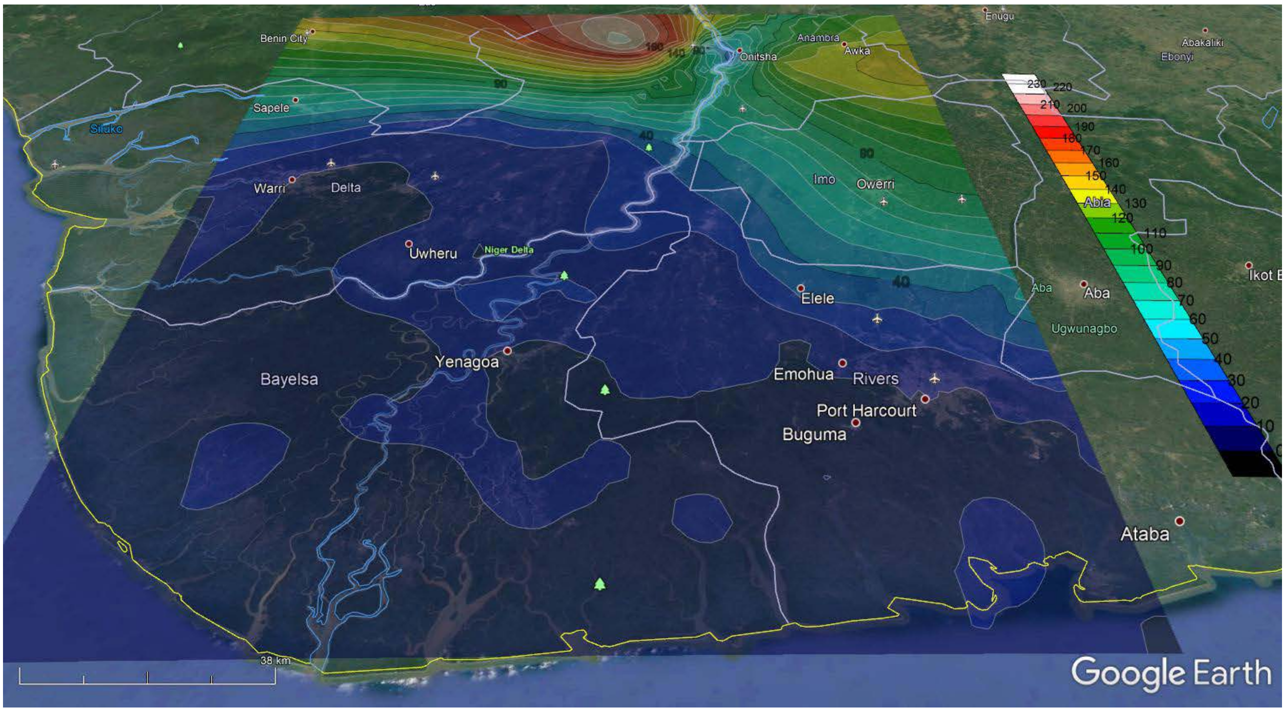

Figure 7. Distribution of Surface Elevation.

season when soils could often be submerged as a result of prolonged rainfall. However, the effect of seasonal influence is diminished with depth and disappears completely below the water table.

The relationship between soil type, physical property of the soils and apparent resistivity is explored in (**Figures 8-10**) for three sub-environments. The coastal plain lowland and lower flood plains of the freshwater swamps consist of soil types that are red ferralsols and dry, soft-firm-stiff, reddish yellow-brown-grey podzol overlying loose coastal sands exhibited relatively high resistivity due to interplay of low moisture regime, low degree of saturation, presence of non-conductive iron oxide in the soil.

The relatively low soil resistivity in the coastal creeks (**Figure 9**), meander belts, and wooded backswamps (**Figure 10**) which are characterized by riverine and lacustrine deposits is on account of the very high-water table, high saturation, preponderance of soft clay in the soils. The mangrove swamps and estuary complexes all of which have some degree of saline content registered the lowest resistivity values and are characterized by soils rich in organic matter, consisting of very soft-soft peaty and bog soil, dark-grey-black organic clay, overlying fine sand deposits. Peaty and bog soils are poorly drained soils rich in organic matter with high humic acid concentrations that result in a high acidity level in the soil responsible for the high aggressivity of the soil. This combination of conditions results in high water saturation, thus enabling high ionic mobility.

Furthermore, not only is the water table encountered at deeper levels but the water quality changes from more conductive saline water in the predominantly mangrove areas to freshwater in the northern section of the delta. The comparatively

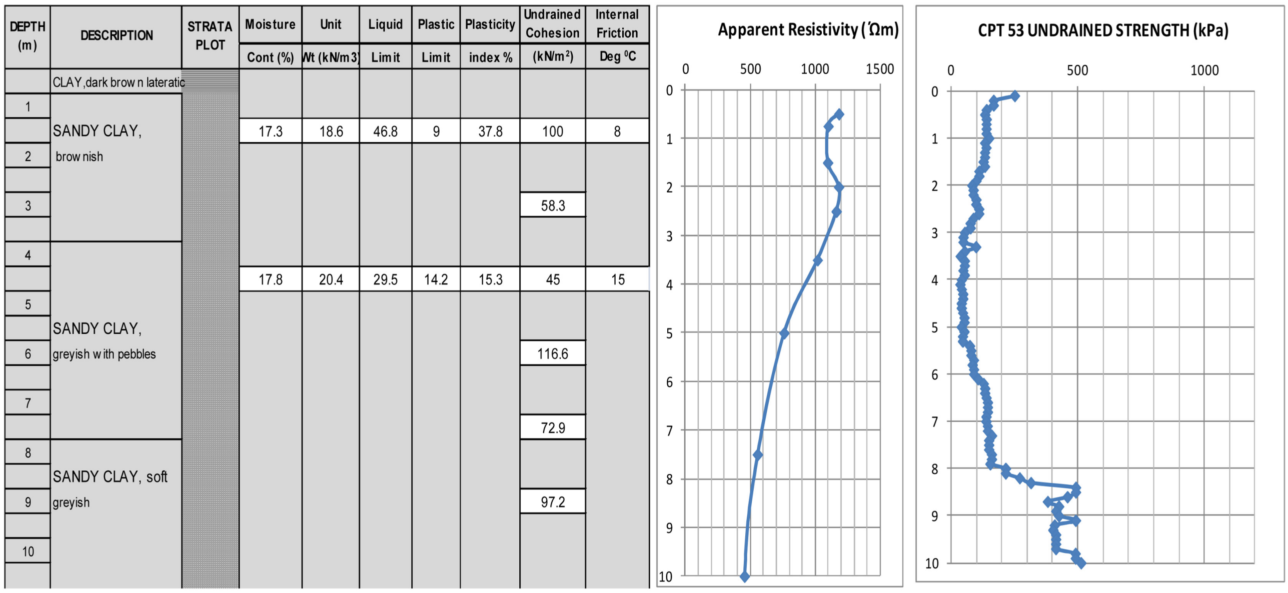

Figure 8. Litholog, strength and resistivity response in the coastal plain sand.

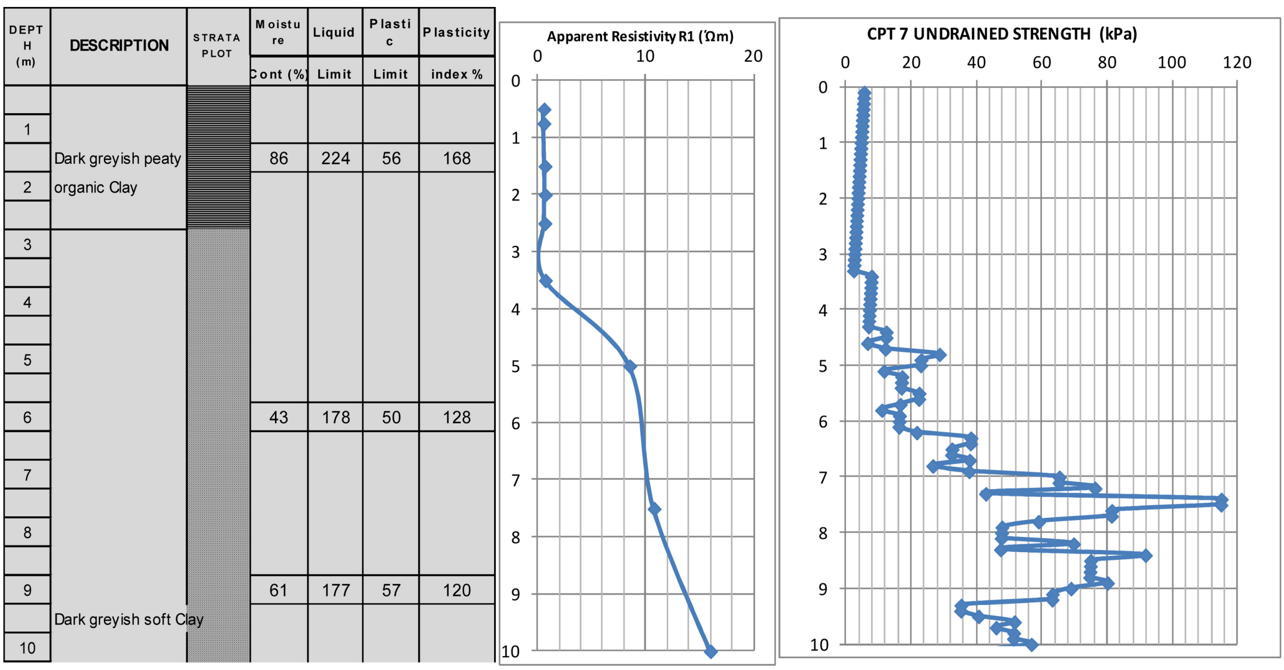

Figure 9. Litholog, strength and resistivity response in the mangrove swamp.

higher resistivity values recorded in the coastal plain, lower flood plain, meander belts and wooded backswamps are essentially a reflection of the water quality. Work by Abam et al. (2021) demonstrates that sections of the Mangrove swamp receiving freshwater discharge from the main river systems recorded slightly higher resistivity values compared to the mangrove soils with no direct link to freshwater discharge. It is therefore probable that freshwater influxes into the sediments such mangrove swamp areas reduce the salinity of soils and by extension increase their resistivity.

The influence of undrained strength was similarly explored by plotting average undrained strength derived from the CPT for 0 - 3 m and 0 - 10 m (Figure 11 and Figure 12) along the 183 km section stretching from Cawthorne Chanel to Obrikom.

The degree of dependence appears to be weak in some sections and fairly strong in others. Consequently, this relationship was further explored within the different sub-environments (Figures 13-15).

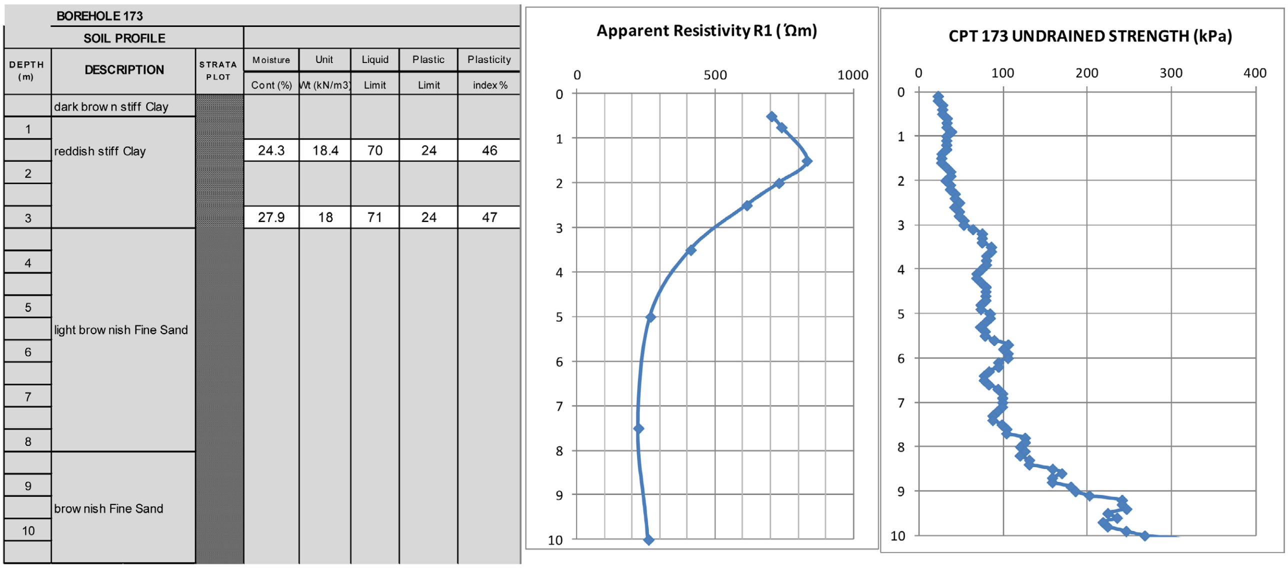

Figure 10. Litholog, strength and resistivity response in the lower Niger flood plain.

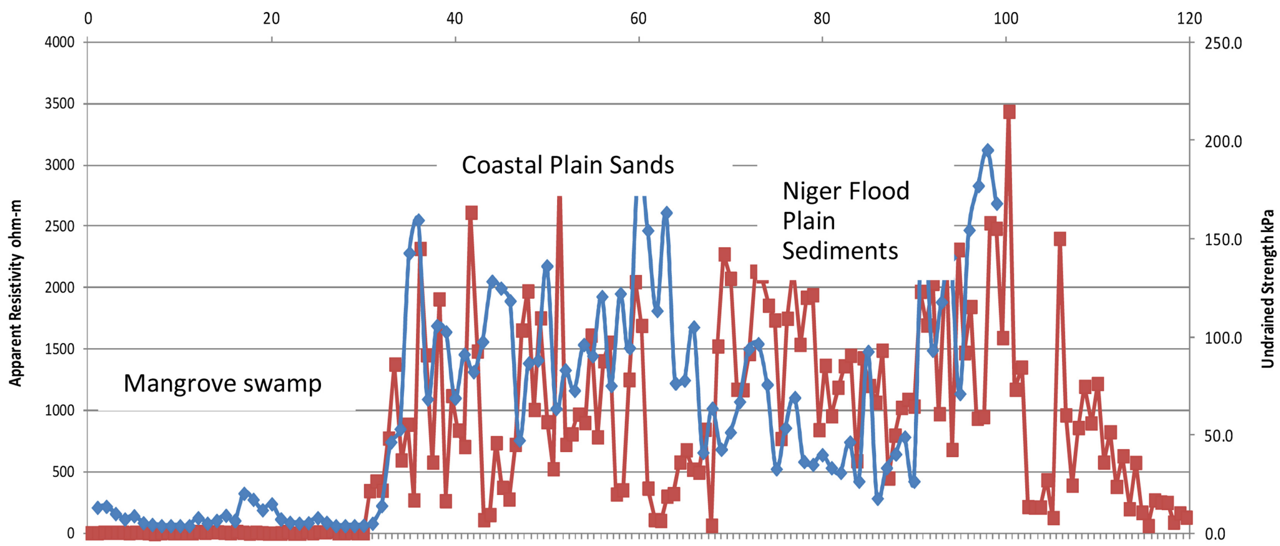

Figure 11. Comparison of Undrained strength and resistivity averaged over 3 m depth across the Cawthorne channel to Obrikom route.

While there may not be good correlation between the undrained strength and apparent resistivity, one can see that for a maximum undrained strength of 20 kPa in the mangrove swamp the highest registered resistivity was less than 18

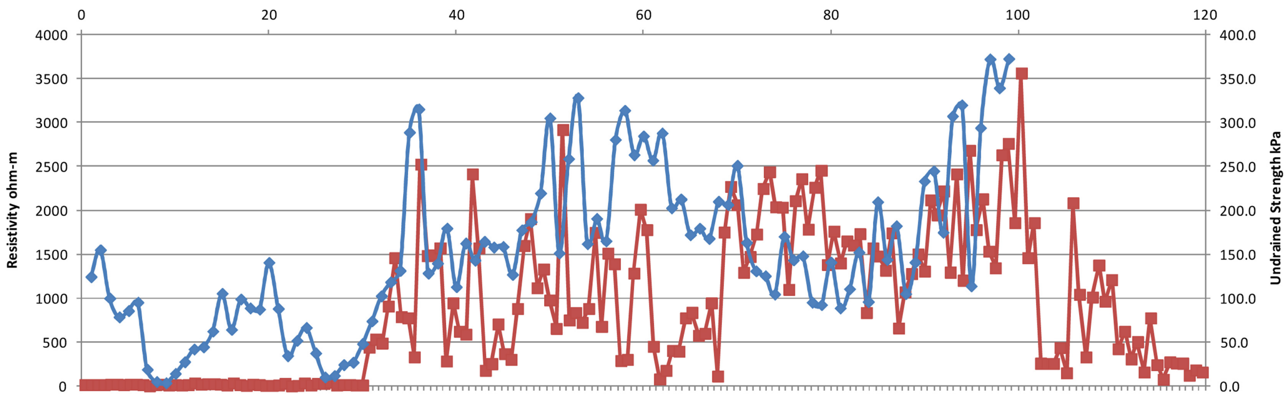

Figure 12. Comparison of Undrained strength and resistivity averaged over 10 m depth across the Cawthorne channel to Obrikom route.

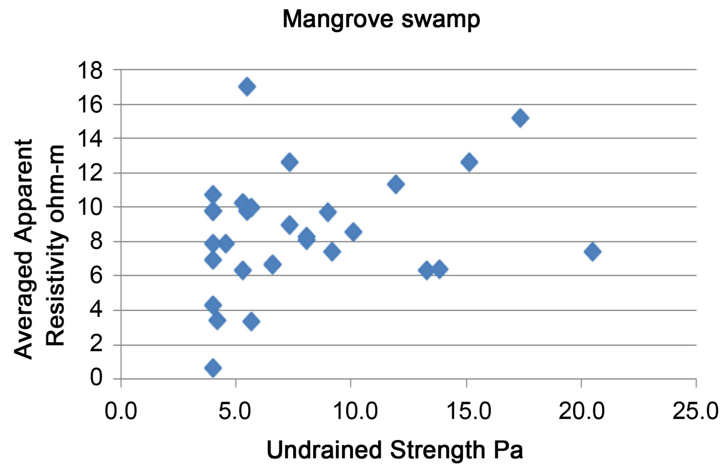

Figure 13. Relationship between undrained strength and apparent resistivity in the mangrove swamp, coastal plain sand and lower Niger flood plain.

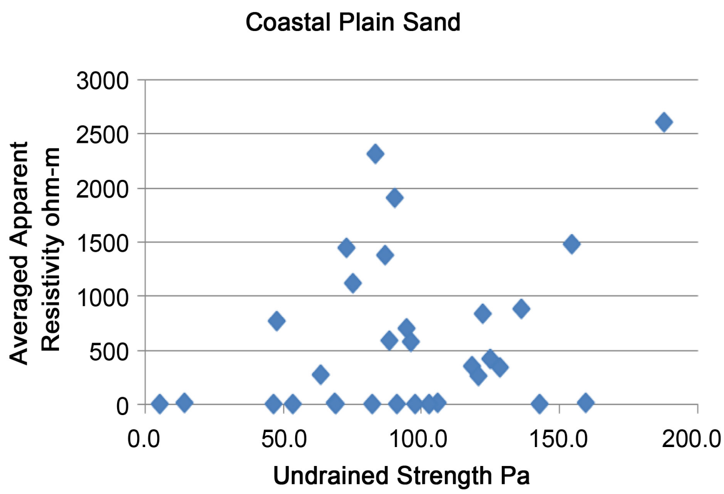

Figure 14. Relationship between undrained strength and apparent resistivity in the mangrove swamp, coastal plain sand and lower Niger flood plain.

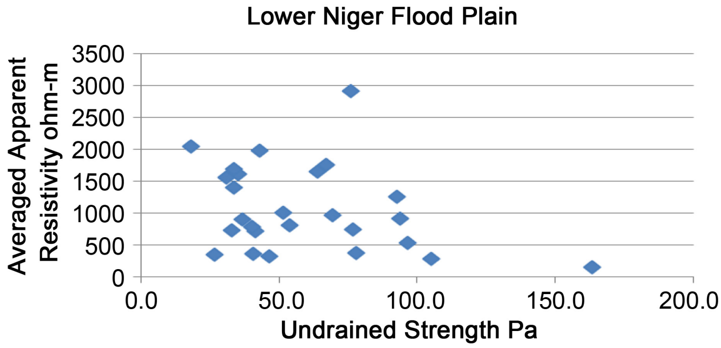

Figure 15. Relationship between undrained strength and apparent resistivity in the mangrove swamp, coastal plain sand and lower Niger flood plain.

ohm-m. Much of the depth explored in the coastal plain sand consists of cohesive and above the water table and therefore, the measured resistivity reflects soil quality. Measured resistivity is more varied in the lower Niger flood plain, due to the interplay of multiple factors, including the lean thickness of the top soil which overlies a predominantly sandy unit coupled with water table close to the surface.

5. Summary and Conclusion

The present work generated the spatial distribution of resistivity within the Niger Delta Region by using 350 VES performed at different geo-referenced locations. 183 Vertical Electrical Sounding VES with the ABEM SAS 1000, using Schlumberger electrode configuration were carried out along a pipeline route to generate resistivity distribution across a linear alignment that traverses three geomorphic sub-environments in the Niger Delta Region. This study has shown that soil resistivity is largely influenced by the depositional environment as each geomorphic zone post depth averaged resistivity values within a narrow range. The study reveals that resistivity generally increases from the mangrove swamps in the coastal zone to the coastal plain sands in the north of the delta. This implies that corrosion hazard is likely to be comparatively more rampart in mangrove swamp soils. By extension, it follows that buried metallic structures in the mangrove swamp will have a higher probability of degradation and therefore shorter service life.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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