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3D Soil Corrosivity signature and model of Delta State in Nigeria for corrosion control

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Abstract

The challenge of data availability for accurately assessing a location's level of corrosivity has lingered for so long and as such, researchers are constantly seeking factors with great influence that can assist in describing how corrosive a location will be toward buried oil and gas infrastructure. Alternative measures are required for making rapid and realistic investment decisions because accumulating these factors to make perfect sense is sometimes time-consuming and expensive. Using MATLAB mathematical computational analysis, this study capitalizes on this gap to build a 3D corrosivity signature and model for Delta state in Nigeria to aid in rapid and realistic investment decision-making. The soil pH and resistivity were identified as key variables that determine the extent of corrosion in this investigation. Vertical Electrical Soundings were utilized to collect soil resistivity data, which was then combined with the soil pH to create a 3D corrosivity signature and model with a 98% R-square factor. During the study, potential limitations were found, and recommendations were made.

Keywords: *Corrosivity, Soil resistivity, Soil pH, Vertical electrical sounding, Delta State*

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1. Introduction

Industries irrespective of their product line aim to optimize the efficiency of their production process by maximizing output, profit, quality, and safety while minimizing cost and losses. The concept of corrosion is of primary importance in the bid to achieve effective cost and loss control, as corrosion represents a costly problem (economic and structural integrity) for metal-using industries amongst which the oil and gas industry is paramount (Zhang and Pan 2019). Corrosion is the degradation and loss of essential properties in metals as a result of electrochemical or chemical and other reactions of the metallic material surface with the enclosing environment. Refined metals are converted into more stable compounds including metal sulphides, metal oxides, and metal hydroxides during this unfavourable process (Zehra et al., 2022). Cardinal corrosion agents include water, air humidity, oils, acids, chemicals, and environmental conditions such as temperature and pH (Balbo et al., 2022). Uniform corrosion is a term used when the loss of metal occurs evenly over the entire exposed surface while the local disintegration of passive layers protecting the material from the environment as seen in pitting and crevice corrosions is called Localized corrosion (Bharatiya et al., 2019). Unfortunately, it is not feasible to completely prevent corrosion as doing so would mean a complete absence of the corrosion agents which is not practically possible. Therefore, controlling the corrosion occurrence rate has been proffered as the most economical solution to its rising challenges.

This review elucidates the current advances in corrosion control in the oil and gas industry, using the present state, challenges, and adopted mitigation measures for corrosion in the oil and gas industrial sector of Delta State, Nigeria as a yardstick. Delta State is named after the Niger Delta (delta of the Niger River sitting directly on the Gulf of Guinea on the Atlantic Ocean with a large portion of it located in Delta State). Owing to the huge deposits of crude oil in Delta, the state is home to several multinational and locally owned oil and gas companies of which the Warri Refining and Petrochemical Company is notable and contributes majorly to the national petroleum products stock. Delta state is ranked to be among the top three oil-producing states in Nigeria alongside Akwa Ibom State and Rivers State and accounts for 21.56% of the National oil production (Enyoghasim et al., 2019). Pipelines are currently the preferred medium for the transportation of crude and refined oils to different process stations across Nigeria and cover several kilometres underground to avoid contact with external influences. The soil is usually corrosive due to the presence of baneful chemicals and microbes that induces the deterioration of pipes through corrosion. Corrosion is hence a primary in-service defect leading to pipeline failures, thereby emphasizing the need to study its mechanism and control alternatives. The severity of corrosion and losses due to it is better appreciated when examined with respect to the associated costs. In reports by the National Association of Corrosion Engineers (NACE), global annual costs related to corrosion are about $2.5 trillion which represents 3.4% of the 2013 global gross domestic product (GDP)(NACE, 2006). Direct costs are expenses involved in the process of maintaining, repairing, and replacing equipment that has been corroded. The indirect consequences of corrosion include decreases in productivity, environmental effects, injuries, halted transportation, and fatalities. Previous reports suggest that 20–25% savings can be made on the annual direct costs of corrosion with the proper use of corrosion monitoring and control technologies (Ameh et al., 2018).

Major factors influencing soil corrosivity are aeration, pH (acidity), moisture content & resistivity and temperature (Wasim et al., 2018). Much emphasis will be placed on pH & resistivity in this review considering the relatively superior role they play in deciding the corrosivity of soil. The rate of corrosion and soil pH are inversely related. In other words, the lower the soil pH (more acidic), the higher the corrosion rate (Wasim et al., 2018). pH levels of 5 or lower cause pipelines to prematurely pit and experience extremely high rates of corrosion (Wasim et al., 2018). Soil pH depends highly on the amount of rainfall, vegetation type, and soil drainage. Since different metal materials react differently to the pH of a soil, soil pH is thus very significant when corrosion studies are being done. Steel, zinc, iron, and lead are very susceptible to corrosion caused by low soil pH while copper is a bit more resistant as hydrogen ions are generally not involved in the copper corrosion process (Hou et al., 2016). In comparison to other variables, moisture content is the most important factor influencing corrosivity Ahmad et al., 2016). Corrosion won't happen if the soil is fully dry because water is one of the three necessary components for electrochemical corrosion (the other two are oxygen and metal). According to experimental data, soils' corrosive potential is increased when their moisture content and the amount of ionic soluble salts present are both increased (Hou et al., 2016). Soil resistivity which measures the extent to which a soil resists electricity and is considered the most comprehensive indicator of a soil’s corrosivity essentially has an inverse relationship with corrosivity. Corrosivity increases as soil resistivity decreases (Wasim et al., 2018).

Vertical electrical sounding (VES), the method of interest in this review, is one of the most popular ways to measure the soil resistivity of the ground vs depth. VES is a geophysical method for examining a geological medium that focuses on detecting the electrical field voltage caused by far-off grounded electrodes in order to determine the medium's electrical conductivity (Shendi, 2020).

To properly address corrosion issues, it is pertinent to understand the soil activities in a region. Thus, the need for regional corrosivity signature or mapping. In simple terms, this involves the production of signatures from numerous geographic regions, illustrating the macroscopic variations in environmental corrosivity (atmospheric corrosivity, soil corrosivity, and so on). This review will therefore provide a comprehensive report on the current trends in soil corrosion in Delta State and present a model and a 3D corrosivity signature for corrosion control.

2. Materials and methods

The variables and materials utilized to develop the corrosivity mapping for Delta State were covered in this section. First, several literary works were used to discuss the value of Delta State's soil resistivity in the corrosivity study. A method for acquiring resistivity data called VES was provided, and comparisons with other methods were done. In order to set the stage for the proposed corrosivity mapping for the area, a critical examination of pH within Delta was followed by a discussion of MATLAB paradigms for exploring subsurface corrosion.

2.1 Soil Resistivity in Delta State

The earth is made up of various materials in different levels of strata. These materials within the earth give it different properties across different locations which makes it serve as a reservoir for excessive charges (Obukoeroro and Uguru, 2021) i.e., some of which include electrical properties of conductivity and resistivity. The resistance of soil, which measures how well the soil resists the flow of electricity, can vary significantly depending on moisture, temperature, and chemical content, with typical values between 1 Ωm and 100 Ωm and exceptional values between 1Ωm and 10,000 Ωm (Oyubu, 2015). Soil resistivity is the measurement of the resistance between two opposite ends of a soil cube with a one-meter side dimension (Johnson, 2006). The electrical resistivity method has been the most widely used method for delineating formation strata because of its measurement equipment portability, ease of operation, and utility in efficient and cost-effective drilling programs(Chinyem, 2013).

Using various measuring techniques, numerous studies have attempted to characterise the range of soil resistivity across various areas in Delta State (Obukoeroro and Uguru, 2021). It is however noted that resistivity differs significantly across the lithologies in the different locations and across depths in all the studies. Factors such as the compaction of the soil, moisture content, and soil nature/texture (clay, sandy, coarseness) contribute to soil resistivity (Igbologe and Okieke, 2022). The work of Igbologe agreed with that of Oyubu that soil resistivity varies with the geotechnical and physiochemical properties of the location under study, and thus it is bound to find different resistivity values across Delta State as seen in Table 1 (Igbologe and Okieke, 2022). It varies vertically as well as horizontally (Unde and Tathe, 2020). In fact, soil resistivity varies from season to season in each location i.e., it varies from the dry season to the rainy season(Unde and Tathe, 2020), which can mean that soil resistivity used for safe design in one season can become unsafe in another season (Kushare and Unde, 2013).

Table 1: Soil resistivity data studies across Niger Delta

Niger Delta States	Soil resistivity	Location	Ref.
Delta	158.15 - 820 Ω-m	Delta State Polytechnic, Ozoro	(Obukoeroro and Uguru, 2021)
Delta	Location 1 – 820.06 Ω-m, Location 2 – 158.3 Ω-m, Location 3 – 402.18 Ω-m, Location 4 – 270.2 Ω-m	Different resistivity values measure in the Faculty of Engineering Complex, DELSU, Ozoro Campus.	(Oyubu, 2015)
Delta	60 – 6000 Ω-m	DELSU, Abraka	(Ofomola et al., 2018)
Delta	42 – 15,000 Ω-m	Sapele Area	(Uchegbulam and Ayolabi, 2014)
Delta	29.3 – 349.9 Ω-m	Ogbe-Ijoh resistivity measurement data	(Ohwoghere-Asuma et al., 2020)
Cross River	Layer 1 – 1.03 – 183 Ω-m Layer 2 – 613 – 1,800,000 Ω-m Layer 3 - 525 – 10,541 Ω-m	Mbat-Odukpani	(Danladi Shehu et al., 2016)
Bayelsa	1,294.60 – 2,058,753.79 Ω-m	Yenagoa city	(Okiongbo et al., 2011)
Niger Delta	2.4 – 3,394 Ω-m	Niger Delta	(Okiongbo and Ogobiri, 2013)

2.2 Vertical electrical sounding

There are two different methods of resistivity surveying that can be used to measure resistivity in a field procedure. They have constant separation and vertical electronic sounding (Okiongbo et al., 2011). The retention of current and potential electrodes in a straight line with the same relative spacing around a fixed central point is the basis of VES (Okiongbo and Ogobiri, 2013). The variation of resistivity with depth from a specific point on the ground for nearly horizontal formation layers beneath is determined by electrical sounding. The Schlumberger array is frequently used for VES, with the current electrode dipole moving from one point to another and the potential electrode dipoles remaining fixed. According to Haldar (2018), the VES method, is less expensive to conduct per unit length and more sensitive to both vertical and lateral electrical structures than other one-dimensional methods like electromagnetic, hence, it is the best geophysical tool for measuring soil resistivity. Table 2 shows the outcome of selected soil resistivity measurement studies done with VES.

Table 2: Soil resistivity measurement through VES using the Schlumberger Array Method

Region	Tool	Soil Variable	Weakness	Strengths	Ref.
Issele-Azagba, Delta State	VES	Resistivity (441.4 Ω.m - 5657 Ω.m)	Study didn’t give PH value of the soil in the regions	Successful use of VES to determine layers and characteristics of the lithologies of the area studied for underground aquifer identification	(Manu et al., 2019)

Niger Delta	Weight Loss Method	Resistivity (54 Ω.m - 62 Ω.m)	The study did not examine how much soil resistivity, as opposed to soil pH, affected the corrosion of buried steel pipes.	The experimental research showed that soil resistivity and pH are both dominating causes of corrosion of the buried pipes.	(Abdullahi et al., 2015)
Niger Delta	VES	Resistivity (5 Ω.m – 481 Ω.m	The temperature of the region was not put into account as a factor that can influence the soil resistivity.	It considered the effect of soil resistivity on buried pipe corrosion at varying soil depth from undulating coastal plain lowland to coastal beach ridges.	(Iserhien-Emekeme, 2014)
Kaduna, Nigeria	VES	Resistivity (Avg. 72.13 Ω.m)	Disperse samples from few regions in Kaduna cannot be used to generalise soil resistivity level of the entire state as they are area of more industrial activities than the other.	According to the study, the soil corrosion spectrum is stochastically changeable, generally varies as one descends underground, and is mildly corrosive on average. It ranges from aggressive at depths of less than about 0.5 m to mildly corrosive at about 4.5 m, considering the soil's resistivity.	(Ikechukwu et al., 2014; Okiongbo et al., 2019)
Bangalore, India	Wenner-method	Resistivity (345 Ω.m – 568 Ω.m)	The pH values of the moistures in the study area were not considered experimentally since the dissolved salts and temperature have a substantial impact on the soil's resistivity value.	This study focuses on measuring soil resistivity throughout the year for several seasons in order to determine the worst value to utilise in design calculations.	(Okiongbo et al., 2019)
North Aceh, Indonesia	Wenner method	Resistivity (10 Ω.m - 200 Ω.m)	Corrosion potential and soil acidity, which must be considered to choose the best sort of protection at each research site, were not considered.	The study was able to demonstrate the role of soil resistivity in identifying possible areas for pipeline corrosion.	(Guma et al., 2015)
Sydney, Australia	LPR	Resistivity (4 Ω.m – 185 Ω.m)	Only electrical current flow was included in the study; as a result, resistivity could not serve as a substitute for the electrolytic ionic diffusion of metal ions.	It demonstrated that air spaces at the soil or metal contact promote differential aeration, which significantly controls corrosion in soil.	(Prabhakar and Deshpande, 2014)

2.3 pH in Delta State

The changes that take place over the course of a pipeline's life will affect any corrosion that occurs to it, whether it be internal, external, or atmospheric (Matloub et al., 2018). The biological and chemical processes of the water in the formation are impacted by the pH, one of the environmental elements, which causes variations in the rate of corrosion based on its level and the type of buried metal (Cordes et al. 2016). Materials are naturally vulnerable as they tend to attain thermodynamic equilibrium or stability, which in turn makes them easily attacked by changes in-situ (Pedeferri, 2018). Protective oxide layers have a tendency to dissolve, and corrosion rates increase for common steel, iron, and cast iron when the pH falls below 4 (Wasim et al., 2017).

Corrosion reaction varies from metal to metal. Metals like copper are mostly unaffected by pH due to the fact that hydrogen ions are often not engaged in copper corrosion (Ngah et al., 2017). Corrosion of copper normally occurs at a rate that is 1/6 that of iron (Yarmolenko, 2021). Aluminium being an amphoteric metal corrodes at both low and high pH values. However, within pH range of 5 to 8.5, corrosivity has little effect on it. When the pH is beyond such bounds, the rate of corrosion increases significantly (Boukerche et al., 2014). Another example is lead and the pH rises significantly outside the range of 4 - 10 (Wasim et al., 2017). An amphoteric metal, zinc is used to galvanize steel to increase its durability. In other words, zinc corrodes in settings with both high pH values (higher than 12) and low pH values (below roughly 5 to 6).

While at a slower rate than iron, zinc corrodes in the same types of soils (Vu et al., 2013).

Corrosion is brought on by the reaction's loss of metal atoms. When the oxide is gone, the metal surface comes into direct contact with the acid solution, which speeds up the corrosion reaction compared to when the pH is higher (Matloub et al., 2018). Therefore, the type of underground pipelines and the amount of dissolved oxygen in the formation water determine how the pH level affects the rate of metal corrosion. The battle between H^+ and the dissolved metal for ligands typically intensifies when soil pH drops, decreasing the metals' capacity for adsorption and bioavailability while increasing the mobility of heavy metals. The pH values at Delta state show a general moderate tendency for corrosion of steel pipes as the range is between 5.22 to 7.86. However, most publications discuss carbon dioxide (Wasim et al., 2017), which is commonly created by decaying soil-based organic matter. Carbon dioxide atmosphere is likely to encourage corrosion, and the corrosion is further aided by the interaction between ferrous ions and the pipeline steel as revealed by a slow strain rate test without carbon dioxide bubbling (Xue and Cheng, 2014). The stress corrosion of carbon steel is determined by pH and carbonate-bicarbonate equilibrium (de Sena et al., 2012). The level of soil corrosivity measured in different areas with regard to pH is shown in Table 3.

Table 3: Studies on the soil pH of Delta State

Location	pH Range	Average pH	Degree of Corrosivity	Ref.
Abbi	5.82 – 6.21	6.02	Moderately corrosive	(Osayande, 2016)
Sapele	6.47 – 6.53	6.50	Neutral	(Osayande, 2016)
Warri	7.02 – 7.18	7.10	Neutral	(Osayande, 2016)
Agbor	5.05 – 5.55	5.30	Moderately corrosive	(Osayande, 2016)
Asaba	5.20 – 6.10	5.65	Moderate corrosive	(Akpoveta et al., 2011)
Bomadi	5.17 – 5.48	5.33	Moderately corrosive	(Osayande, 2016)
Ughelli	5.37 – 5.50	5.43	Moderately corrosive	(Osayande, 2016)
Isoko	5.11 – 5.74	5.43	Moderately corrosive	(Osakwe, 2014)
Abraka	7.01 – 7.07	7.04	Neutral	(Akpoveta et al., 2011)
Agbor	7.74 – 7.97	7.86	Neutral	(Akpoveta et al., 2011)
Oghara	5.10 – 6.40	5.75	Moderately corrosive	(Anegbe et al., 2018)
Ovade-Ogharefe	4.20 – 7.50	5.85	Moderately corrosive	(Irunkwor and Ngerebara, 2018)
Omavovwe - Agbarha	5.16 – 5.28	5.22	Moderately corrosive	(Martin, 1993)

2.4 3D Signature using MATLAB

MATLAB is a dynamic mathematical computational analytical platform that can generate results in two-dimensional and three-dimensional viewpoints (François et al., 2021). Its wide range of flexibility makes it ideal for simulations of real-world settings when the variables causing the changes are known. Table 4 shows corrosion investigations done with MATLAB and highlights flaws that researchers have not addressed yet.

For a good 3D corrosivity signature, a linear polynomial regression analysis was conducted on MATLAB and the soil resistivity and soil pH were the variables serving as a function of the corrosion severity F(x,y). The general formula for polynomial regression is represented in Equation (1), however, this can be expanded as the powers and variables increase during regression.

$$y = \sum_{i=1}^{n+1} p_i x^{n+1-i} \qquad (1)$$

A pilot test was conducted based on the soil pH and soil resistivity data from works of literature in Sections 2.1 and 2.3. Also, Equation (1) served as a guide for developing the model for the Delta State corrosivity using MATLAB. The 95% confidence boundary and goodness of fit are important conditions during regressions that consider large variables (Abbas et al., 2018), therefore, these boundary conditions were also considered while arriving at the 3D corrosivity signature to guide our inferences.

Table 4: Corrosion signatures using Computational Numerical Analysis

Software	Corrosion	Variables	Strengths	Weakness	Ref.
MATLAB	Erosion	Corrosion rate, speed of agitation, temperature	The 3D signature created a visible interaction between the independent variables which could be easily compared with similar corrosion studies.	The 3D mapping changes with temperature and agitation, therefore it is only a representation of 0.1N HCL attack under agitation and temperature changes	(Abdelhadi et al. 2010)
MATLAB	Stress cracking	XYZ Morphology of corroded concrete sample	The flexibility of viewing corrosion damage from different angles and cross-sectional areas	Analysis on MATLAB was limited to surface effect and the inability of estimating the rate of stress cracking from the signature.	(Xiao et al. 2022)
MATLAB	Stray current corrosion protection	Rail current & Distance, Leakage current & distance, stray current & distance	The impact of NaCl in soil was easily observed from variances in signatures as stray current changes.	2D signatures were used to describe the rail drainage network-earth	(Li et al. 2021)
MATLAB	General corrosion of buried pipelines	Corrosion rate, Chloride, and pH, Corrosion rate, sulfate and pH, Corrosion rate, chloride, and sulfate	The clarity in differences between the impacts of chloride, sulfate, and pH. Models were developed to aid the protection of buried pipelines.	Models are limited to experimental ranges; signatures are not absolute but were rater used to clarify findings.	(Chung et al. 2021)
MATLAB	Concrete surface corrosion	XYZ morphology of eroded and uneroded samples	Clear surface discrepancies, easily color-coded to identify unique layers	Corrosion is time-dependent, but the 3D views in the study were static at a particular time.	(Xiao et al. 2021)
MATLAB	Corrosion under insulation (buried pipelines)	Temperature, insulation type, and corrosion rate. Corrosion rate, temperature, and environment type	Determined the extent of corrosion under insulation, a pictorial description of changes in 3D, accounted for pipe complexities.	One signature does not represent all conditions, it is not environment-specific, scarcity of data made the presentation limited.	(Mohsin et al. 2019)

3. Results and discussion

In order to confirm the concepts presented in this study, which was to develop a corrosivity 3D signature that would be used as analogue data for decision-making, a pilot test was carried out in Delta State. A 26-point data was obtained, and its soil pH and Soil resistivity were related to numerical corrosivity level based on the proposals of works of literature that have stated that corrosivity might be of different levels. The assumption made was that the extent of corrosivity down the acidic scale was similar to the alkaline scale. Therefore, the soil resistivities of >10,000 Ω.m, 1,000>x>10,000 Ω.m, 100 > x > 1,000 Ω.m, 10 > x > 100 Ω.m and <10 Ω.m were related to the corrosivity levels of 1 (pH: 7), 2 (pH: 5 or 9), 3 (pH: 3.5 or 11.5), 4 (pH: 2 or 12), and 5 (pH: 1 or 13) respectively. Using the MATLAB simulator, the 26-point data generated the 3D signature in Figure 1, supporting Abdelhadi et al. (2010) study that the corrosion behaviour of a material toward an environment can be represented in 3D. However, this study's findings were based on soil pH and resistivity. For a clearer description of the corrosion severity, a contour plot was presented in Figure 2 showing the spread of corrosivity at different levels of soil pH and resistivity. Figure 3 is a 2D view of the corrosivity signature for Delta state.

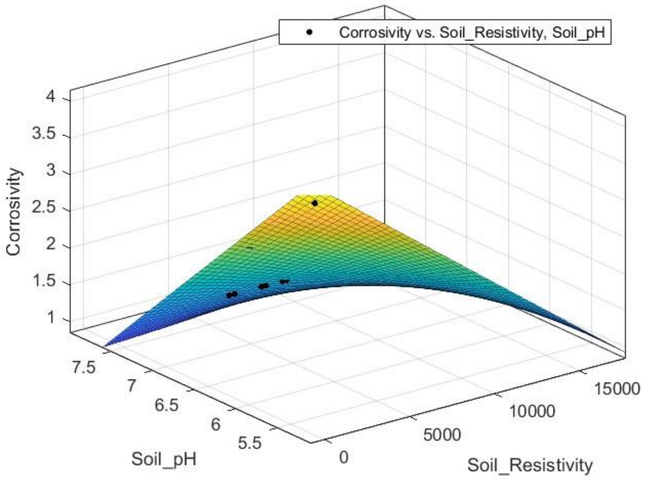

Fig. 1: 3D signature of Delta State corrosivity

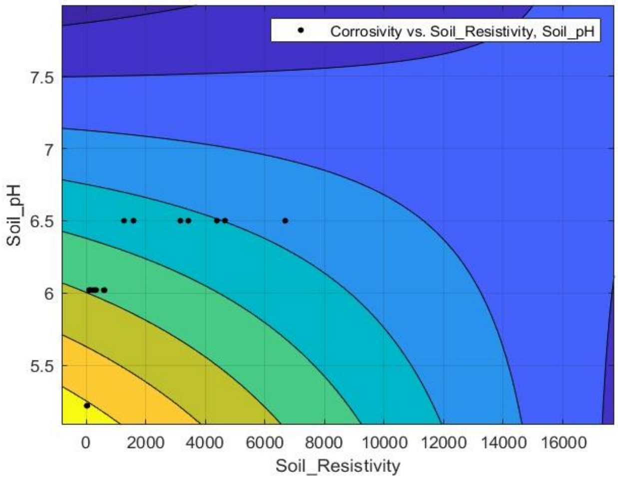

Fig. 2: Contour plot showing Delta State corrosivity

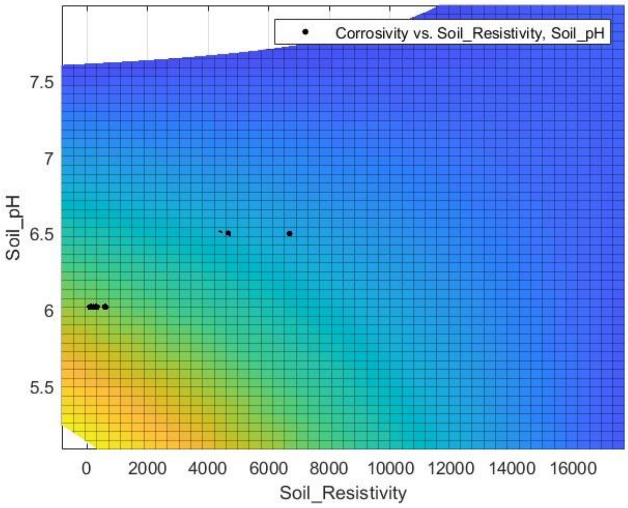

Fig. 3: 2D representation of the change in corrosivity with respect to soil pH and resistivity

The signature developed was unique to Delta State to the extent of the correctness of data generated, this could serve as an analogue representation of the state's corrosivity and can be compared with that of other states or regions where similar underground activities are done. The spread of corrosivity suggested that soil pH and resistivity have a clear relation to the level of corrosivity and the severity decreases as soil resistivity increases and as soil pH tends to 7. Reviews in this study suggested that the Delta State soil pH over time was within the range of 5.22 - 7.86 disregarding external effects of human action. This means that the blue shades indicated low corrosivity while the yellow shades imply higher corrosivity experienced mostly around acidic regions (Guma et al., 2015; Wasim et al., 2018). A second-degree polynomial model was further generated to express the relationship between the two variables (soil pH and resistivity) with respect to corrosivity as shown in Equation (2).

$$f(x,y) = p00 + p10.x + p01.y + p11.x.y + p02.y^2 \qquad (2)$$

The coefficients from Equation (2) at 95% confidence bounds are represented by:

$$p00 = 10.9(5.84, 15.97)$$

$$p10 = -0.000589(-0.0007971, -0.0003809)$$

$$p01 = -1.299(-3.008, 0.4094)$$

$$p11 = 7.924 \times 10^{-5}(4.922 \times 10^{-5}, 0.0001093)$$

$$p02 = -0.002902(-0.147, 0.1412)$$

Four statistical tools were used to describe the Goodness of fit of the correlation in Equation (1) and they are the Sum of Squared Errors (SSE) which was 0.218 (22%), R-square factor which was 0.9872 (99%), Adjusted R-square factor which was 0.9846 (98%) and the Root Mean Square Error (RMSE) which was 0.1044 (10%). The four tools all suggested that the model made a good representation of the data. The R-square factor suggested that the soil pH and soil Resistivity strongly influenced the extent of corrosiveness of an environment, regardless, there are possibly other factors that have little impact on the corrosivity (Chinyem, 2013; Cordes et al., 2016). Furthermore, the correlations represented on the contour plots and signatures, make it easier for an engineer or operator to know the specifications of materials best fit or coating thickness or composition for underground pipe laying in an environment since Ngah, et al., (2017) have earlier suggested that metals corrosivity are highly influenced by the soil nature (pH and resistivity).

4. Conclusion

In conclusion, the evaluations of soil corrosion in Delta State show that the corrosivity of an environment was an important factor to consider when making decisions on pipeline construction, and that soil resistivity and pH are key predictors of corrosion severity over time. Also, the relation between soil pH, resistivity, and corrosivity was not linear but polynomial, with an R-square factor of 98%. Several studies have also been employed to depict corrosion activities of buried pipelines, with both 2D and 3D viewpoints being used to clarify illustration; nevertheless, 3D stands out due to its static and dynamic nature. The 3D corrosivity signature, created with MATLAB, covered the gap of not having a static representation of an environment in terms of corrosivity, and the signature can be used as analogue data for critical comparisons with other regions, making the material selection for underground facilities and corrosion decision-making easier. In general, the findings suggest that Delta State was a moderately corrosive region. However, to solidify the 3D corrosivity signature of Delta, a more comprehensive assessment of the State (particularly oil-producing regions and areas where underground pipelaying may be viable) was required to develop a standard corrosivity signature for the region. This might be extended beyond Delta State to the entire Niger Delta region, where oil and gas activities are prevalent, and a general corrosivity signature and mapping could be completed for widespread corrosion control and management.

Conflict of Interest

No conflict of interest

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