

Geoelectrical and Physicochemical Investigation of Corrosive Nature of Soil towards Buried Pipelines in Kolo and Environs, Bayelsa State, Nigeria

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Abstract: Geoelectric sounding technique and laboratory analytical methods were used to investigate the effect of certain physicochemical parameters deemed to influence soil corrosivity within some pipeline host communities in Bayelsa State, Nigeria. Eight vertical electrical soundings (VES) were systematically conducted using the Wenner four pin configuration method while soil samples were collected at a depth of 1.5m from twenty four boreholes drilled in the vicinity of the soundings and analyzed for pH, moisture content, chloride, sulphate, carbonate, oxidation-reduction potential and resistivity using standard methods. The overall analytical results show that the soils fall into the mildly corrosive to moderately corrosive categories as regards their effect on buried metallic installations. The designated corrosivity status of each soil sample was determined based on the aggregate concentration of the various analyzed physicochemical parameters. Corrosivity values apparently increased from east to west in the study area with soils at the southeastern section comparatively least corrosive while soils at the northern and central locations are most corrosive. In addition, the resistivity sounding delineated four distinct geoelectric layers which include topsoil, underlain by a predominantly low resistivity layer, and two successive layers with significantly higher resistivities. Considering that most oil pipeline infrastructures are concealed within the potentially more corrosive 2nd layer (0.75 – 2.2m), it is recommended that adequate protective and corrosion control measures be put in place to checkmate occurrences of pipeline failure that may arise from soil corrosivity.

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I. Introduction

Corrosion which is the degradation of a metal by reaction with its environment, affects almost all metals¹. As well as having a direct impact on pipeline networks, corrosion can also result in the contamination of soils and groundwater as a result of leakages and bursts. This does not only affect potable water supplies but can also have a significant effect on agricultural land quality for many future years. Fire and explosion caused by rupturing fuel lines and leaking gas mains has the potential to cause great harm, especially within an urban environment. It is a fact that a product placed within the earth (soil) will ultimately revert, by deterioration and corrosion, to their original form². It has been observed that corrosion of most metals is inevitable and corrosion prevention is all but impossible, however, fortunately corrosion control is possible³. The predominant form of soil corrosion is electrochemical; resulting in the formation of corrosion pits⁴. Soil environments generally have good electrolytic properties which are essential for the redox (oxidation-reduction) reactions that take place during corrosion whereby metallic substrates are converted into oxides, hydroxides and aqueous salts within a cathode-anode system. The complexity and heterogeneous dynamics of soil environments means that soil influenced corrosion is a complicated and not entirely understood phenomenon.

The application of geophysics in the investigation of the corrosivity of the earth materials prior to sub-surface pipe laying has become a standard practice in recent times. Environmental Impact Assessment (EIA) requires knowledge of subsurface distribution of resistivity in construction projects that would involve burial of steel pipes and cables, and other sub-surface network of piping⁵. The electrical resistivity method is highly significant in in-situ determination of the degree of corrosiveness of soils; its application is hinged on the fact that the electrical resistivity of earth materials depends on environmental parameters such as mineral and fluid content, degree of water saturation in the rock/soil, permeability, grain size, degree of grain cementation, concentration of saturating fluids, conductivity of matrix and soil porosity. Low resistivity in soil can be directly related to a high corrosivity/aggressiveness index of the soil material⁶.

It has been reported that soil is generally considered “mildly corrosive” if the sulphate and chloride concentration in the soils are below 200 and 100 mg/l respectively, with pH ranging between 5-9 and resistivity greater than 50 Ohm-m. The presence of sulphate more than 200 mg/l in soils can pose significant corrosion risk to buried structural materials because it can be readily converted to highly corrosive sulphides by anaerobic sulphate-reducing bacteria⁷. Soil humidity and consequently soil moisture is an important factor for corrosion rates in soils. Soil moisture is intrinsically linked to the electrochemical properties of the soil mass essential for corrosional processes. Even in the absence of oxygen, iron will still undergo corrosion by the process of oxidative reaction in water⁸. Organic matter and carbonate content of soils can initially cause an increase in the corrosion rate at the time of burial. This could be the result of humus rich and cohesional clay soils inhibiting the formation of an anti-corrosion surface layer on the metal object, something that other soil environments allow^{9,10}. Soil pH bears a strong correlation with ferrous iron pipe pitting rates¹¹, and studies considering water mains corrosion in Toronto, Canada showed that the use of pH measurements increased the correlation coefficient of resistivity based study¹².

It appears that within the literature most corrosion studies have been instigated as a need by the petroleum, water, and highways sectors. The electricity and telecommunications sectors appear to be little affected by subsurface corrosional processes as cable design has often mitigated this risk and there is little published knowledge stating the contrary. Electricity pylons have been subject to corrosional processes, however the use of cathodic protection has often greatly reduced this risk over recent decades¹³.

Oil spills in the Niger Delta have been a regular occurrence and a major source of environmental degradation. This has caused significant tension between the people living in the region and the multinational oil companies operating there and thus cannot be glossed over with a cursory attention. The study area has in the last three decades had its share of this environmental menace and the culprit in some of the cases has been corrosion. This present study therefore employs conventional laboratory analytical methods and geoelectric sounding techniques to investigate the soil physicochemical properties that have proven to contribute to soil corrosivity. The study area is host to a network of petroleum pipelines belonging to major oil producing companies in Nigeria.

II. Geology and Site Description

The area of study lies between Latitude 4°45'00"N - 4°55'00"N and Longitude 6°15'0"E - 6°25'0"E in Bayelsa State, Nigeria (Figure1). The area can be accessed in the north by the Mbiama-Yenagoa road and in the south by the Nembe and Brass Rivers. Accessibility within the study area is via a network of existing motorable roads that links the various communities as well as several pipeline installations and well head locations.

The tectonic evolution, geomorphic features, as well as the present physiography of the area traversed by the pipeline right-of-way can best be discussed within the context of the geologic history of the Nigerian continental margin and in particular the development of the Niger Delta. The Niger Delta geology and tectonic evolution have been extensively discussed by several published works. The Niger Delta province is a Coastal Sedimentary basin that has been the scene of three depositional cycles. The first began with a marine incursion in the Middle Cretaceous and was terminated by a mild folding phase in the Santonian. The second included the growth of a proto-Niger Delta during the Late Cretaceous and ended in a major Paleocene marine transgression. The third cycle from Eocene to Recent marked the continuous growth of the main Niger Delta. The three major lithostratigraphic units defined in the subsurface of the Niger Delta are the upper sandy Benin Formation, an intervening Unit of alternating sandstone and shale named Agbada Formation, and a lower shaly Akata Formation. These three units extend across the whole delta and ranges in age from Early Tertiary to Recent. Stratigraphic equivalent units to these three formations are exposed in southern Nigeria. The formations reflect a gross coarsening-upward progradational clastic wedge deposited in marine, deltaic, and fluvial environments^{15,16}.

The climatic condition of the zone indicate an indistinct dry and wet seasons. The rains are more between June and September, while the period between November and March experiences less rain on the average. The topography is generally low-lying with elevations ranging from below sea level in the southwestern flank of the region to about 40 m further inland.

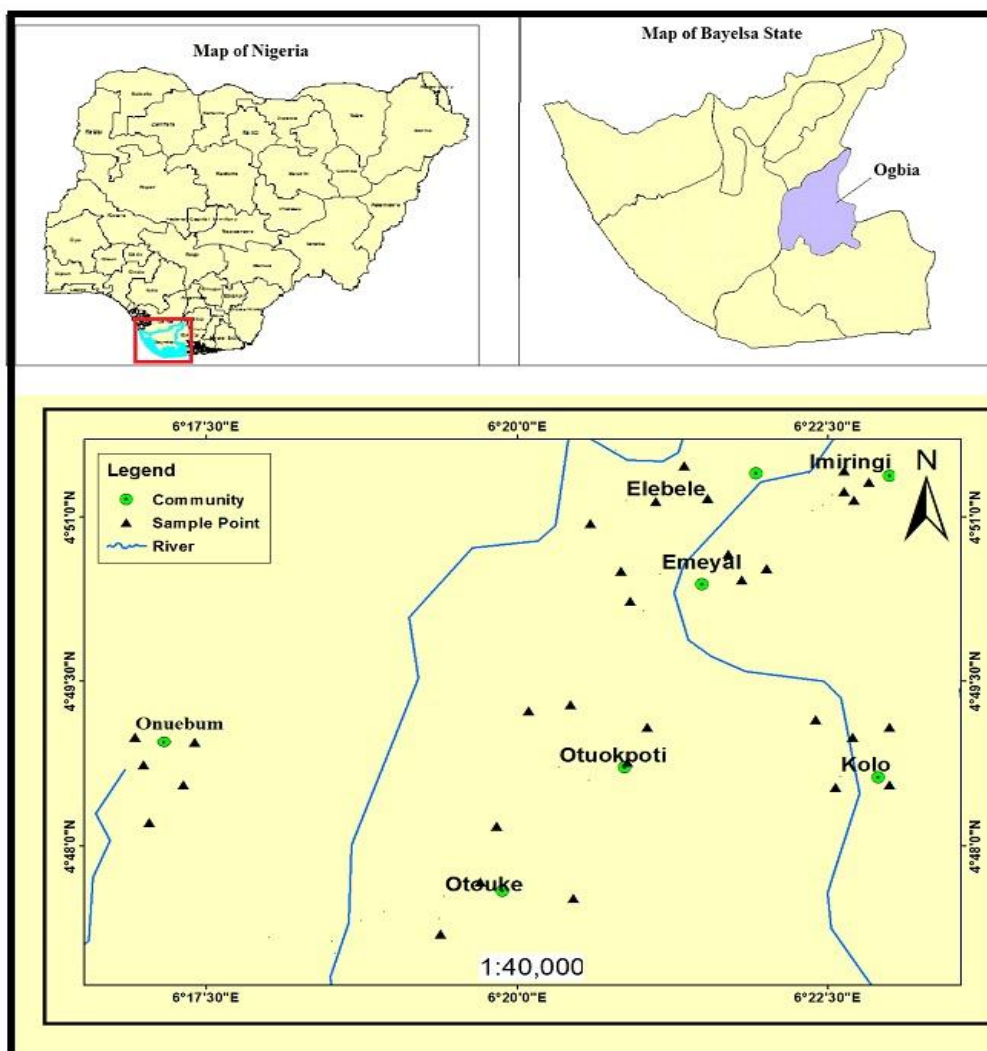


Figure. 1: Map of study area showing borehole sample points

III. Methods of Study

The study methods include:

- (a) Sample collection and analysis
- (b) Geoelectrical survey

Sample collection and laboratory analysis

Twenty four soil samples were collected at a depth 1.5m from the ground level. The sampling depth (1.5m) was chosen owing to the consideration that most oil pipelines are typically buried at a depth of about 0.91- 1.83m. The soil samples were retrieved from the boreholes with conventional open-tube sampler 100mm in diameter and 450mm in length. The open-tube sampler consists essentially of a lower end and upper end screwed into a drive head that is attached to the rods of the rig. The sampler is driven into the soil by dynamic means using a drop hammer. Each sample was put in an air tight polyvinyl bag so that the moisture remained same for the period of moisture content analysis in the laboratory. Sampling was carried out without adding any preservatives in the field to avoid any form of artificial contamination. The pH and electrical conductivity/resistivity of the sediment samples were determined using Horiba U – 10 digital meter. The conductivity was determined by dipping the electrode into a 1:2 soil-water suspension that had been stirred and allowed to equilibrate for about 1hour in accordance with standard methods. Soil resistivity being reciprocal of conductivity was computed using:

$$ER = 1/EC$$

Where

ER = Electrical Resistivity

EC = Electrical conductivity

The oxidation-reduction potential (ORP) of the samples were determined with the aid of a digital potentiometer following ASTM G200-09¹⁶ standard stipulated procedures. Moisture content (MC) of the soil samples was determined using the weight loss approach in accordance with ASTM D4959-07¹⁷ standards. Sulphate was determined by the turbidimetric method, chloride by thiocyanate titration method, and carbonate by silver nitrate titration.

Geoelectrical survey

Eight vertical electrical soundings (VES) were conducted in the vicinity of BH 2, 5, 8, 11, 14, 17, 20 and 23. VES is a resistivity survey technique in which a current of known value is applied to the ground through two current electrodes (C₁ and C₂) and then measuring the resultant potential difference (ΔV) between the potential electrodes (P₁ and P₂). As the electrode spread increases, depth of the probe increases, thereby, giving a vertical electrical sounding. The ABEM terrameter (SAS) 1000 with a liquid crystal digital readout and an automatic signal averaging microprocessors was used for the data acquisition.

Measurements of electrical resistance were carried out in the field using the Wenner four pin configuration method (ASTM-57, 2001)¹⁸ and were taken in two (x, y) directrices at each VES central point from which the average was subsequently calculated and recorded.

Generally the resistivity of a soil layer is given by:

$$\rho = 2\pi a \Delta V / I \tag{1}$$

Where ρ is the apparent resistivity, ΔV is the potential difference, I represents the current and “a” is the electrode spacing. Equation (1) can be rewritten as:

$$\rho(xy) = 2\pi a R(xy) \tag{2}$$

Where R(resistance) = ΔV/I

The true resistivity, thickness and depth of the geological strata were determined from the acquired field geoelectric data using the IP2WIN interpretation software.

IV. Results and Discussions

Results of the physicochemical and geoelectric parameters obtained from the laboratory analysis and electrical sounding are presented in Tables 1 and 2 respectively, while a summary of the correlation between the various physicochemical parameters of the soil samples analyzed is presented in Table 3. Correlation gives insight into the relationship or interdependence of the various physiochemical parameters on one another. The correlation result shows very high correlation coefficient (R) for MC vs resistivity and ORP vs resistivity of 0.96 and 0.88 respectively. Correlation coefficient for ER vs pH, Cl vs ER, Cl vs MC, Cl vs ORP, SO₄ vs ER, SO₄ vs ORP, SO₄ vs Cl, were in the range between 0.59 – 0.64. The correlation coefficient of MC vs pH, ORP vs pH, SO₄ were less than average (0.38 – 0.49) whereas the correlation between CO₃ and all other parameters are approximately negligible.

Table 1: Analytical results of soil physicochemical parameters

Bore hole No	pH	Resistivity (Ohm-m)	Moisture content (%)	ORP (mV)	Cl ⁻ (mg/l)	CO ₃ ²⁻ (mg/l)	SO ₄ ²⁻ (mg/l)
1	6.2	64.5	33.8	117.2	36.2	0.81	12.9
2	6.9	74.1	35.5	132.8	31.1	0.76	17.2
3	6.6	100.5	34.8	140.5	23.8	0.98	13.5
4	6.8	143.9	23.7	213.6	29.6	1.24	16.0
5	6.7	151.5	25.0	204.9	37.5	1.80	19.1
6	6.9	197.4	24.5	255.1	41.2	0.08	22.4
7	6.7	156.3	25.6	272.9	32.4	0.85	18.5
8	6.1	48.8	41.6	108.0	25.2	1.26	9.5
9	6.4	84.0	34.1	161.2	27.6	0.09	11.0
10	6.1	87.7	32.7	183.5	28.1	0.99	8.7

11	6.2	132.5	24.9	224.1	33.6	1.22	15.2
12	6.4	46.5	37.8	113.6	20.5	1.00	12.8
13	6.5	36.9	41.8	107.3	21.0	0.68	9.1
14	5.8	46.1	39.2	110.5	24.2	0.72	12.4
15	6.6	62.5	37.5	122.5	30.5	0.96	9.8
16	6.4	76.9	35.4	141.0	25.0	1.45	17.5
17	6.8	112.8	30.6	192.3	28.3	0.08	13.2
18	6.4	153.8	23.2	228.4	36.6	0.54	21.7
19	5.9	23.6	42.5	105.2	27.3	0.30	18.5
20	5.6	25.0	40.2	102.7	32.8	0.45	13.0
21	5.7	57.5	37.0	120.5	24.5	1.08	10.3
22	6.9	80.0	33.9	134.0	21.2	0.92	14.6
23	6.7	107.5	32.5	209.1	28.0	1.34	17.0
24	6.3	116.3	25.3	196.5	31.4	0.52	19.1

Table 2: Sounding results of geoelectrical parameters

VES No.	Thickness of layers (m)				Resistivity of layers (Ohm-m)				
	h ₁	h ₂	h ₃	h ₄	ρ ₁	ρ ₂	ρ ₃	ρ ₄	ρ ₅
1	0.86	1.79	2.25	4.65	234	81	346	1406	2820
2	0.75	1.18	6.82	7.74	146	215	771	1936	3387
3	0.92	1.5	2.4	5.9	114	53	451	279	165
4	0.55	1.72	3.33	9.67	83	157	30	307	1128
5	0.84	0.78	3.5	9.2	76	42	118	512	2453
6	0.79	1.25	2.16	8.4	388	135	517	1683	4864
7	0.65	1.58	4.06	7.2	172	32	278	644	1297
8	0.62	1.1	2.2	8.73	304	128	42	584	1765

Soil moisture content

Moisture content of samples collected and analyzed ranged from 23.2 - 42.5%. Only four of the samples had moisture content values greater than 40% while the remaining twenty samples had moisture content values between 20 – 40%. The former were designated moderately corrosive while the latter were categorized as mildly corrosive towards buried-galvanized steel and cast-iron materials on the basis of their moisture content.

Soil pH

The pH of soil samples analyzed was in the range of 5.6 – 6.9, indicating they are slightly acidic to moderately acidic. Four samples with pH ranging from 5.6 – 5.9 were designated moderately corrosive, whereas 50% of the remaining samples were either mildly corrosive with pH (6.0 -6.5) or negligible with pH (6.6 -6.9). Within the pH range of 4-8.5 iron can be immune, passive (corroding slowly) or corroding depending on the redox potential of the soil¹⁹. However, it has been suggested that at low pH values, the passive corrosion protection layer is unable to form, leading to a higher corrosion rates, while at near neutral pH the soil permits an amenable environment for sulfate reducing bacteria (SRB) to develop⁹.

Sulphates, Chlorides and Carbonates

Corrosion pitting as a phenomenon is often induced by aggressive anions, such as chlorides (Cl) and sulphates(SO₄). Chloride ions in particular can introduce pitting corrosion of the protective layer (passive film) decreasing the overall protection of the buried metal asset, while the oxidation of pyrite (FeS₂) undergoes biological and chemical reactions ultimately leading to the formation of sulphuric acid, which is not only inherently a problem with relation to the corrosion of metallic materials but also a significant environmental pollution risk to surface and ground waters¹³. Table 1 shows that the concentration of both chlorides and sulphates are significantly below 100 and 200 mg/l respectively and therefore their contribution to the overall corrosive status of the soil samples analyzed in the study area is considered to be negligible. The results also show that carbonate (CO₃²⁻) levels are also negligible and did not exceed 1.5 mg/l in the analyzed soil samples. This might be attributed to the high rainfall

responsible for large leaching of bases like carbonates from the soil and the replacement of the colloidal complexes by the hydrogen ions (H⁺)²⁰.

Table 3: Correlation of soil physiochemical parameters

	pH	Resistivity	MC	ORP	Cl	CO ₃
Resistivity	0.5962					
MC	0.4843	0.9607				
ORP	0.4944	0.8896	0.1196			
Cl	0.1552	0.6166	0.6529	0.6032		
CO ₃	0.0583	0.0762	0.0714	0.0000	0.1407	
SO ₄	0.3780	0.6443	0.6405	0.6217	0.5930	0.0775

Table 4: Relationship between soil resistivity, chloride and sulphate content and soil corrosivity⁷

Soil parameter	Soil corrosive rate
Soil resistivity (Ohm-cm)	
>20,000	Non-corrosive
10,000 – 20,000	Mildly corrosive
5,000 – 10,000	Moderately corrosive
3,000 – 5,000	Corrosive
1,000 – 3,000	Highly corrosive
< 1000	Extremely corrosive
Chloride (ppm)	
< 1000	Mildly corrosive
Sulphate (ppm)	
< 1000	Mildly corrosive

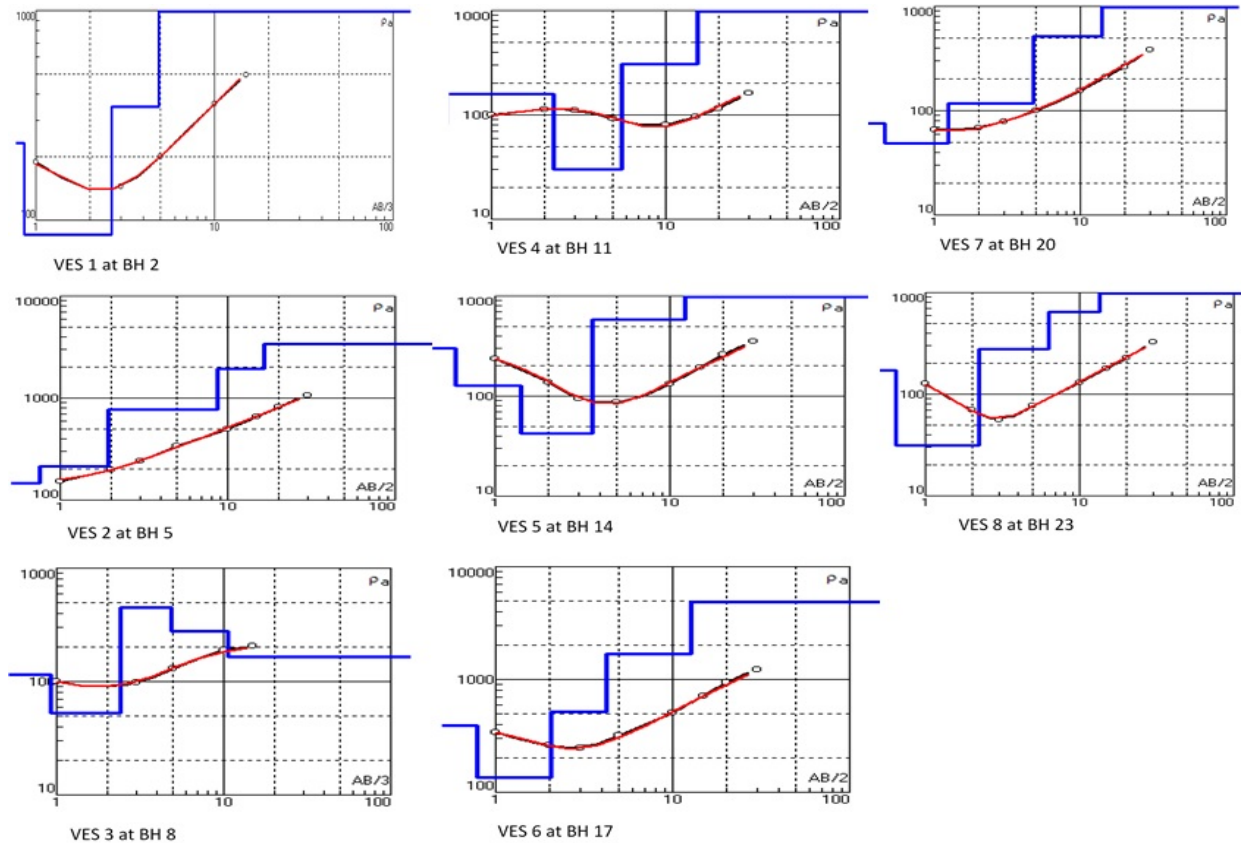


Figure 2: Computer modeled curves from geoelectric sounding

Soil resistivity

Soil resistivity is an indication of the ability of a soil environment to carry corrosion currents. In this study, this parameter was determined via two approaches (laboratory analysis and sounding). Whereas the former requires drilling and recovering of a representative sample at specific depths, the latter is non-invasive and attempts to rapidly provide a “picture” of multiple layers of the subsurface. The resistivity values from the laboratory analysis of the twenty four samples range between 23.6 – 197.2 Ohm-m, while the values from eight soundings for the same depth (1.5m) range between 42 – 215 Ohm-m. The results from both methods show that although there are slight variations in the measured resistivities, all the values approximately fall within the same range of corrosivity rating (Table 6) for a particular sample/sounding site (Table 1 and 2). The geoelectic sections (Fig. 2) and table 2 shows four delineable subsurface layers with resistivity values generally increasing within the depth probed. This indicates buried metallic infrastructures at lower depths are potentially less vulnerable to soil corrosion than those at shallow depths in the study area. The sounding results further suggest that the target depth of sampling (1.5m) appears to fall within the low resistivity layer, occurring within an average depth of 0.75 – 2.2m. This zone is considered to be relatively more susceptible to corrosive behavior than the immediate underlying layer which occurs at an average depth of 2.2 – 5.54m and resistivity range of 30 -771 Ohm-m (Table 2). Statistics of the physicochemical results extracted from table 1 shows that six soil samples have resistivity values less than 50 Ohm-m, eight samples are in the range between 50 – 100 ohm-m while the resistivity values of ten samples are between 100 – 200 Ohm-m. Based on the above, the three categories of soil samples analyzed in the study are classified as corrosive, moderately corrosive and mildly corrosive respectively.

Oxidation-reduction potential

The measurement of oxidation- reduction potential (ORP) of soils is significant to explain soil corrosivity towards buried – structural materials, particularly metallic pipes. In general, anaerobic soils with ORP less than 100 mV do not favour the formation of passive oxide layers on the surface of the materials because of the lack of oxygen necessary for the reaction to take place²¹. Also, the ORP of a particular soil indicates whether or not the soil is capable of sustaining sulphate reducing bacteria (SRB), which contribute greatly to the corrosion problem. A low ORP indicates that oxygen content in the soil is low, which is consequently an ideal condition for the proliferation of SRB, increasing the sulphide content in the soil by reducing sulphate to sulphide¹³. The distribution of the ORP values in this study shows that seven samples have ORP values in the range of 100 -200 mV and are designated moderately corrosive whereas seventeen soil samples were between 200 - 400 mV and classified as mildly corrosive on the basis of ORP²².

Table 5: Rating of soil corrosivity based on oxidation-reduction potential of soils²²

Oxidation-reduction potential (mV)	Soil corrosivity
>400	Non-corrosive
201 - 400	Mildly corrosive
100 - 200	Moderately corrosive
< 100	Severely corrosive

Corrosivity rating

In order to determine the overall effect of the individual physicochemical parameters and further produce a representative corrosivity map of the area, it was imperative to assign weights to the contributing parameters and subsequently evaluate an aggregate for each sample analyzed. Table 6 and 8 shows the individual and aggregate weight range respectively and their corresponding corrosivity rating for the parameters analyzed in the study. Table 7 outlines the designated corrosivity rating for each contributing parameter and the aggregate weight for each sample. From the results, the values of chloride, sulphate and carbonate for all the samples fell within the same rating range (negligible/non-corrosive) and were thus excluded in the summation of weight aggregates (Table 4). The final results show that thirteen samples were of the mildly corrosive category while eleven were categorized as moderately corrosive. Fig 4 is a contour map produced from the results of both field and laboratory investigation of this study. The map shows that the soils at the southeastern section of the study area are comparatively the least corrosive while soils at the north central are potentially most corrosive to buried metals. Corosivity also generally decreased from north to south of the study area and apparently increased westward.

Table 6:Soil corrosivity rating and assigned weight

Soil corrosivity rating	N e g l i g i b l e	Mildly corrosive	Moderately corrosive	C o r r o s i v e	Extremely corrosive
Assigned weight	0	1	2	3	4

Table 7: Soil corrosivity rating and calculated weight aggregates for analyzed soil samples

Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Weight aggregate	6	5	4	3	3	3	3	7	6	6	4	7	8	8	5	6	3	4	9	9	7	5	3	4

Table 8: Soil corrosivity rating and range of weight aggregate

Range of weight aggregate	Soil corrosivity rating
< 2	Non-corrosive
2 - 5	Mildly corrosive
6 - 9	Moderately corrosive
> 9	Corrosive

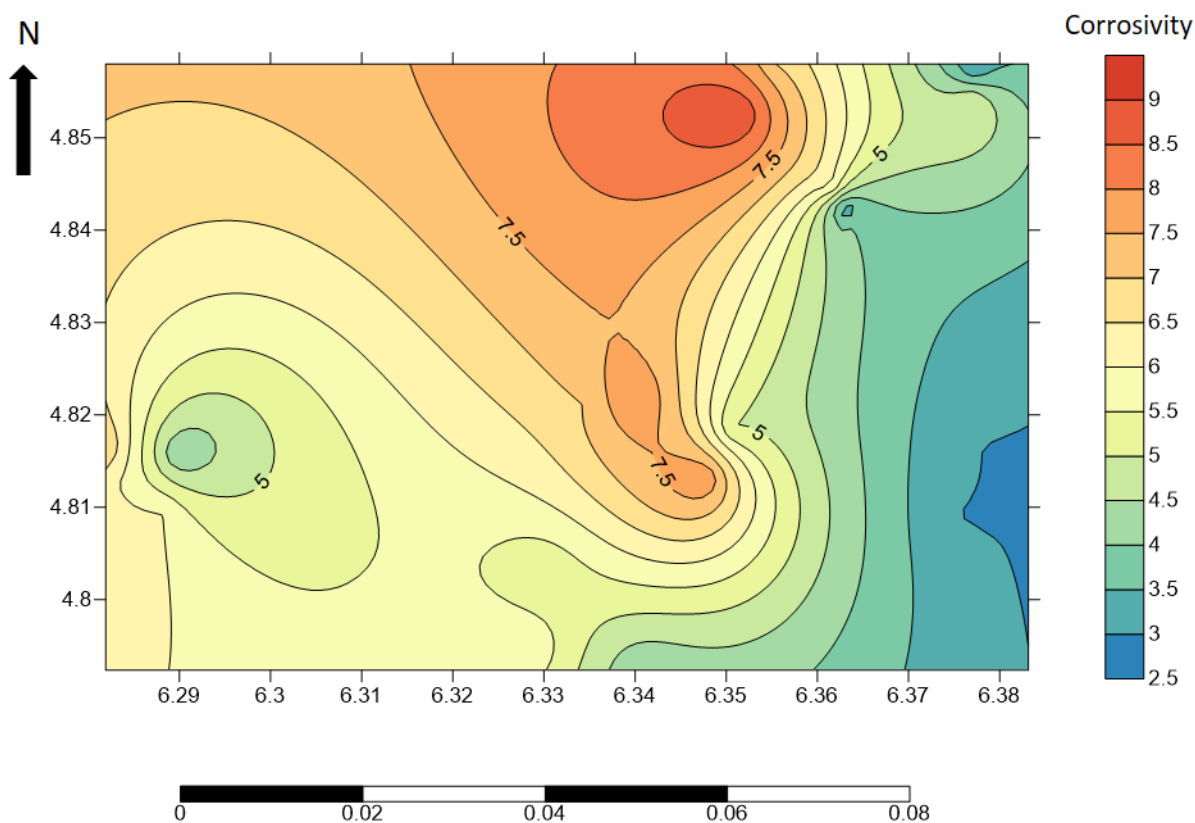


Figure 3: Corrosivity rating map of study area

V. Conclusion

This study has critically evaluated some of the factors that influence soil corrosivity. The physical and chemical parameters that contribute to soil corrosivity do not occur in isolation and are often interrelated. Summary of the analytical results with respect to the physicochemical parameters show that thirteen out of the twenty four samples were of the mildly corrosive category, while eleven were moderately corrosive. Corrosivity apparently decreased from north to south of the study area with the southeastern section showing the lowest recorded corrosivity rating values. In addition, a good correlation was found between the resistivity values obtained from the sounding and laboratory analysis. The geoelectric results delineated four distinct layers which include topsoil, underlain by a predominantly low resistivity layer, and two successive layers with significantly higher resistivities. Considering that most oil pipeline networks are concealed within the 2nd geoelectric layer (0.75 – 2.2m), adequate protective and corrosion control measures should be put in place to checkmate occurrences of pipe failure arising from corrosion effects.

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