Geoelectrical and Geotechnical Investigations of Subsurface Corrosivity in Ondo State Industrial Layout, Akure, Southwestern Nigeria*

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Abstract

Fifty two vertical electrical sounding (VES) data and six subsurface soil samples were collected at Ondo State Industrial Layout, Akure, south-western Nigeria in order to determine the subsurface corrosivity. The VES results delineated 3 to 5 geoelectric layers across the area, which correspond to topsoil, weathered layer, weathered basement, weathered/fractured basement and the presumed fresh bedrock. The layer resistivity values range from 22 to 602 ohm-m, 7 to 2468 ohm-m, 17 to 436 ohm-m, 25 to 39 ohm-m and 203 to 10023 ohm-m in the topsoil, weathered layer, weathered basement, weathered/fractured basement and the presumed fresh bedrock respectively. The iso-resistivity maps at depth slices of 1 and 2 m show that the northeastern, southeastern and the upper central part of the area are non-corrosive (above 350 ohm-m) to slightly corrosive (250 - 350 ohm-m), while the lower central, northwestern and southwestern parts of the area are moderately (150 - 250 ohm-m) to strongly corrosive (60 - 150 ohm-m). Soil sample analysis shows liquid limit results that vary from 37.6 to 59.7, while the plasticity limit results vary from 29.3 to 42.5 and all the plasticity index plots were below the A line indicating presence of non-plastic clay. The natural moisture content values vary from 21.4 to 35.5 %. The 2 m depth slice isoresistivity map and clay plasticity factor were synthesized using additive model to generate subsurface CR-index corrosivity model map which indicates that the northwestern, north-eastern and southern parts of the area are moderately (0.4 - 0.6) to strongly corrosive (0.6 - 0.8), while the upper central area and the flanks are slightly corrosive. The moderately and strongly corrosive zones correspond to the low elevation and water logged zones of the study area. The corrosivity model map was validated by the pH and corrosivity data.

Keywords: Geotechnical, Liquid Limit, Plastic Limit, Plasticity Index, Clay Plasticity

1 Introduction

Corrosion is defined as the degradation of a material or its properties due to a reaction with the environment (Owate *et al.*, 2002) and it exists in virtually all materials but is mostly associated with metals. Effects of corrosion on engineering structures include; loss of stress, fatigue, reduced bond strength, limited ductility and reduced shear capacity (Gebremedhin *et al.*, 2013). Soil corrosivity is caused by several soil properties such as; resistivity, pH, redox potential, sulfides concentration, percentage clay content and moisture content (Najjaran *et al.*, 2004 and Idornigie *et al.*, 2006).

Few woks have been done on corrosivity; Najjaran *et al.*, (2004) demonstrated the application of fuzzy logic in predicting deterioration of cast/ductile iron water mains using soil properties. This approach utilized a model consisting of a series of 'IF THEN' rules to determine soil corrosivity potential based on soil properties such as resistivity, pH, redox potential, sulfides, percentage clay content and moisture content. Different models relating corrosivity potential and different soil properties had been generated. Idornigie *et al.*, (2006) carried out 1063 Vertical electrical sounding (VES) at Akungba-Akoko, Ondo State and environs in order to determine subsoil corrosivity. The work classified the subsoil into four corrosivity zones; very strongly corrosive (less than 10 ohm-m), moderately corrosive (10 - 60 ohm-m), slightly corrosive (60 - 180 ohm-m) and non-corrosive (180 ohm-m and above). Oyedele *et al.*, (2012) combined electrical resistivity tomography and hydro-chemical analysis in assessing coastal soil corrosivity at Lekki, Lagos, Nigeria. The subsurface in the area were classified into four corrosive layers; Non-corrosive (greater than 100 ohm-m), mildly corrosive (50 - 100 ohm-m), moderately corrosive (20 - 50 ohm-m), corrosive (7 - 20) and very corrosive (less than 7 ohm-m). Gebremedhin *et al.*, (2013) used AAS-UV spectrophotometer-generated hydro-geochemical data obtained from surface water, hand dug wells and boreholes in Mekelle city, Ethiopia. Water from the three sources gave Larson Index (LI) above the 0.5 threshold which were considered indicative of aggressive corrosivity. Bayowa and Olayiwola (2015) adopted electrical resistivity method in evaluating the subsurface corrosivity within the campus of Ladoke Akintola University, Ogbomoso, Nigeria. It was concluded that layers with resistivity values of 200 ohm-m and above,

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100 - 200 ohm-m and less than 100 ohm-m could be classified as non-corrosive, moderately corrosive and highly corrosive respectively. Abdullahi *et al*., (2016) acquired 10 VES data at Convocation Square, Kaduna State University, Kaduna Northwestern Nigeria in order to investigate the corrosivity of the subsurface soil. The subsurface were classified into three corrosivity layers; corrosive (80 - 150 ohm-m), slightly corrosive (150 - 200 ohm-m) and non-corrosive (above 200 ohm-m).

This study attempts to combine the effect of moisture and presence of water holding lithology like clay on subsurface corrosivity.

1.1 The Study Area

The study area is Ondo State Industrial Estate, Akure, Southwestern Nigeria which lies between longitude 803800 and 806400 m (Eastings), and latitude 738600 and 740600 m (Northings) based on Universal Traverse Mercatum System (WGS 84) and the area extent is about 2.8 km^2 (Figs. 1, 2 and 3). The study area is characterized by wet (April to October) and dry (November to March) seasons and mean annual rainfall range between 1000 and 1500 mm. The vegetation of the area is of tropical rain forest type which is characterized by thick forest. The annual mean temperature ranges from 21.9 to 30.4 ^{0}C, while humidity is relatively high during the wet season and low during the dry season with values ranging annually from 39.1 to 98.2% (Adeyemo et. al., 2017). The area is underlain by Precambrian rock typical of the Basement Complex of Nigeria (Fig. 2). The main rock type in the area is charnockite which occurs as outcrops, residual hills and boulders in some places, and they vary in texture from fine to coarse grained structural characteristics (Rahaman, 1988 and Owoyemi, 1996).

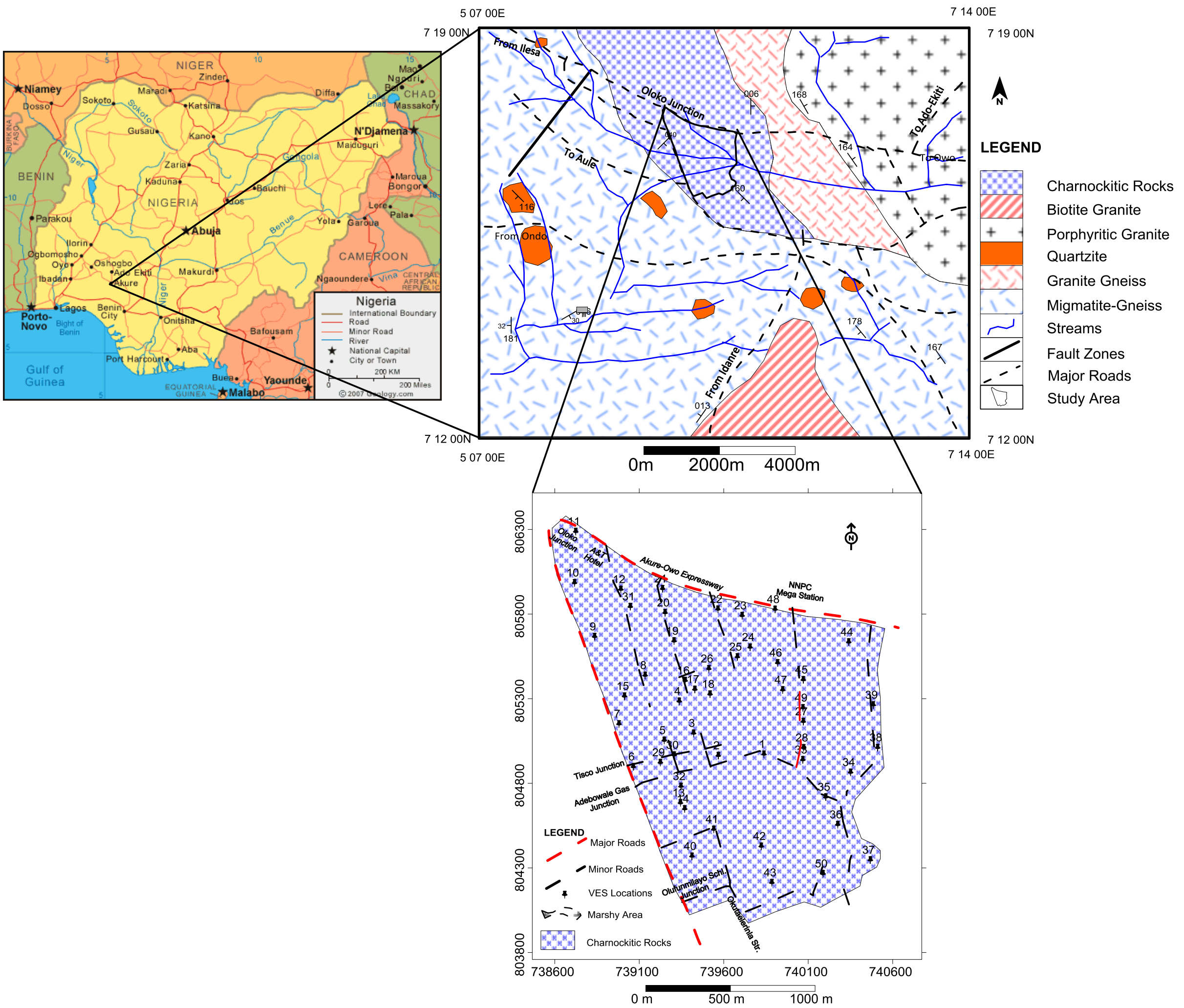

Fig. 1 (Left); Administrative Map of Nigeria, (Upper); Simplified Geological Map of Akure (Modified after Owoyemi, 1996) and (Lower); Geological Map of the Study Area

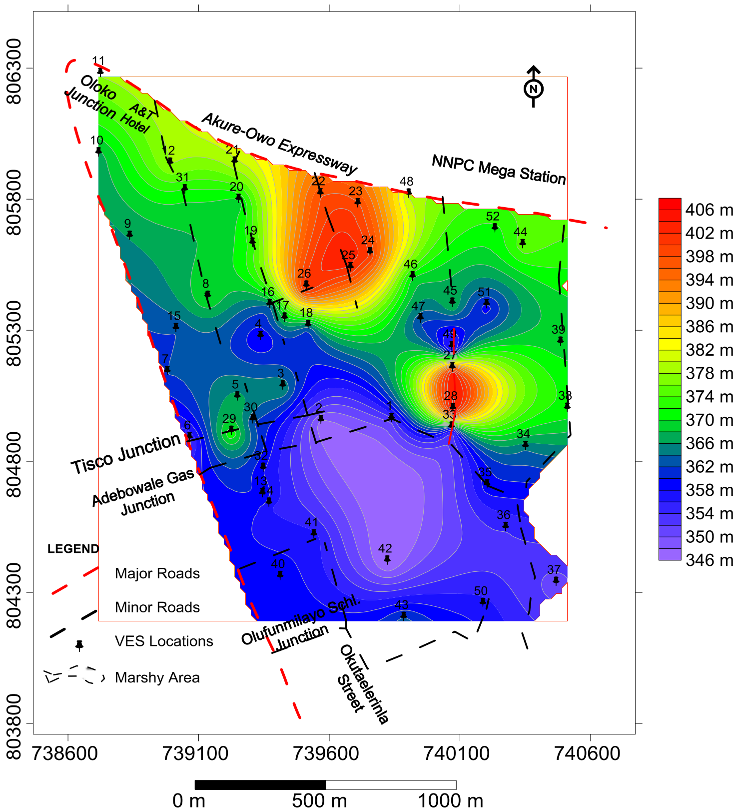

Fig. 2: Elevation Map of the Study Area

2 Resources and Methods Used

2.1 Data Acquisition and Interpretation

This study combined geoelectric sounding and geotechnical approach in investigating subsurface corrosivity at Akure Industrial estate, Akure Ondo State. The vertical electrical sounding (VES) survey utilized Schlumberger electrode configuration (Zohdy, 1965 and Koefoed, 1979). The half-current electrode spread was varied from of 1 to 150 m and a total of 52 VES was acquired across the study area (Fig. 3). The field data was interpreted using the conventional partial curve matching techniques (Zohdy, 1965 and Koefoed, 1979) and the resulting geoelectric parameters were further refined using Resist Version 1.0 software (Vander Velpen, 2005). Subsurface soil samples were collected at constant depth of 2 m across six (6) selected locations. The samples were prepared and used to determine the Liquid Limit (LL), Plastic Limit (PL) and Plsticity Index (PI). The PI value assisted in determining the clayey nature and clay type encountered in the area. The results of both geolectric sounding and consistency test were synthesized using an additive model developed by Chachadi (2005) and adopted by Adeyemo *et al.*, (2017) to generate the final corrosivity model map. The corrosivity model map was subsequently subjected to validation using conductivity and pH values obtained from water sample.

3 Results and Discussion

The results (Table 1) of the fifty-two (52) VES data acquire across the study area delineated nine (9) different curve types; A, H, HA, HKH, K, KAH, KH, KQH and QH. The most predominant curve type in the study area is the KH which account for 59.6%. HA, H and A and curve types accounts for 38%, 21% and 5.8% respectively while HKH, KAH, KQH and QH account for 1.9% each. The VES results also delineated three (3) to five (5) geoelectric layers across the area which corresponds to topsoil, weathered layer, weathered basement, weathered/fractured basement and the presumed fresh bedrock. The layer resistivity values range from 22 - 602 ohm-m, 7 - 2468 ohm-m, 17 - 436 ohm-m, 25 - 39 ohm-m and 203 - 10023 ohm-m in the topsoil, weathered layer, weathered basement, weathered/fractured basement and the presumed fresh bedrock respectively, while layer thickness varies respectively from 0.5 - 7.4 m, 1.1 - 21.7 m, 1.7 - 44.8 m and 12.5 - 55.9 m in the topsoil, weathered layer, weathered basement and

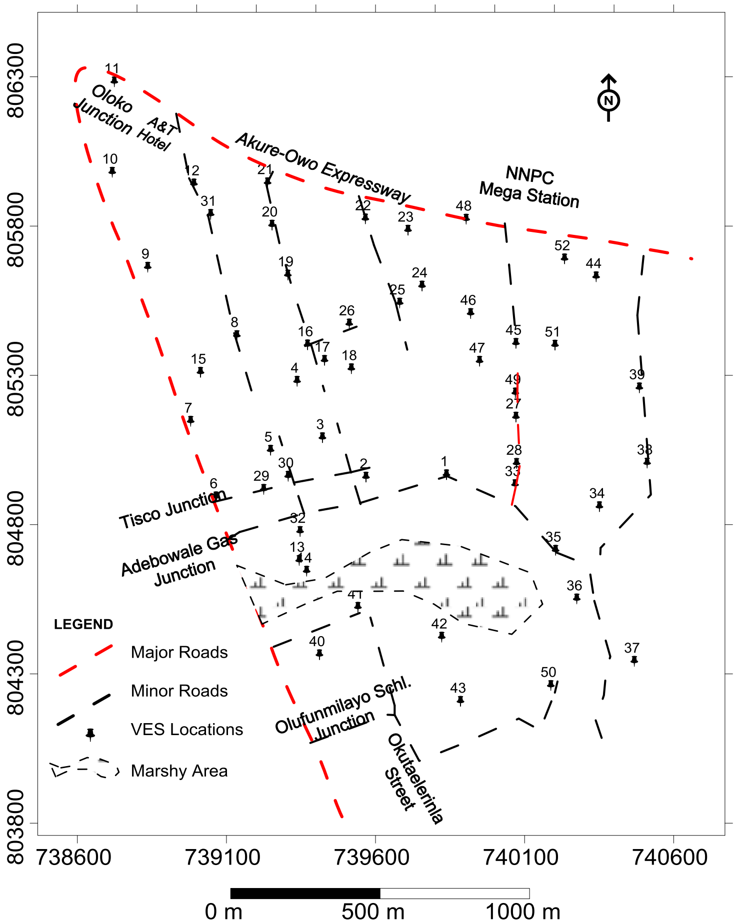

Fig. 3 Base Map of the Study Area showing VES Locations

weathered/fractured basement. The VES results were also presented as resistivity depth slice maps at 1, 2 and 3 m (Figs. 4 - 6).

3.1 Depth Slice Maps

The iso-resistivity map at depth slice of 1 m (Fig. 4) indicates that the northeastern, southeastern and a segment of the southwestern part of the area is non-corrosive (above 350 ohm-m) to slightly corrosive (250 - 350 ohm-m), while the central, northwestern and southwestern part of the area are mildly (150 - 250 ohm-m) to strongly corrosive (60 - 150 ohm-m). The 2 m depth slice iso-resistivity map (Fig. 5) look similar to 1 m depth slice iso-resistivity map. It shows that the northeastern, southeastern and the upper central part of the area are non-corrosive (above 350 ohm-m) to slightly corrosive (250 - 350 ohm-m), while the lower central, northwestern and southwestern parts of the area are moderately (150 - 250 ohm-m) to strongly corrosive (60 - 150 ohm-m). The iso-resistivity map at depth slice of 3 m (Fig. 6) also shows a similar pattern to the first two depth slice maps. The map (Fig. 6) indicates that the upper central, eastern and a portion of southwestern parts of the area are non-corrosive (above 350 ohm-m) to slightly corrosive (250 - 350 ohm-m), while the north-western and central southern parts of the area are moderately (150 - 250 ohm-m), to strongly corrosive (60 - 150 ohm-m) and very strongly corrosive (0 - 60 ohm-m).

3.2 Natural Moisture Content and Consistency Limit Tests

Soil analysis results in (Figs. 7(a-f) and Table 2) from all the six (6) samples collected for the consistency limit test shows that liquid limit results vary from 37.6 to 59.7, while the plasticity limit results vary from 29.3 to 42.5 and all the plasticity index plots were all below the A line indicating presence of non-plastic clay such as chlorite, halloysites and kaolinite. The natural moisture content results (Table 2) vary from 21.4 to 35.5 %. This suggests that the low resistive nature of some part of the area indicating corrosivity are as a result of their high moisture contents and it is also believed that the non-plastic clayey nature of the subsurface will enhance fluid and ions movement which in turn will contribute to their corrosivity. In view of the presence of non-plastic clay such as chlorite, halloysites and kaolinite in the area subsurface plasticity index was also considered in the generation of corrosivity model map of the study area.

Table 1: Vertical Electrical Sounding Results

VES No	No of Layers	Resistivity (Ohm-m) $\rho_{1/}\rho_{2/}\rho_{3.....}\rho_{n-1/}\rho_n$	Thicknesses (m) $h_{1/}h_{2/}h_{3.....}h_{n-1/}h_n$	Curve Type
1	4	22/17/177/1666	1/3.9/1.7	HA
2	4	132/197/46/308	0.7/2.1/20.3	KH
3	4	36/199/70/1398	0.6/2.6/17.8	KH
4	4	110/423/57/1625	0.8/8.0/26.4	KH
5	4	70/140/65/543	0.9/4.4/12.0	KH
6	4	94/242/18/12167	0.5/3.4/19.6	KH
7	5	58/167/127/39/175	1.4/7.7/19.4/12.5	KQH
8	4	108/131/64/271	0.7/6.4/22.0	KH
9	4	43/54/24/1438	1.0/4.1/6.7	KH
10	3	30/64/203	0.9/3.3	A
11	4	38/30/53/2575	0.9/4.4/33.2	HA
12	4	110/166/110/2228	1.0/6.1/16.6	KH
13	4	391/1000/143/3251	0.8/3.3/24.2	KH
14	4	383/1387/68/1368	0.6/2.6/39.9	KH
15	4	167/618/62/1838	0.9/6.0/31.3	KH
16	4	90/297/33/1214	0.8/4.9/17.8	KH
17	4	85/309/21/539	0.9/3.8/20.1	KH
18	4	251/367/45/555	1.5/2.8/21.2	KH
19	3	279/49/2094	3.1/21.7	H
20	4	72/290/20/1613	0.6/3.6/16.8	KH
21	3	40/510/229	0.9/6.6	K
22	4	124/503/92/2190	0.8/3.1/47.4	KH
23	4	602/213/158/630	0.9/5.3/28.3	QH
24	5	261/363/251/25/496	0.8/2.2/11.6/55.9	KAH
25	3	40/64/204	2.8/20.7	A
26	4	159/316/134/759	0.9/3.0/23.6	KH
27	3	100/22/1985	1.4/6.9	H
28	3	509/34/835	2.7/11.9	H
29	4	80/280/90/228	1.0/7.7/23.4	KH
30	4	66/242/82/473	0.9/9.7/24.6	KH
31	3	204/65/518	3.9/21.2	H
32	4	217/318/107/256	1.1/10.4/32.6	KH
33	3	231/194/274	3.9/12.9	H
34	4	126/984/257/10023	0.7/4.3/6.9	KH
35	4	109/136/62/7495	0.9/3.5/28.9	KH
36	3	249/989/11130	3.0/1.1	A
37	3	200/40/460	3.7/11.4	H
38	3	428/135/7382	0.8/4.7	H
39	4	164/560/299/7318	0.7/4.5/13.0	KH
40	4	71/255/17/517	1.4/3.5/23.9	KH
41	3	146/7/484	1.8/7.8	H
42	5	298/19/107/30/300	1.4/4.7/17.9/14.9	HKH
43	4	117/253/25/8606	0.6/1.1/2.2	KH
44	3	241/177/1442	2.3/10.1	H
45	4	156/333/130/248	0.8/2.7/12.1	KH
46	4	126/465/81/513	0.8/2.8/25.3	KH
47	4	257/559/35/2441	0.9/2.6/18.6	KH
48	3	590/81/323	7.4/36.4	H
49	3	270/24/1202	1.0/7.6	H
50	4	381/2468/436/1820	1.2/16.4/44.8	KH
51	4	100/274/79/2459	0.8/2.8/16.0	KH
52	4	70/93/17/791	0.9/1.9/2.1	KH

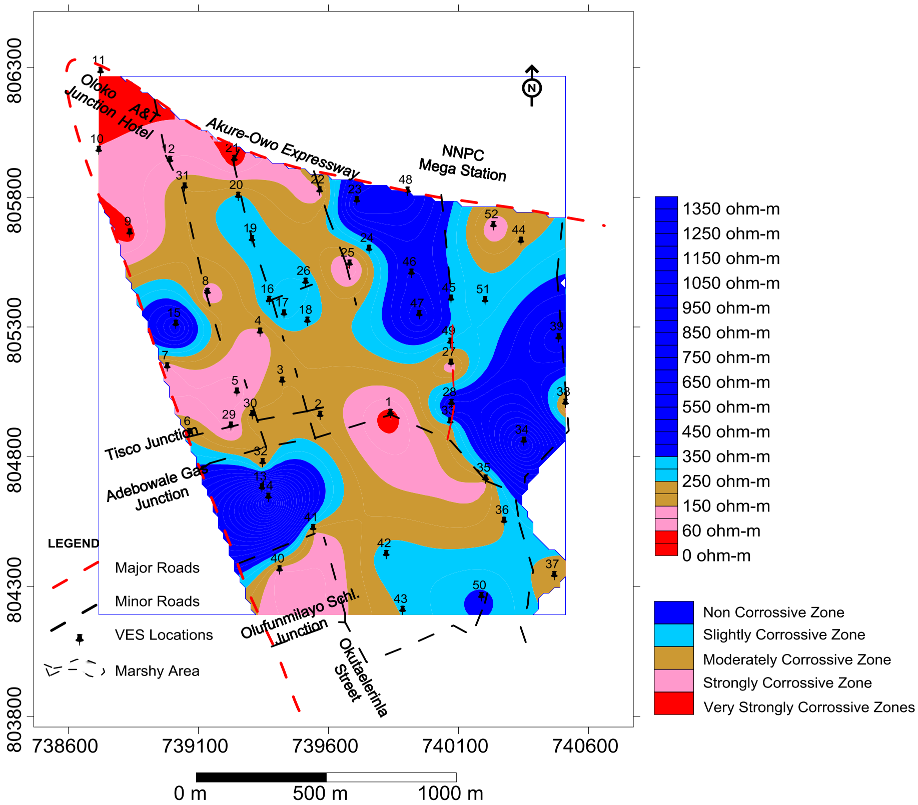

Fig. 4 Resistivity Depth Slice at 1 m

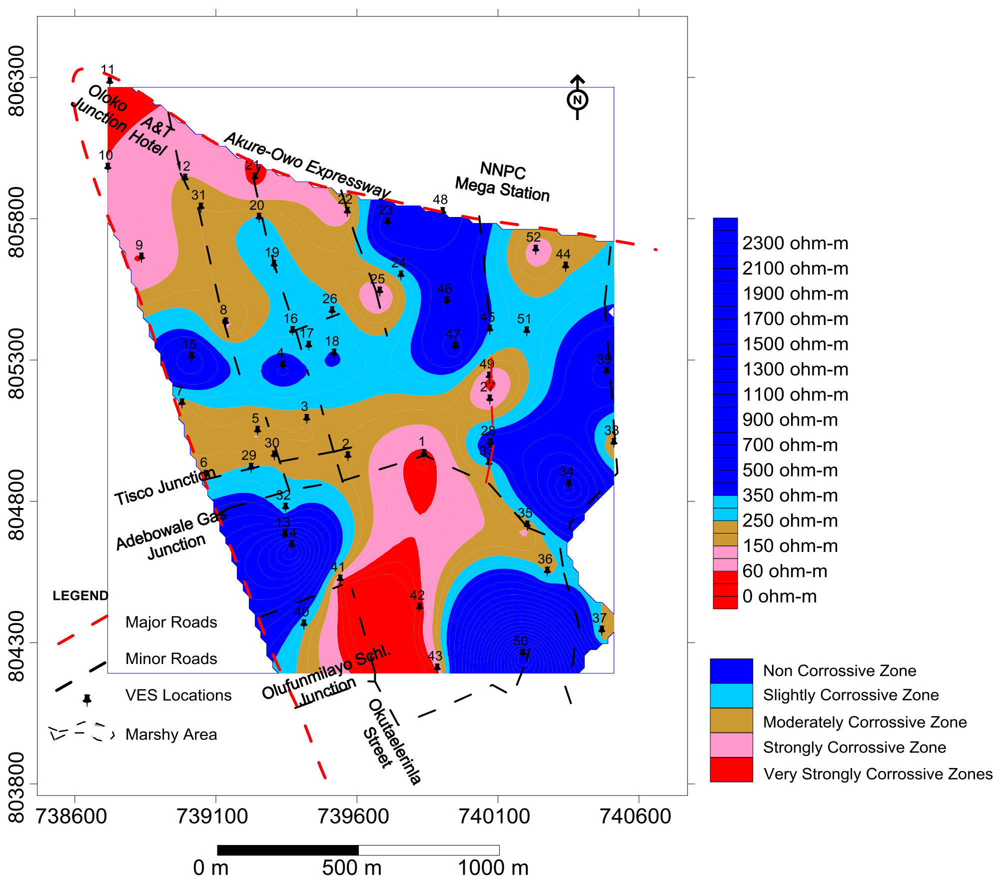

Fig. 5 Resistivity Depth Slice at 2 m

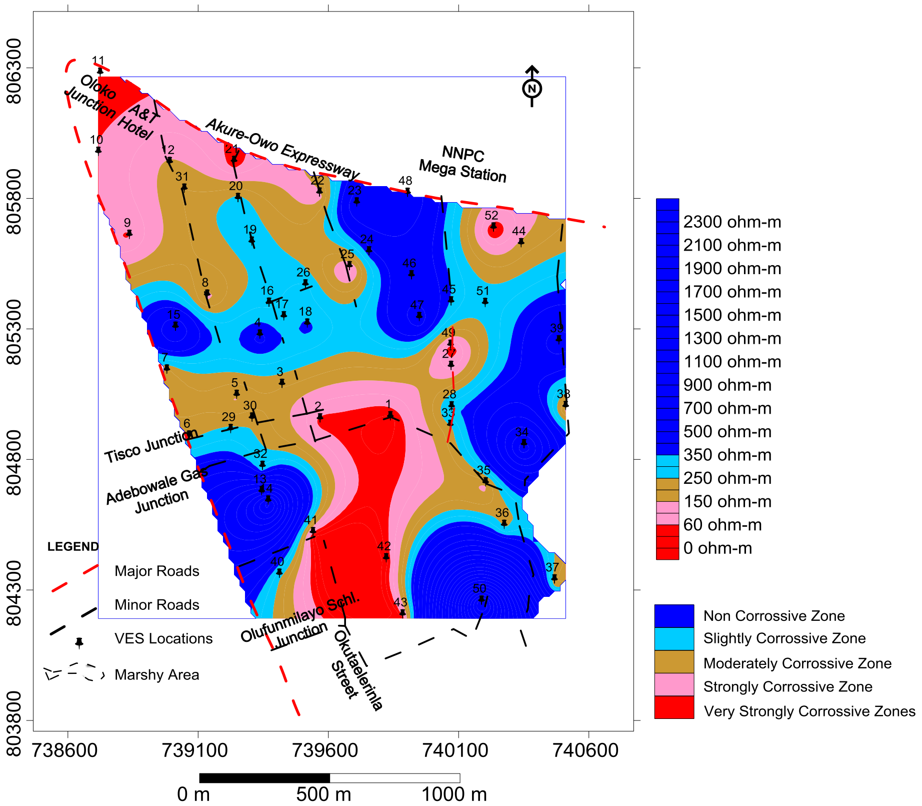

Fig. 6 Resistivity Depth Slice at 3 m

3.3 Corrosivity Model Map

The depth slice isoresistivity of 2 m and clay plasticity factor were synthesized using additive model (Chachadi, 2005 and Adeyemo *et al.*, 2017) to generate subsurface corrosivity model map and the mathematical relationship for the CR-index value was given in equation 1. The depth slice isoresistivity of 2 m was considered the most appropriate because most metallic utilities (storage tanks, pipes and others) were buried around 2 m depth and also the soil samples were taken from the same depth of 2 m. The two factors; clay plasticity and subsurface resistivity were assigned weight according to their perceived contribution to corrosivity (Table 3) and each factor were given different ratings based on their increasing values (Tables 4 and 5).

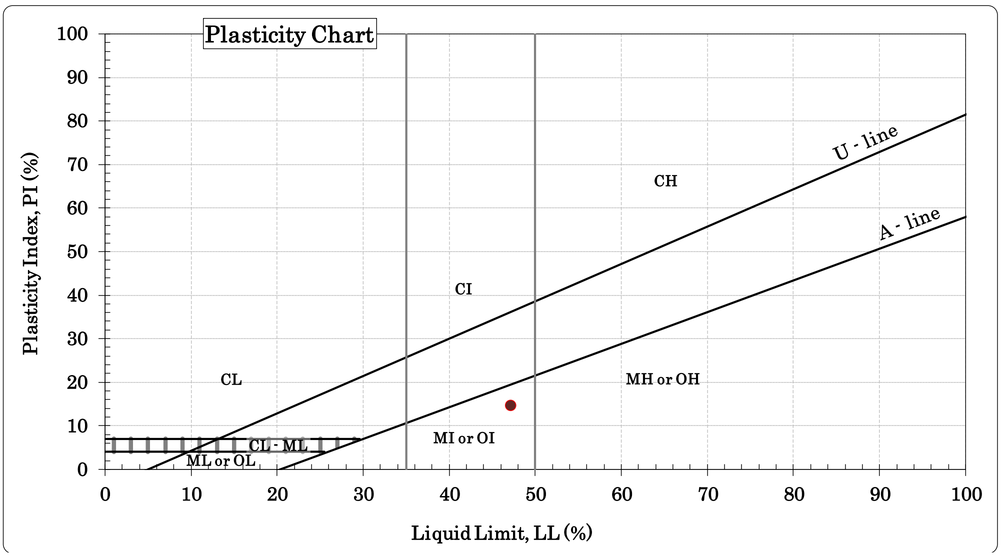

Fig. 7a Plasticity Chart of Sample A

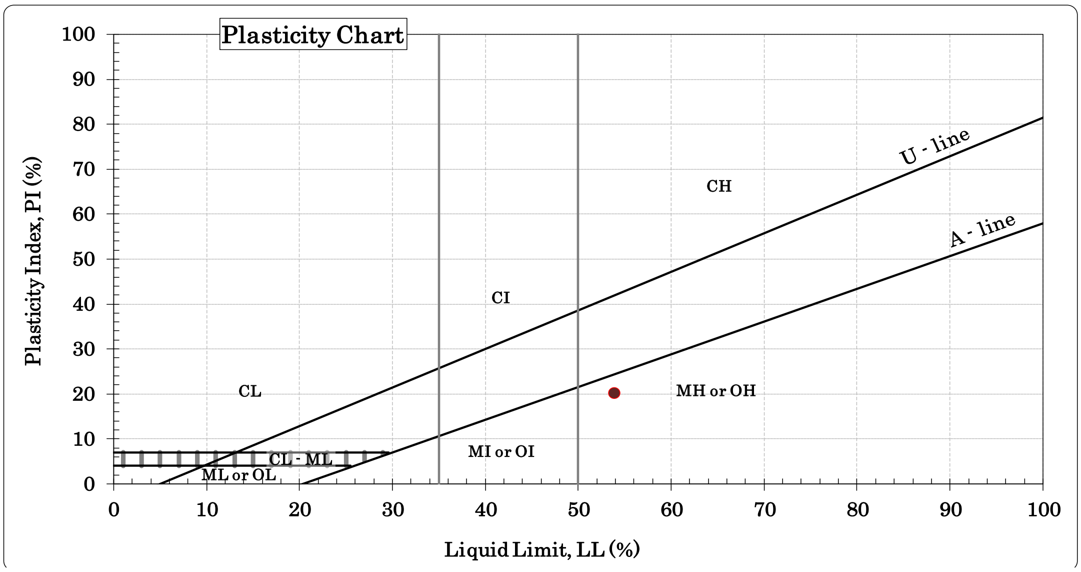

Fig. 7b Plasticity Chart of Sample B

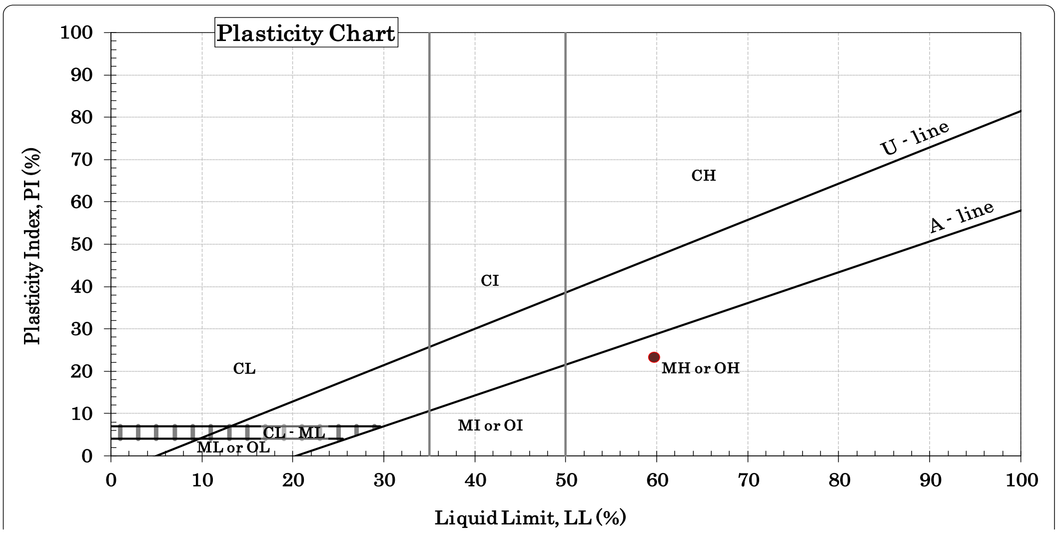

Fig. 7c Plasticity Chart of Sample C

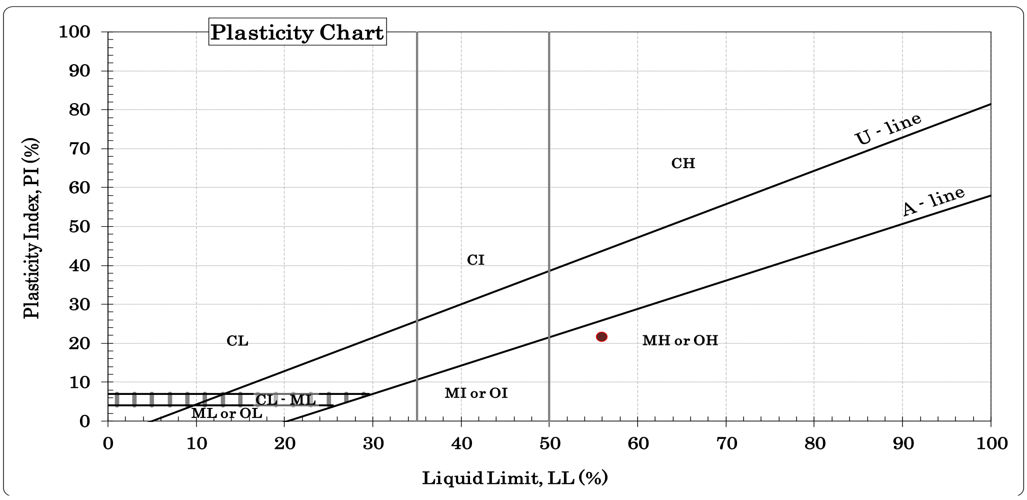

Fig. 7d Plasticity Chart of Sample D

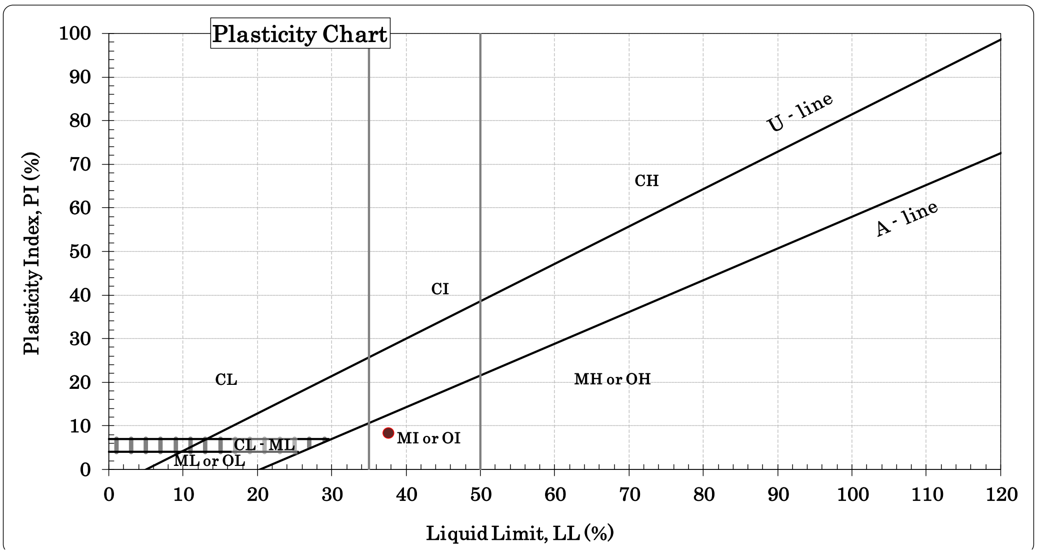

Fig. 7e Plasticity Chart of Sample E

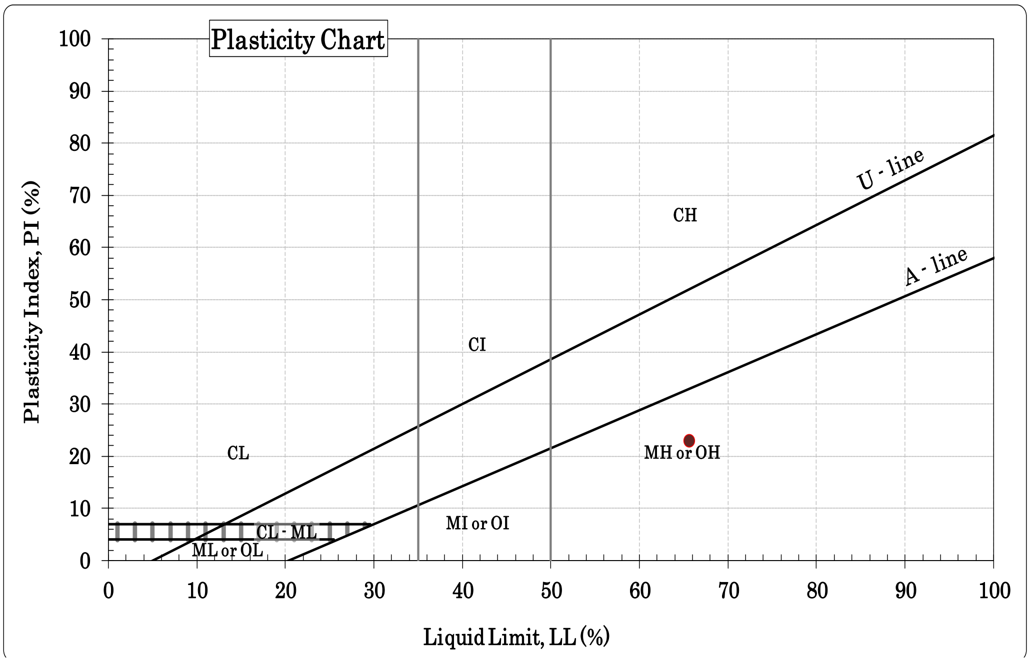

Fig. 7f Plasticity Chart of Sample F

Table 2 Summary of Consistency Limit Tests and Moisture Content

Sample Location	Natural Moisture Content	Consistency Limits		
		LL%	PL%	PI%
A	21.4	47.1	32.3	14.8
B	32.5	53.8	33.5	20.3
C	33.5	59.7	36.4	23.35
D	25.7	55.9	34.2	21.75
E	28.6	37.6	29.3	8.35
F	35.5	65.6	42.5	23.1

The clay plasticity and subsurface resistivity were synthesized using the following relationship;

$$\text{The CR-index value} = [(Wt_{Clay\ Plasticity} * Rt_{Clay\ Plasticity}) + (Wt_{Surb\text{-}Rest} * Rt_{Surb\text{-}Rest})] \quad (1)$$

where,

Wt = Weight

Rt = Rating

The CR-index corrosivity model map (Fig. 8) shows that the northwestern, northeastern and southern parts of the area are most vulnerable to corrosivity. They are considered to be moderately (0.4 - 0.6) to strongly corrosive (0.6 - 0.8), while the upper central of the area and the flanks are considered to be slightly corrosive (0.2 - 0.4). It was observed that the moderately and strongly corrosive zones correspond to low lands and water logged parts of the study area. The CR-index corrosivity model map was validated using the obtained pH and conductivity values from the physico-chemical analysis of soil samples (Table 6). The pH (5.5 - 6.9) and conductivity (007 - 086) values indicated that the samples are slightly acidic and moderately conductive and this obviously validated the generated CR-index corrosivity model. Soil pH is one of several properties used as a general indicator of soil corrosivity and generally soils that are either highly alkaline or highly acid are likely to be corrosive to metals while soils that have pH of 5.5 (Table 6) or lower are likely to be highly corrosive to concrete.

Table 3 Weighting of factors for Subsurface Corrosivity

Parameters	Normalized Weight
Subsurface Resistivity	0.63
Subsurface Plasticity	0.37

Table 4 Rating of Clay Plasticity

Clay Plasticity	Rating
Plastic Clay (above U-Line)	0.75
Non-Plastic (between A and U line)	0.50
Non-Plastic Clay (below A line)	0.25

Table 5 Rating of Resistivity

Iso-resistivity (ohm-m)	Rating
0 – 60	1.0
60 – 150	0.8
150 – 250	0.6
250 – 350	0.4
350 – above	0.2

Table 6 pH and Conductivity Test Results

Sample Location	pH	Conductivity (mhos)
A	6.7	033
B	6.9	086
C	6.5	039
D	6.4	029
E	5.7	042
F	6.2	007

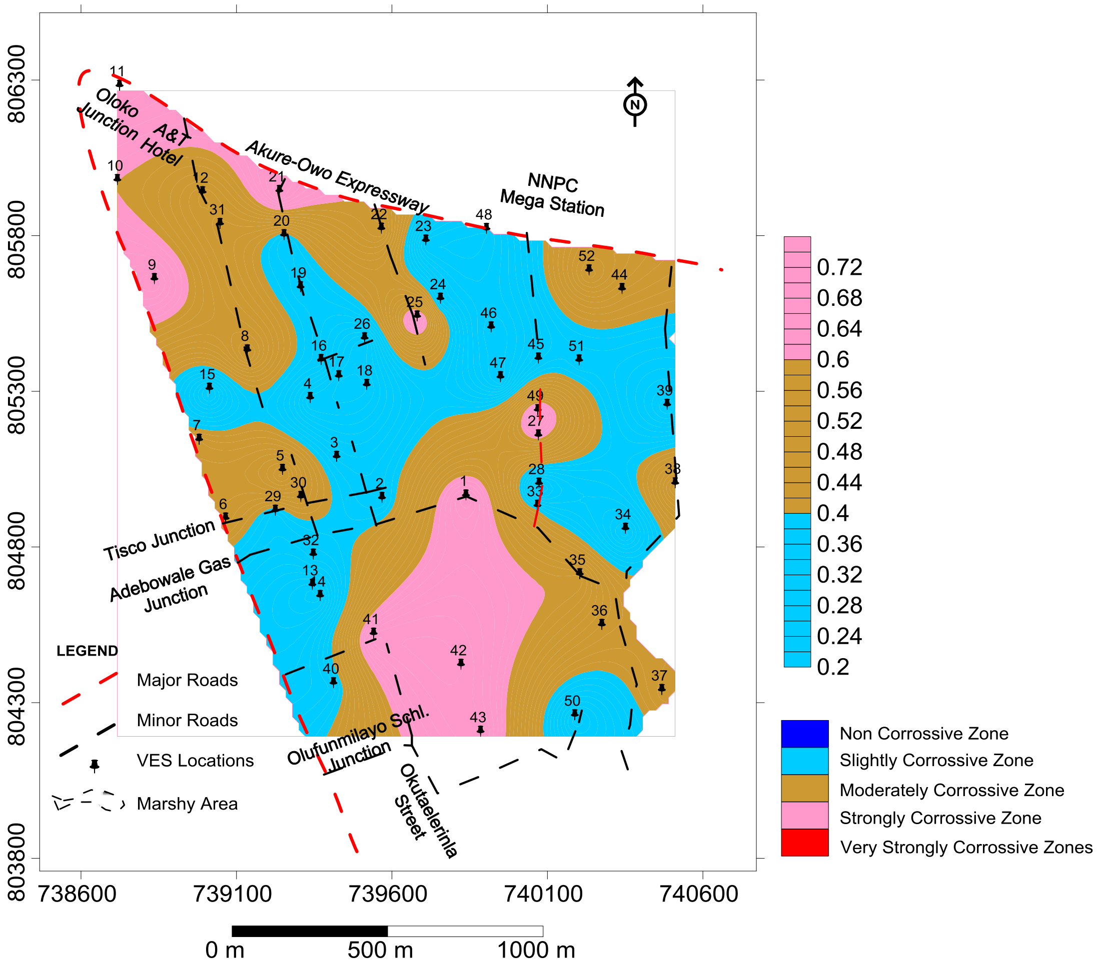

Fig. 8 CR-Index Corrosivity Model Map of the Study Area

4 Conclusions

Fifty two vertical electrical sounding (VES) data and six subsurface soil samples were collected at Ondo State Industrial Layout, Akure, Nigeria to determine the subsurface corrosivity. The iso-resistivity maps at depth slices of 1 and 2 m shows that the northeastern, southeastern and the upper central part of the area are non-corrosive (above 350 ohm-m) to slightly corrosive (250 - 350 ohm-m), while the lower central, northwestern and southwestern parts of the area are moderately (150 - 250 ohm-m) to strongly corrosive (60 - 150 ohm-m). Soil sample analysis results shows that all the plasticity index plots were below the A line indicating presence of non-plastic clay. The natural moisture content values vary from 21.4 to 35.5 %. The 2 m depth slice isoresistivity map and clay plasticity factor were synthesized to generate subsurface CR-index corrosivity model map which shows that the northwestern, northeastern and southern parts of the area are moderately (0.4 - 0.6) to strongly corrosive (0.6 - 0.8), while the upper central area and the flanks are slightly corrosive. The moderately and strongly corrosive zones correspond to the low elevation and water logged zones of the study area. The corrosivity model map was validated by the pH and corrosivity data.

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