Geoelectrical investigation of external corrosion of earth buried pipeline in the coastal area of Gulf Of Guinea

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Abstract: Earth buried transmission pipeline which is coated and protected by impressed current cathodic protection system have been noted to show evidence of external corrosion in its segment buried within low resistivity geomaterials. The resistivity of the geomaterials within the pipeline environments was investigated using electric drilling technique set-up in Schlumberger array. The earth resistivity measured at Ikot Abasi showed low resistivities (12.41-520Ωm), while the geomaterials at Ikot Osuteng produced high resistivity values (1616-15272Ωm). Potential profiling employing close interval potential survey was used to determine extent of the external corrosion as well as the effectiveness of the cathodic protection system. The potential at Ikot Abasi ranges between 331-910mV while that of Ikot Osuteng ranges between 1117-1811mV. The standard practice protective criteria (SP0169) of -850mV showed that the pipeline segment at Ikot Abasi is under severe corrosion while the segment at Ikot Osuteng is well protected by the cathodic protection system.

[Okiwelu, A. A., Evans, U. F. , and Obianwu, V. I. **Geoelectrical Investigation of External Corrosion Of Earth Buried Pipeline in The Coastal Area of Gulf Of Guinea.** Journal of American Science 2011;7(8):221-226]. (ISSN: 1545-1003). http://www.americanscience.org.

Key words: Potential, Protection, Cathodic, Resistivity, Corrosion, Pipeline

Introduction:

Pipeline used for the transportation of petroleum products are usually of steel material (alloy of carbon and iron). The iron content of steel wares off when the pipeline is exposed to hostile subsurface conditions thereby, degrading the pipeline. Corrosion weakens the strength, ductivity and other mechanical properties of a pipeline. This often results in the failure of pipeline when allowed to continue without mitigation. Accompanied with pipeline failure are potential explosion, human and economic risk and environmental disaster (Okoroafor, 2004; Alawode and Ogunleye, 2011). The primary protection for earth buried pipeline against failure due to external corrosion is surface coatings, while cathodic protection systems serve as secondary protection, especially where there are coating holidays (Rajani and Kleiner, 2003; Osakuni and Abam 2004; Koster, 2004; Wansah, 2008 and Evans et al., 2010). The major cause of external corrosion of earthburied pipeline is the soil resistivity which gives a better prediction of soil corrosiveness than any other soil properties (Andrew et al., 2005). Therefore, soil resistivity measurement is imperative in the investigation of external corrosion of buried pipelines.

Soil resistivity can be measured “On line” or “Off line”. The Off line measurements involve collection of core sample within the pipeline environments. The resistivity of the sample is measured in the laboratory using resistivity box (Rim-rukeh and Awatefe, 2006). The “On line” method is referred to as in-situ method; it involves taking surface measurement in the field. The most popular of this method in corrosion investigation are horizontal profiling with Wenner array or vertical profile with Schlumberger array (Ekine and Emujakporue, 2010; Osakuni and Abam 2004 and Evans et al., 2010). A detailed corrosion investigation requires the combination of soil resistivity measurement and electrical potential profiling. The electrical potential profiling uses close interval potential survey (CISP) to scan the pipeline for flaws; this helps in predicting the extent of corrosion as well as the effectiveness of the functioning cathodic protection system installed for the pipeline. CISP involves potential profiling using a saturated $Cu/CuSo_4$ electrode, a high impedance voltmeter, coated copper wire and making electrical contact to the pipeline at test stations spaced along the pipeline route. However, Raouf and Ahmed (2011) reported that pipe-to-soil potential of any earthburied pipeline could equally be obtained segmental along the pipeline route without the need for both the test stations and $Cu/CuSo_4$ half cell. This is by using the new electric concept of pipe-soil-earth system. This method, however has not gained enough confidence in corrosion studies. Crude oil and gas pipelines are considered protected when the minimum potential of –850mV or more negative value measured with Cu/Cuso4 is achieved (SP0169-2007 criteria).

The nature of the local geology and the presence of stray current sources along the pipeline right of way in the area of study were sources of motivation for this study. Stray current has been noted to be a major cause of cathodic protection failure due to induced stray voltage on the pipeline which later flow off pipelines through low resistivity geomaterials. Induced voltages destabilizes the cathodic protection system allowing the cathodic part of the corrosion cell to behave as anode, thereby causing corrosion on the pipeline in the face of the functioning cathodic protection system that may be installed for the pipeline. This has been a major problem in the petroleum industry. Even though the pipelines have been subjected to impressed current cathodic protection, there is still some degree of corrosion which leads to explosion of the pipelines and eventual environmental degradation. This study demonstrates a geophysical approach for the detection and mitigation of external corrosion of the pipelines in the part of Nigerian sector of the Niger Delta.

The study area is in close proximity to the Jaja creek which opens into the Gulf of Guinea in the Southern part of Nigeria. Geographical coordinates of the study area lies between lat. $4^0\ 30^{'}$ N – $4^0\ 45^{'}$ N and long.$7^0\ 30^{'}$ E – $7^0\ 42^{'}$ E (Figure. 1). The area is typical of the Niger Delta flood plains with an equatorial climate. The forest in the area is swampy with mangrove trees and experiences two seasons (wet and dry) which are not clearly defined. The wet season is noted for heavy rain fall while dry season do have light showers of rain. This gives rise to seasonal fluctuations in the ground water table in the area. The near surface geology of the study area shows that the sediments are muddy, clayey, silty and lateritic and of medium-coarse and poorly sorted grained sands. The area is regionally underlain by the Quaternary to Tertiary near shore sediments of the Benin Formation (Figure 2).

Materials and Methods:

The flow of electrical current through an electrolyte can be represented by Laplace's equation (Adey and Hang, 1999), given as

$$\rho \nabla^2 E = 0 \qquad (1)$$

where E is the potential gradient and ρ is the resistivity of electrolyte. The introduction of Green's theorem to the Laplace's equation, gives the boundary element method formulation (Brebbia and Dominguez, 1980):

$$\int_{\Sigma} E\left(\nabla^2 E^*\right) d\rho = \int_{\Gamma}\left(q^{\bullet} E - E^* q\right) d\Gamma \qquad (2)$$

where E^* is the weighting function, q is the normal derivative of E, ρ is resistivity of electrolyte, q^* is the normal derivative of E^* and Γ is the surface condition of the pipe given by

$$\Gamma = \Gamma_A + \Gamma_c + \Gamma_1 \qquad (3)$$

where Γ_A is the anode surface, Γ_c is the cathode surface, and Γ_1 is the insulated (coated) surface. Applying variable transformation in equation (2) and introducing boundary elements, we have

$$K_j E_j = \sum_{j-1}^{N} \int_{\Gamma j} \left(E^* q - E q^*\right) d\Gamma_j \qquad (4)$$

where N is the numbers of boundary elements and K is a dimensionless constant.

The matrix form of equation (4) is given by

$$[A]\{E\} = \{J\} \qquad (5)$$

where $[A]$ is the coefficient of the matrix, $\{E\}$ is a vector of unknown values of potential and normal electric field on the boundary, and $\{J\}$ is an independent vector, which represents the current density.

The electrode Kinetics describes the oxidation and reduction processes that take place between the anode and cathode respectively. These processes can be expressed mathematically as non-linear relationship involving the density current and potential on the metallic surfaces (Adey and Hang, 1999) given as:

$$Ja = fa(Ea) \qquad (6)$$

$$Jc = fc(Ec) \qquad (7)$$

where a and c are anode and cathode respectively, J is the current density, f is a function which represents the relationship between the potential and current due to electrode kinetics, and E is the surface electro potential. Equations (6) and (7) are functions of structure and environmental factors. In most cases one of the important factors is the buildup of calcareous deposits on the cathode section of structure (pipe) wherever the structure is polarized sufficiently in saline environment. This deposit is in addition to any organic film and marine growth being formed (Harvey, 1995). The polarization reduces the effective surface area of the structure involved in the corrosion process by introducing an additional physical resistance, which builds up over time. Thus polarization describes not only the electrochemical reduction but also the environmental factors, which can generally be expressed as

$$J = f\left(E, h, v, D, T\right) \qquad (8)$$

where v is the flow velocity of the electrolyte (in this case, it is referred to as transmissivity), D is depth, T is the temperature and h is the film thickness.

Equation (8) can be assembled to form a mathematical model in vector form given by (Adey and Niku, 1992):

$$\vec{J} = \vec{B}(E, h, v.......) \quad (9)$$

where $\vec{B}$ is a coordinate vector.

Applying equation (9) to equation (5) we have

$$AE = B(E, h, v, A........) \quad (10)$$

Therefore,

$$A - B(E, h, v......)/E = O \quad (11)$$

Equation (11) is the non-linear system of equations, which can be solved to obtain the potential E and consequently current density J.

The soil electrical resistivity was measured using McOhm terrameter and its accessories. During the field survey all precautionary measures to ensure that the pipeline does not influence measured resistivity were adhered to. One of such precautions was planting of electrodes not closer than 5m to the pipeline right of way (Figure 3). The vertical electrical sounding (VES) technique employing Schlumberger electrode array was used to obtain fourteen (14) sounding using two chosen profiles. The maximum current electrodes spacing used for the investigation was forty (40) meter; this was due to the relative shallow depth of burial of the pipeline (1.8m). For detailed survey, the sounding points were chosen between 20-25m along a profile parallel to pipeline right of way.

The pipe-to-soil potential measurement was carried out using the "On" mode close interval survey at a spacing of 5m intervals. The $Cu/Cuso_4$ electrode was used as a reference electrode (nonpolarizable electrode) and a contact was made with the permanent test points. The potential between the pipeline segment and the soil was recorded from the high impedance voltmeter (Figure 4). Resistivity data analysis started with the conversion of measured resistance to apparent resistivity values, which were then manually plotted against half the current electrode spacing for purposes of manual smoothening. The smoothened data were fed into IPI2Win software developed for forward modeling. The data obtained were iterated using the same software to obtain the final geoelectrical layer parameters.

Results and Discussion

Typical model curves for the study area are presented as Figure 5 and 6. A correlation of the VES data with geology of the area obtained from borehole lithology log shows that the geologic section differs slightly from the geoelectric sections in their thickness. Hence different resistivity values were assigned to the same geologic layer. This is due to the near surface variations in the electrochemical properties of the soil. However, the resistivity range indicates the same geologic material between 1.8 and 9m (Figure 7). Therefore a good correlation was achieved. Figure 8 also shows a good correlation between geology and geoelectrical sections. The pipe-to-soil potential measured shows evidence of corrosion as well as ineffectiveness of the cathodic protection system at Ikot Abasi indicating that the protective potential is more positive than – 850mV (Figure 9). The pipeline segment at Ikot Osuteng produces potential more negative than -850 mV. Therefore, this segment of pipeline is considered to be adequately protected.

The presence of stray current sources periodically play down on the effectiveness of the cathodic protection system which causes current to flow off the pipeline along the path of least earth resistance. The resistivity survey showed that Ikot Abasi is the site for low resistivity. This low resistivity is due to the clay mineral delineated at pipeline depth. Hence it is the site for corrosion hot spot. Whereas the high resistivity values of geomaterials at Ikot Osuteng impedes current from flowing off the pipeline, hence the pipeline segment is maintained as cathode with respect to the environment. The corrosion nature of the pipelines adjacent to the study area had earlier been reported by Ogbonna (2008) using atmospheric corrosion mechanism. The results from this study have shown that the subsurface is also corrosive to buried metals

Conclusion:

This study shows that the pipeline segments in the area of study are well protected at Ikot Osuteng but poorly protected at Ikot Abasi. The presence of stray current sources along the pipeline right of way is believed to destabilize the functioning cathodic protection system leading to current flowing off the pipeline through the low resistivity geomaterials at Ikot Abasi. The geomaterials identified at Ikot Abasi are lateritic and clayey with low resistivity (14.81-37.22 Ωm) within the limit of maximum current penetration. While the geomaterials identified at Ikot Osuteng were medium - coarse grained sands and fine sands with high resistivity values (1132-3710Ωm). These differences in geomaterials as well as their resistivities variation along the pipeline depth invariably made the segment at Ikot Abasi anodic with respect to the cathodic segment at Ikot Osuteng. However, if the effectiveness of the cathodic protection system was not sacrificed by the stray current sources in the pipeline environments, every segment of the pipeline will remain protected. To mitigate corrosion due to stray current, an earthing system compatible with the functioning cathodic protection system is recommended. The earthing system will complement the cathodic protection system as well as the coating system. This can go a long way to safeguarding the pipeline against external corrosion. Excavation for direct inspection and repairs is also recommended.

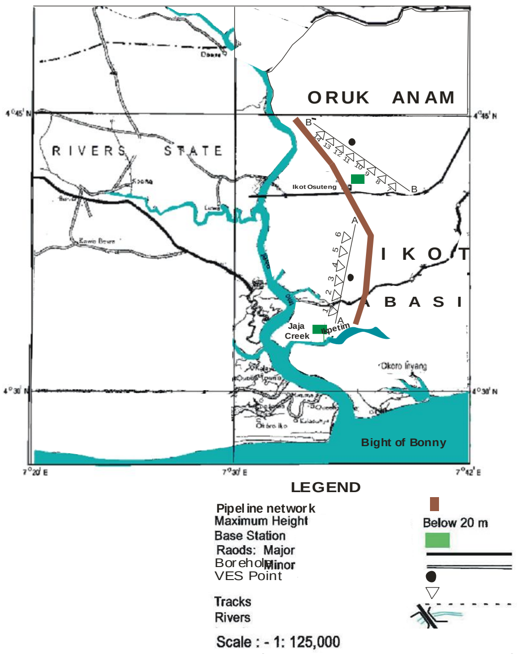


Figure 1. Location map of the study area (Adapted from soil and land use map of Akwa Ibom State, 1989)

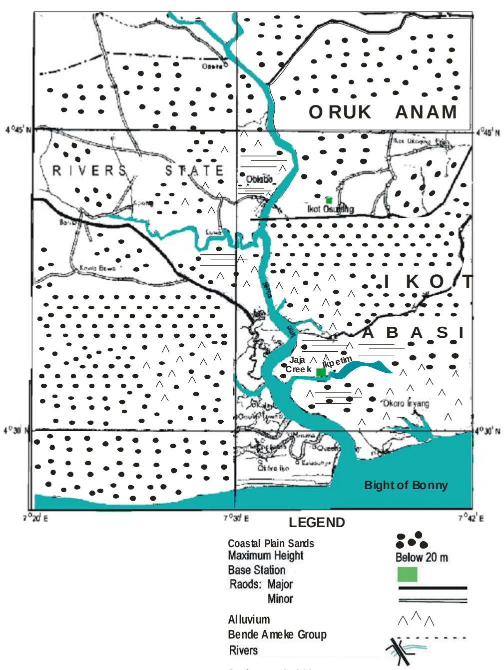


Figure 2. Geological map of the study area (Adapted from soil and land use map of Akwa Ibom State, 1989)

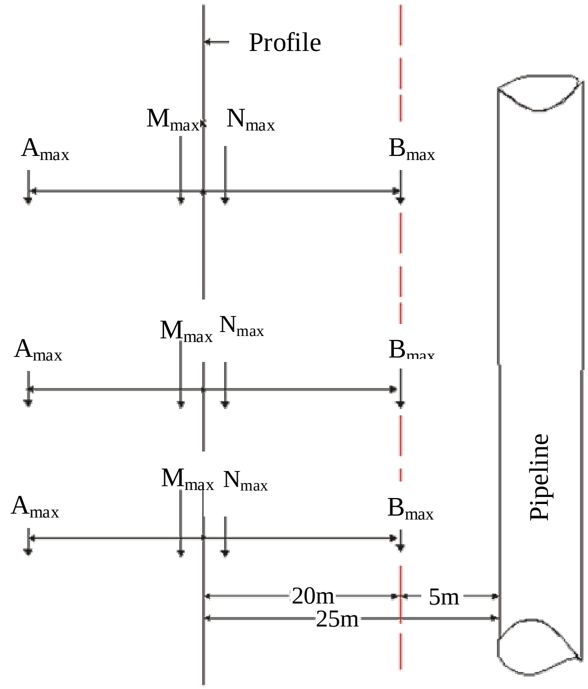


Figure 3. Resistivity measurement within earth buried pipeline system

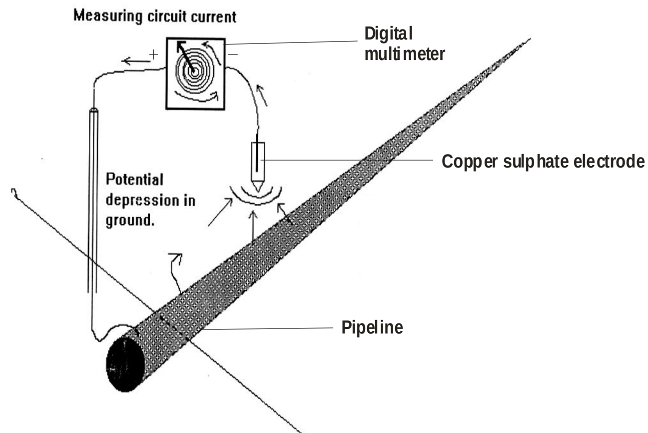
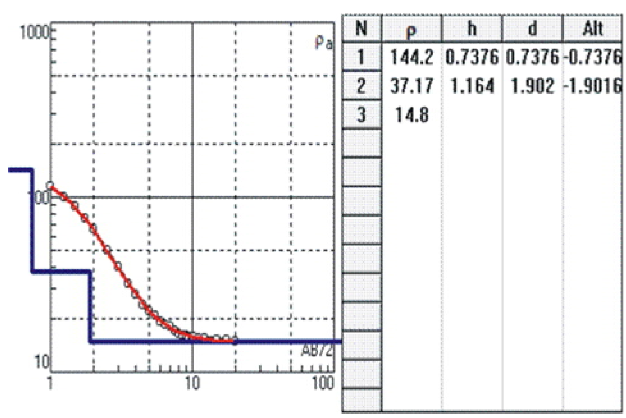


Figure 4. Electrical potential profiling using close interval survey



N	ρ	h	d	Alt
1	144.2	0.7376	0.7376	-0.7376
2	37.17	1.164	1.902	-1.9016
3	14.8			

Figure 5. Representative modeled curve for Ikot Abasi

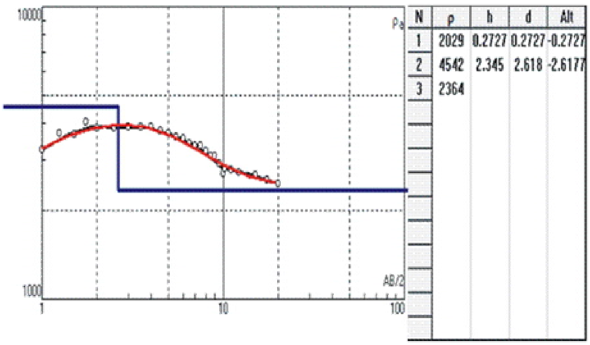


Figure 6. Representative modelled curve for Ikot Osuteng

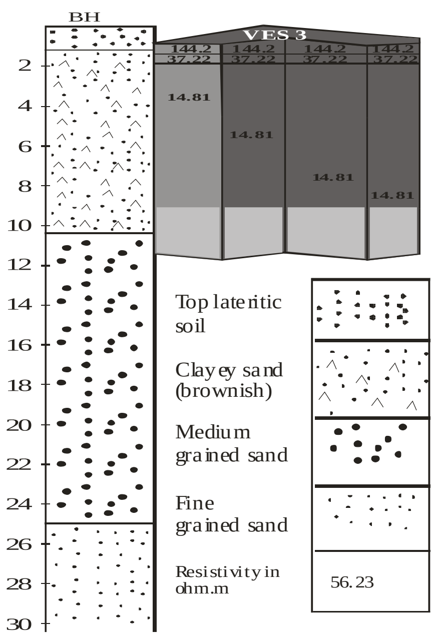


Figure 7. Correlation of VES data with borehole log at Ikot Abasi

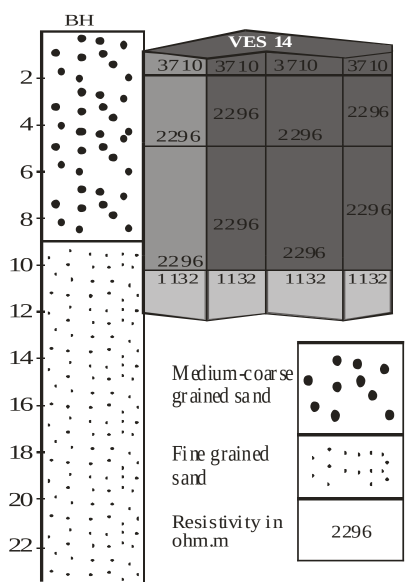


Figure 8. Correlation of VES data with borehole log at Ikot Osuteng

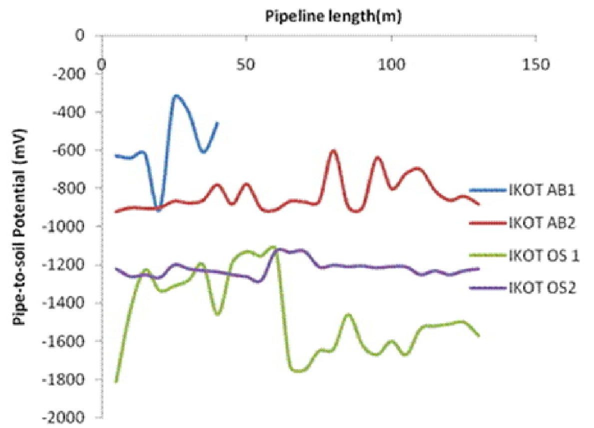


Figure 9. Graph of pipe-to- soil potential against pipeline length

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