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Integration of 3-D and 4-D Time Lapse Geo-Resistivity Techniques for Oil Spill Characterization in Kegbara-Dere, Gokana, Rivers State

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Abstract: ***Intensive monitoring of oil spills is required to investigate the dynamic processes which occur in a spill site over a period of time. The use of time-lapse tomographic algorithm is required to obtain the image of the dynamic processes resulting from the hydrocarbon contamination. 3-D resistivity data acquisition usingorthogonal sets of 2-D on a 50 by 100m grid for measuring the resistivity values at various time-lapse phases and monitor the contaminant dynamics in the study area. ERT models from repeated resistivity investigation on the same spot which were conducted at second phase (time-lapse) within nine months, shows a marked reduction in resistivity values. Data interpretation and modelling using earth imager revealed change in the resistivity values, contaminant volume and depth. Subsurface resistivity values at initial phase monitoring is higher than the values obtained from final phase monitoring implying dynamics in contamination and attenuation over time.***

Keywords: 3D and 4D geophysics, electrical resistivity, contaminant plume, oil spill, hydrocarbon, depth-slice, time –lapse, tomography, resistivity anomaly, environmental studies for oil spill, spill remediation monitoring

1. Introduction

The earth is a 3-Dellipsoid and heterogeneous in nature, therefore soils and rocks properties change with time. In regions affected by oil spills, there is need to monitor these changes over time using multi-dimensional using resistivity techniques such as 3-D and 4-D. This is because 1-D and 2-D (Wenner and Schlumberger) techniques does not provide all the necessary information as regards to subsurface dynamics which result from hydrocarbon contamination. Albert Einstein proposed the concept of the 4th dimension as the introduction of abstract concepts of time and space.4-D imaging is required to investigate the changes which occur within a body over time. Hydrocarbon is a complex phenomenon, which requires the use of integrated techniques to monitor the changes which occur with time, so as to obtain the requisite information that would be useful for future remediation.

2. Study Area

Kegbaradere is part of the Gokana Local Government area of Rivers State, Nigeria. It is located along these geographical coordinates: Lat 7°25"36' & 7°26"70' and Long 4°67"60' & 4°67"43'. The area is deltaic plain with a low-lying topography with elevation ranging between 3-6m above seas level. It is part of the Niger Delta and it bears similar lithologies, vegetation and relief with other parts of the Niger delta. The study area is located within the prolific prospective Niger Delta region, and sits on several oil reserves which have resulted to massive oil exploration and production from multinational oil companies. (UNEP 2011) Kegbara-dere community is populated with about 50, 000 persons. It was initially a hotspot for oil exploration and production activities, but oil industry activities has ceased due to violent clashes resulting from oil spill pollution in the area which can be seen from various oil spill relics. There is an environmental emergency in the area as a result of persistent and pervasive oil spill which has led to the total devastation of the soil and water on which the lives of the people depend on, thereby affecting their means of livelihood. There is need to monitor the area to provide information that would be relevant for remediation.

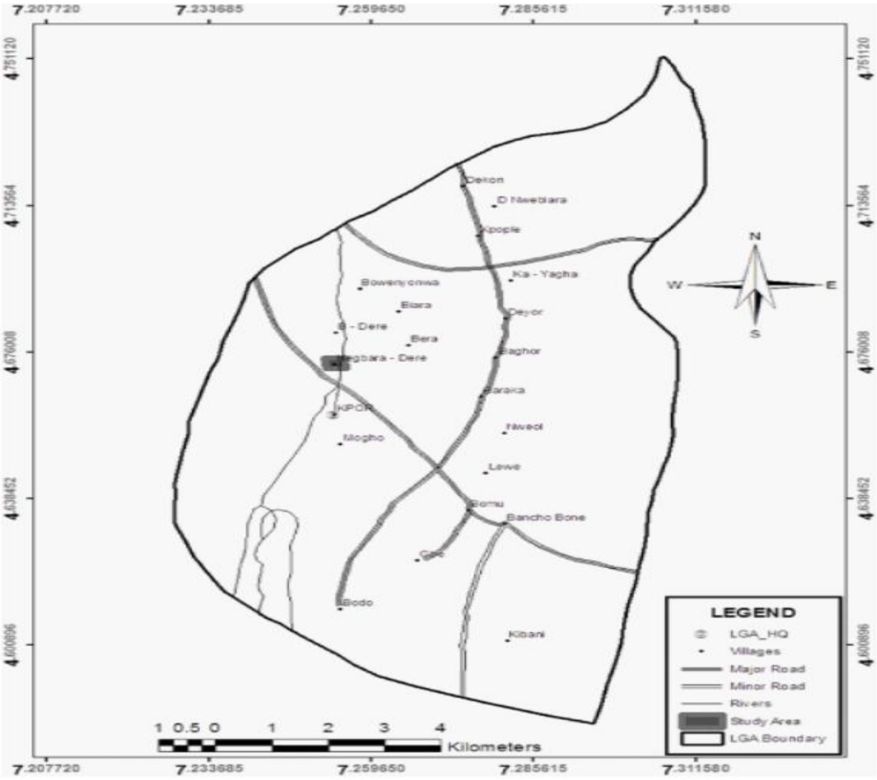


Figure 1: Map of Gokana LGA with K-Dere inset (UNEP2011)

3. Materials and Methods

The materials used for this investigation include: PASI 16-GL hybrid resistivity meter, 21 electrodes, cables, hammer, base map, etc. The materials used for 3-D and 4-D are the same with the materials used for conventional 2-D resistivity technique, but the array used for 3-D is a new technique and differs in geometry and configuration. American Geophysical institute (2003) opined that the purpose of various arrays is to obtain different sets of information. The data acquired from each technique depends on the array spread and configuration. The area was surveyed using21 electrodes arranged on a 50m by 100m rectangular grid (See Figure 3). The purpose is to obtain the 3-D model of the area under investigation. Unlike the 2-D conventional techniques which requires measurement of resistivity changes in two directions (x and y). The 3-D resistivity measures and obtains apparent resistivity changes along three directions (x, y, z).

Figure 2: Data acquisition

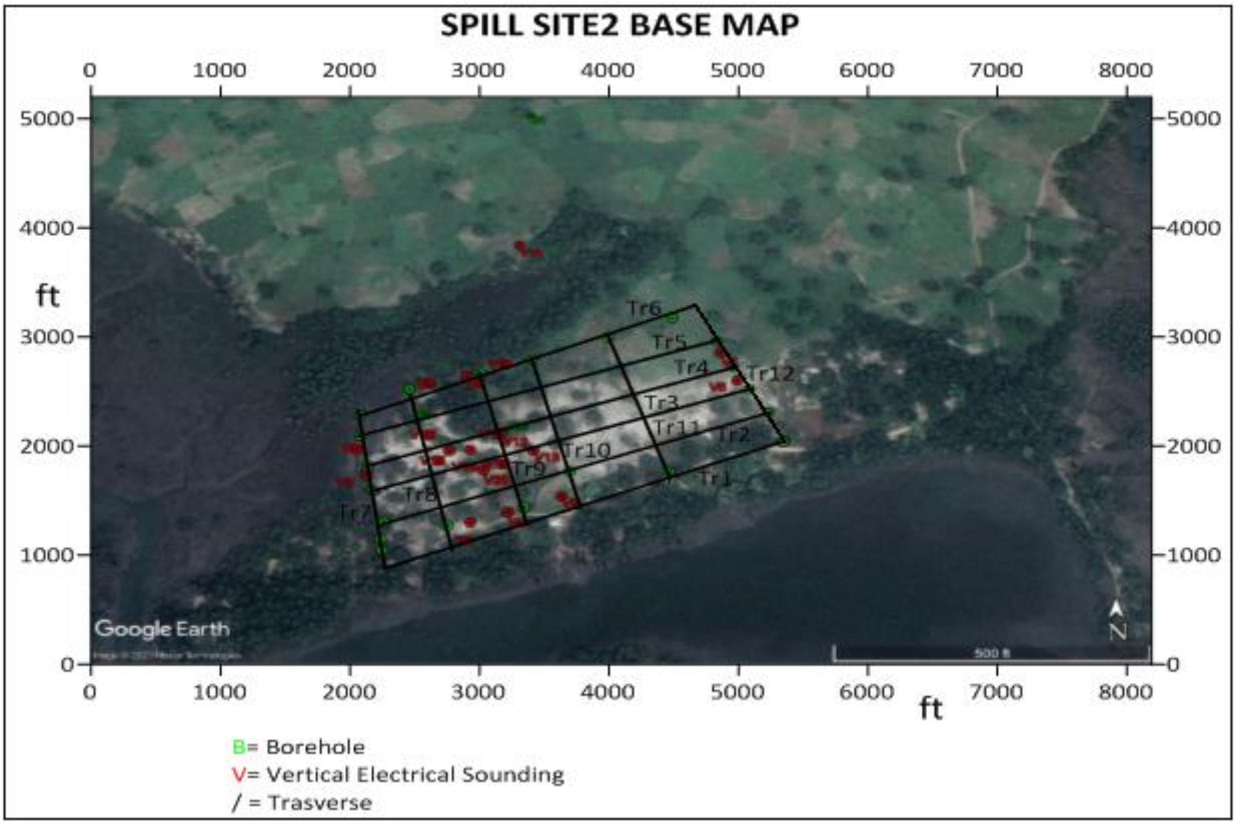


Figure 3: 50m by 100m grid on the Base map of the spill site for 3-D and 4-D acquisition

Due to the complexities associated with the composition and distribution of oil spill contaminants, it is necessary to use a method that can provide information forvarious dimensions of subsurface resistivity measurements. Using the conventional 1-D and 2-D resistivity techniques (Wenner and Schlumberger) obtained measurements are due to resistivity changes in only two directions, therefore 2-Dresistivity tomogram sections can only reveal limited information about the subsurface (Slater et al, 2002).3-D electrical resistivity technique can be deployed to provide a more accurate model of the subsurface because it obtains measurements due to resistivity variations in three directions, namely the vertical, horizontal and perpendicular directions, the x, y and z respectively (Loke, 2004).

3-D resistivity technique is laborious, expensive and time – consuming and has less often been used for oil spill investigation. It requires a different electrode configuration which is usually carried out in a grid. Wenner-Schlumberger method was used to obtain data along orthogonal sets of traverse lines on a rectangular gridded area with dimension 50m by 100m (Figure 3). The electrodes were placed along measured points of the grid traverses and the measured apparent resistivity readings are displayed at the meter and recorded for each of the points on traverses. All the data were collated using a collation code and fed into the Earth Imager program to generate inversion model of the area. The model obtained from 3-D data acquisition is a 3-D resistivity cube tomogram representing the subsurface volume.4-D investigation is useful for monitoring and it involved the repetition of the 3-D acquisition along the same grid traverse over a period time.

The earth is heterogeneous and its processes are dynamic. It is believed that there would be significant changes over the same region with time. The 4-D involves repeated 3-D resistivity measurement on the same point at various times so as to obtain relevant information which reveals changes in apparent resistivity of the affected spill site under investigation. Therefore, the concept of the fourth ($4^{th)}$ dimension was introduced into the data acquisition which is the introduction of an abstract concept of time to the 3-D measurement.4-D is deployed for the purpose of determining the contaminant changes. In the study area, the first phase of the monitoring (time-lapse 1) was done in November 2021, while the second phase of the monitoring (time-lapse 2) was acquired in September 2022. The first phase was monitored during the rainy season whereas the 2^{nd} phase was monitored during the dry season.

4. Interpretation

The 3-D model of the area was obtained by software iteration using the Earth Imager program (Fig 5a and 5b).3-Dtomograms reveals the length, width and depth of the contaminant within the subsurface. The tomogram model is the 3–D resistivity cube tomogram (Figure 4) for the various phases of time-lapse investigation. The 3-D resistivity tomogram is an iteration of the hydrocarbon contaminant volume of the region under investigation. The depth-slices were obtained using least-squares inversion for various layers of the 3-D tomogram. Depth-slices are used for 4-D studies to investigate the internal dynamics of the hydrocarbon plume across the layers (Figure 6).3-D contaminant volume can be determined provided that, the length and the width of the grid and depth of the contaminant plumes are known, then the contaminant volume of the polluted area can be estimated as follows:

The 3-D tomogram at phase 1 reveals resistivity signatures as high as 10, 000Ωm (Figure 5a) at first phase while the resistivity value is reduced at 2nd phase to 7191Ωm (Figure 5B)

A) Resistivity value of contaminant plume at 1ST phase monitoring of oil spill siteis 10, 000 Ωm at depth of 19m.

Contaminant volume calculated using volume (Length x width x depth)
Length of the rectangular grid= 100m
Width of the rectangular grid =50m
Average Depth of the contaminant plume=19m
The volumeof the plume under the gridded area = Lxbxd
Average plume at first phase monitoring: 100m x 50 x 19m= 90, 000 m^3

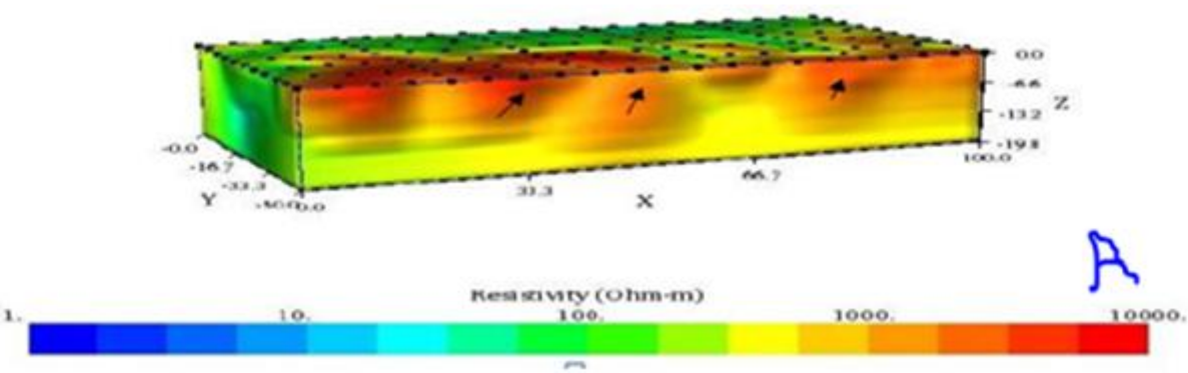
B) Resistivity value of contaminant plume at 2nd phase monitoring is 7, 191 Ωm at depth of 13.2m

Contaminant volume calculated using volume (Length x width x depth)
Length of the rectangular grid= 100m
Width of the rectangular grid =50m
Average Depth of the contaminant plume=13.2m
The volume of the plume under the gridded area = Lxbxd
Average plume volume at second phase monitoring: 100m x 50 x 13.2m= 66, 000 m^3

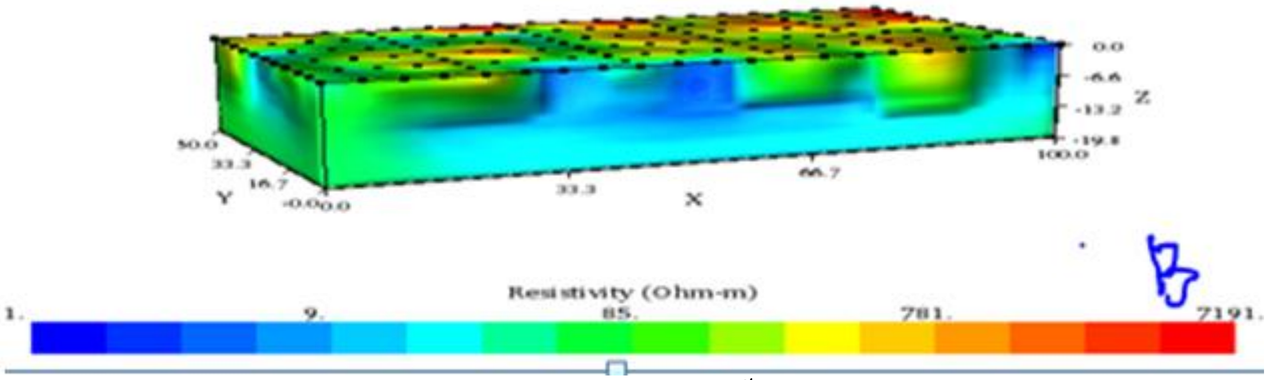
The resistivity value obtained for the first monitoring is as high as 10, 000Ωm and average contaminant volume is 90, 000 $m^{3.}$

The first monitoring was conducted during the rainy season. It is possible that the precipitation contributed by the rainy season led to increase in the plume volume within the subsurface. The high plume volume and high resistivity values indicates the prevalence of high amounts of liquid phase hydrocarbons within the aquifers during the rainy season. On the other hand, the resistivity value for the 2nd phase is 7191Ωm and the computed contaminant plume volume for the second phase monitoring hasreduced to 66, 000 $m^{3.}$ The second monitoring was conducted during the dry season. The absence of precipitation during the dry season is also responsible for the reduction in spill contaminant volume. During the second-phase monitoring, the average plume volume is low and the resistivity values were also low which implies that, there is a reduction of liquid phase hydrocarbons within the aquifers during the rainy season. The reduction in resistivity values is indicative of the reduction in spill strength during the dry season. It is assumed that attenuation is caused by mechanisms such as dispersion and degradation.

3-D and 4D (3-D time-lapse) tomograms



A: 3-D Electrical Resistivity Cube Mode for oil spill site at K-dere at 1st Phase Monitoring (Nov 2021)

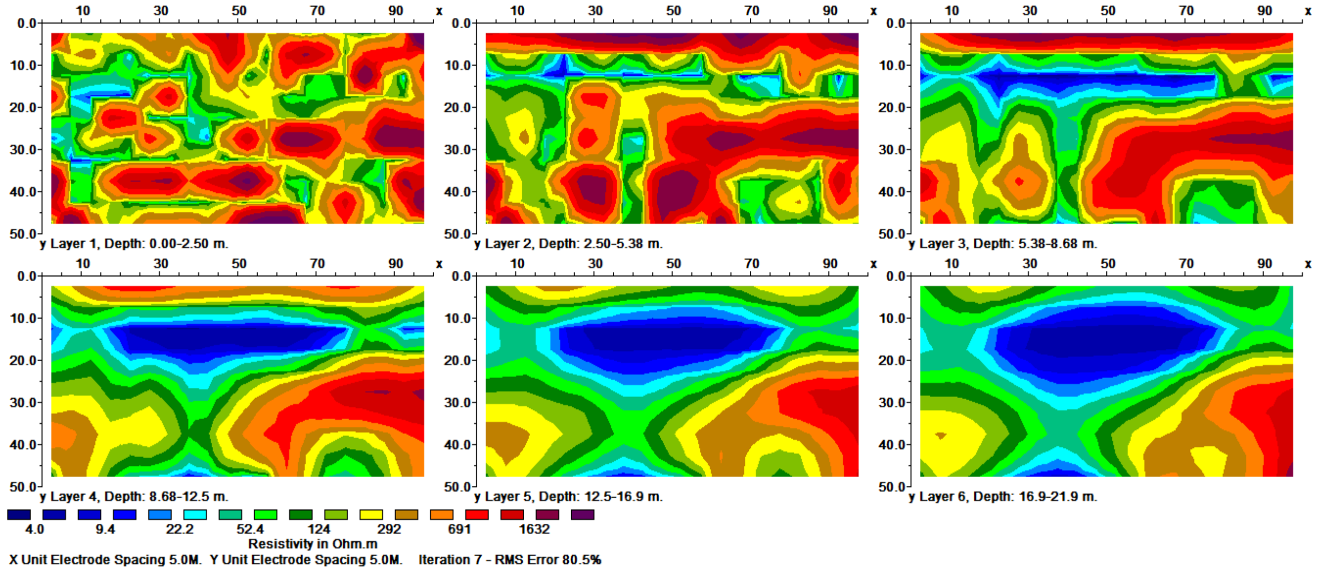


A: 3-D resistivity tomogram for oil spill site at K-dere at 1st Phase Monitoring (September 2021)

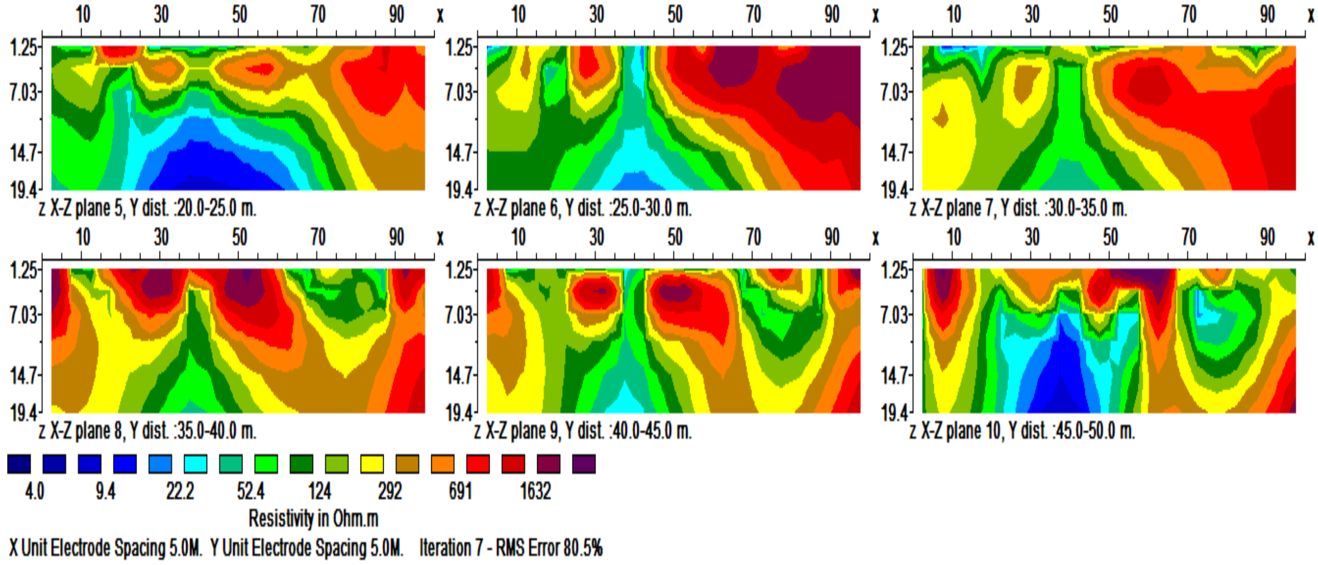
Figure 5: 3-D tomogram for firstand second-phase monitoring arranged in 4-D time lapse mode

Images reveal contaminant dynamics showing the variation in contamination

A) Resistivity value of contaminant plume at 1ST phase monitoring of oil spill site is 10, 000 Ωm at depth of 19.5m
B) Resistivity value of contaminant plume at 2nd phase monitoring is between 100Ωm-7, 191Ωm at depth of 13.2m



A: Horizontal depth slice from phase-1 monitoring at spill site



B: Horizontal depth slice at phase-2 monitoring at spill site.

Figure 6: Horizontal depth slices across six layers

Horizontal depth slice across six layers obtained from 3-D tomograms for the 1st and second phase monitoring reveals the dynamics of the individual contaminant plumes (See Figure 6). From the depth-slice sections of the layers, the contaminant dynamics as well as migration patterns of the contaminant plumes were identified. The anomalies (in red) shows migration pattern towards the North. The depth slice for Figure 6A indicate plumes with high resistivity signatures as high as 7000 to 9500 Ωm.

5. Conclusion

From the research, it is possible to monitor and image subsurface dynamic processes within a unit area of a polluted site. The volume and depth of the hydrocarbon contaminant in the investigated area can be modelled using the integration of 3-D and 4-D electrical resistivity techniques. The knowledge obtained from this research can be integrated into other literatures and can serve as a tool for estimating contaminant volume and changes within the region. The migration pathways of the plumes can be modelled using the horizontal depth-slices as a tool for predicting the migrating behaviours of the plume. The information from these findings are also required for remediation.

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