Research Journal of Environmental and Earth Sciences 4(3): 270-281, 2012
ISSN: 2041-0492

Submitted: November 17, 2011 Accepted: December 27, 2011 Published: March 01, 2012

Imaging and Detecting Underground Contaminants in Landfill Sites Using Electrical Impedance Tomography (EIT): A Case Study of Lagos, Southwestern, Nigeria

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Abstract: This paper presents an imaging technique called Electrical Impedance Tomography (EIT) which is a purely medical imaging technique, for imaging and detecting underground contaminants in landfill sites in Abule Egba and Solous 1 dumpsites in Lagos, Nigeria. Conventional electrical imaging technique using Wenner configurations was also carried out on each of the sites in order to validate the EIT results. Three methods of impedance data acquisition techniques were employed; neighboring, opposite and cross and the inversion of the data was accomplished using the Electrical Impedance and Diffuse Optical Reconstruction Software (EIDORS) version 3.0 toolkit for MATLAB to obtain three - dimensional conductivity profiles. The scheme utilized in this work is a forward solution solved with a mesh of 768 finite elements with 205 nodes. The conventional electrical resistivity data was inverted using DIPRO software to obtain 2D resistivity structures. With the aid of the 3D impedance tomograms, two distinct contaminant plumes were mapped and identified within and around the landfills. These are highly conductive leachate contaminant plumes with conductivity values ranging from 1,000 to 5,000 mS/m and highly resistive gaseous contaminants (with negative conductivity values on the tomograms) which are probably due to landfill gases as a result of the anaerobic decomposition of the landfill organic wastes. These contaminants are migrating in depths and distance away from the landfills into the aquifer. The study shows that the soil and groundwater system had been contaminated beyond the depth of 50 m in the study areas.

Key words: Aquifer, contaminants, electrical impedance tomography, groundwater, landfills, leachate

INTRODUCTION

Characterizing and imaging the underground conditions of landfills and the location of subsurface contaminants has always been a challenge. Conventional environmental monitoring used to determine the spread and fate of groundwater contamination is performed by the expensive and labour intensive task of drilling closely spaced boreholes for point sampling (Granato and Smith, 1999; Adeoti *et al*., 2008). More advanced, non-invasive geophysical techniques, less costly and more environmental friendly, were developed as tools for interpreting the underground structures without disturbing them. Contaminant plumes usually have a sufficiently high contrast in physical properties against the host media due to an increase in dissolved salts in the groundwater and a resulting decrease in pore water resistivity; therefore they may be detected by geo-electrical techniques (Ayolabi and Peters, 2005).

The generation of leachate in a landfill results principally from the flow of percolating water through waste materials (Olowofela and Akinyemi, 2001). Leachate composition is determined by the nature of the waste at a specific site, the amount and rate of flow through the waste and the in-situ geochemical conditions. The evolution of leachate composition in a waste landfill site typically follows a four-stage decomposition process from aerobic, anaerobic, methanogenic and returning to aerobic conditions as degradation nears completion (Radulescu *et al*., 2007). The aerobic and methanogenic phases generate high concentration and acidic leachate, which has high contaminative potential and the potential to mobilise metals. Waste decomposition also leads to the generation of gas as a separate phase and/or dissolved in the leachate.

In most developing nations, almost one hundred percent (100%) of generated waste goes to landfill. Because of this, landfill is likely to remain a relevant source of groundwater contamination (Ugwu and Nwosu, 2009). The management of solid waste landfills has been a major problem of urban centers in Nigeria and other developing countries worldwide. These urban centers have witnessed tremendous increase in population. In recent past, wastes are generated daily and disposed indiscriminately in rivers and landfills without recourse to the underground environment, local geology and their

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Fig. 1: Abule-Egba dumpsite

Fig. 2: Solous 1 dumpsite

proximity to the living quarter and as such, huge masses of diverse wastes are generated far more than could be removed (Ball and Stove, 2002).

Lagos State is the commercial nerve centre of Nigeria and is small in landmass, having 3,600 square kilometres area, with an approximated population of about 15million people (United Nations Report, 2010). The state presently has a very high population density of over 4, 000 persons per square kilometer. According to United Nation (UN) estimation, going by 6% growth rate, Lagos will be the third largest mega city in the whole world by the year 2015 (United Nations Report, 2010). This will consequently increase the quantity of waste disposed.

The Electrical Impedance Tomography involves the injection of current into a body using circular electrode arrangements or configuration patterns to image the internals of the medium under investigation. The method has been extensively used in the medical field to image organs of interest. It allows the generation of three - dimensional (3D) images of electrical conductivity for a given profile or volume of ground. The technique is suitable for non-invasive investigation of landfill sites due to its sensitivity to high electrical contrasts as caused by changes in material types, fluid saturation and ion concentration levels. Most waste fluids are highly conductive due to their elevated ion concentrations. In contrast, dry waste or regions with high concentration of landfill gas tend to be associated with high electrical resistivities. Electrical images, or tomograms, can provide valuable insight on the distribution of waste and waste fluids within landfills as well as identity potential flow paths.

The study, therefore, aims to experiment the use of Electrical Impedance Tomography in landfill sites investigations with the specific objectives of identifying the presence of any contaminants at the sites and to examine the reliability and effectiveness of the method which is a purely medical imaging technique.

Sites description and accessibility: The study areas are two dumpsites in Lagos State. These are some of the major dumpsites controlled by the Lagos State Waste Management Authority (LAWMA, 2007). They are: Abule- Egba dumpsite at Agbado- Oke- Odo Local Council Development Area, Fig. 1; and Solous 1 dumpsite at Alimisho Local Government Area (Fig. 2). Abule-Egba dumpsite is bounded by Lagos - Abeokuta expressway in the East and other regions by residential buildings, filling stations, offices, and Ile-Epo markets. Its geographical location is 6.87ºN, 3.38ºE. The dumpsite is located on a 21-hectare of land and was opened in 1982. The waste at this site is dumped in one area adjacent to the only vehicular entrance to the site. Due to lack of proper equipment, the waste has been “pushed” only so far inwards as the equipment on site can go. As a result, the waste elevation is much higher near the entrance compared to further back. With no soil cover, heavy burnings of the waste has been occurring over time and continued random burning was observed during the work at his site. The site is accessible by tarred road.

Solous 1dumpsite is along LASU-Isheri expressway and covers an area of about 7 hectares. Its geographical locations are 6.53ºN, 3.32ºE. It is surrounded by residential, commercial and industrial set-ups and has witnessed rehabilitation which consisted of reclamation of land, construction of accessible road for ease of tipping, spreading and compaction of waste since inception. This was ongoing during the course of this study. Solous 1 receives waste from entire Lagos metropolis. In its quarterly report, Lagos State Waste Management Authority reported that a total of 469,202.50 ton of Municipal Solid Waste (MSW) was land filled in 2007 alone (LAWMA, 2007). It is accessible by tarred roads.

The waste stream in both sites is made up of domestic, market, commercial, industrial and institutional origins. The wastes are of different types, ranging from organic to inorganic, hazardous and non-hazardous.

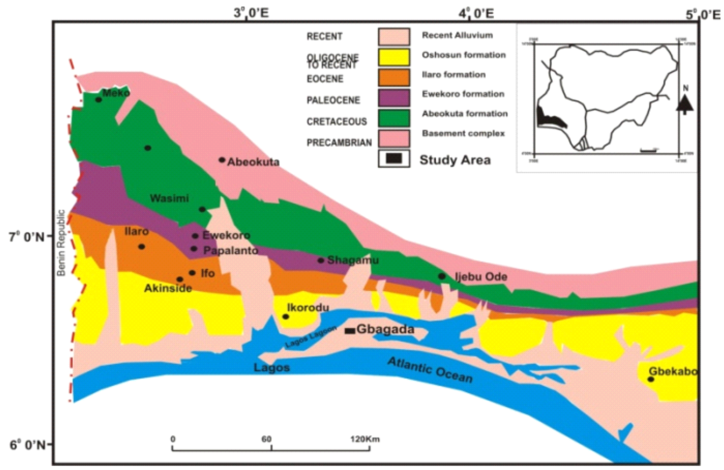


Fig. 3: Geological map of eastern dahomey basin (Billman, 1992)

Geomorphology and geology of Lagos: The geology of Lagos was extensively studied alongside the geology of the Nigerian portion of Dahomey basin by many researchers (Jones and Hockey, 1964; Omatsola and Adegoke, 1981; Agagu, 1985; Enu, 1990; Nton, 2001). The oldest formation identified in Dahomey basin is the Abeokuta formation (Jones and Hockey, 1964). This was upgraded to a group status with three formations by (Omatsola and Adegoke, 1981), comprising Ise formation having a conglomeratic and grity base overlain by coarse to medium grained sandstone with interbeded kaolinite; followed by a coarse to medium grained sandstone with interbeded shale, siltstone and claystone, having a sandy facies that is tar-bearing while the shale is organic-rich, called Afowo formation (Enu, 1990); overlain by Araromi formation, which is the youngest in the group: a Cretaceous sediment made of fine to medium grained sandstone at the base, overlied by shale, siltstone with interbeded limestone, marl and lignite. Abeokuta group is overlain by Ewekoro formation. This formation is made of a shaly limestone unit reported to be highly fossiliforous (Jones and Hockey, 1964). Oshoshun is the next formation comprising pale greenish grey laminated phosphate and glauconitic shale of Eocene age. This is overlain by massive yellowish and poorly consolidated cross-bedded sandstone called Ilaro formation. The youngest formation in the basin is the Benin formation, also known as the coastal plain sands (Jones and Hockey, 1964). It comprises poorly sorted sands with lenses of clays.

Lagos belongs to the coastal plain sand formation which is made up of loose sediment ranging from silt, clay and fine to coarse grained sand (Fig. 3). The exposed rock unit in the area consists of poorly sorted sands with lenses of clays. The sands are in part cross bedded and show transitional to continental characteristics according to Jones and Hockey (1964), Omatsola and Adegoke (1981), Agagu (1985), Enu (1990) and Nton (2001).

MATERIALS AND METHODS

Data acquisition: This requires providing a perfect circular layout for the electrode positions. This was achieved by using the thick white thread marked out at 10m distance each for 16 electrodes. The circular layout showed where to plant electrodes on a circumference of 160m. PASI terrameter (model 16 GL) was used for the acquisition of data.

In the Neighboring method (Brown and Seagar, 1987) current is applied through neighboring electrodes and the voltage is measured successively from all other adjacent electrode pairs. Here we applied current through electrodes 1 and 2 (Fig. 4) and the voltage is measured successively with electrode pairs 3-4, 4-5, …,15-16. From these 13 voltage measurements were obtained. All these 13 voltage measurements are independent. The next set of 13 voltage measurements is obtained by feeding the current through electrode 2 and 3. This continues until current is fed into 16 and 1. For our 16 electrode arrangement, we obtained 16×3 = 208, voltage measurements.

In the Cross method of Impedance measurement (Hua *et al*., 1987) adjacent electrodes are first selected for current and voltage reference electrodes, respectively. Here electrode numbers 16 and 1 were first selected for current and voltage reference electrodes respectively (Fig. 5) the other current electrode, electrode number 2 was first used. The voltage was measured successively for all other 13 electrodes with electrode 1 as a reference. The current was then applied through electrode 4 and the voltage was again measured successively for all other 13

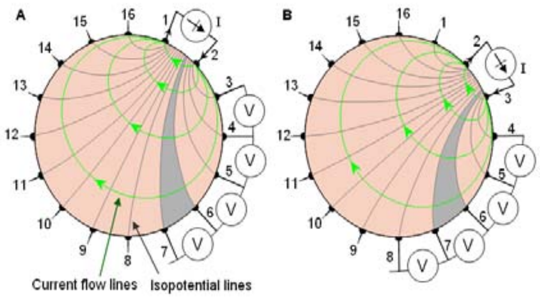


Fig. 4: The neighboring method of impedance data collection with 16 equally spaced electrodes (a) The first four voltage measurements for the set of 13 measurements are shown. (b) Another set of 13 measurements is obtained by changing the current feeding electrodes.

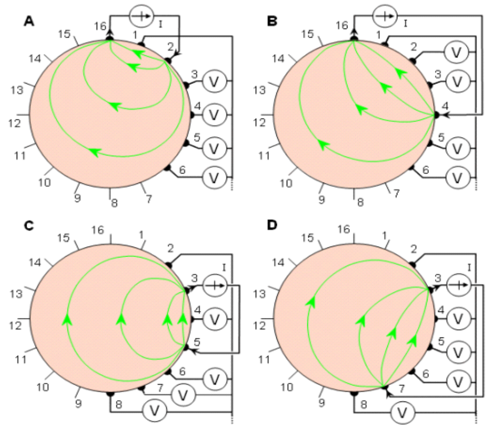


Fig. 5: The cross method of impedance data collection. The four different steps of this procedure are illustrated in A through D.

electrodes with electrodes 1 as a reference. The procedure was repeated using 6, 8, and 14; which gave 7 x 13 = 91 measurements. The measurement sequence was then repeated using electrodes 3 and 2 as current and voltage reference electrodes, respectively. We then applied current first to electrode 5 and then measured the voltage successively for all other 13 electrodes with electrode 2 as a reference. The procedure was again repeated by applying current to electrode 7, 9, 11, ----, 1 and measuring the voltage for all other 13 electrodes with 2 as a reference, we obtained another 91 measurements. From the cross method, we obtained 182 voltage measurements.

Under the Opposite method (Hua *et al*., 1987) current is injected through two diametrically opposed electrodes (Fig. 6). We first applied current through electrodes 16 and 8. The electrode adjacent to the current-injecting electrode (electrode 1) was used as the voltage reference.

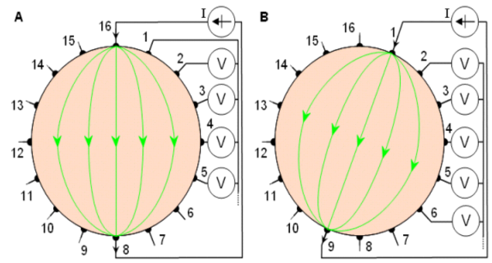


Fig. 6: The opposite method of impedance data collection

Voltage was then measured from all other electrodes except from the current electrode, yielding 13 voltage measurements. The next set of 13 voltage measurements was obtained by selecting electrodes 1 and 9 for current electrodes. This was followed by 2 and 10, 3 and 11, …., 8 and 9. With our 16 electrode arrangement, this method yielded 8×13 = 104 data points.

The Wenner array electrode configuration was used for the 2D resistivity imaging. The same PASI terrameter was used. Profiles were run on each site with measurements made at sequences of electrodes at 10m interval using four (4) electrodes at each profile to cover a distance of 160 m - 180 m. Figure 7 and 8 show the base maps of the survey areas.

Data processing and inversion: The processing of the EIT voltage data was accomplished using the EIDORS toolkit for MATLAB. It is a MATLAB program package developed collaboratively by EIT research groups in order to help advance the field of EIT as a whole. The data processing portion of this paper was accomplished with the EIDORS V3.0 toolkit (Polydorides, 2002). However, some modifications were made to the EIDORS package in this work, in the area of depth of resolution and in the number of ring used. The toolkit was essential because of the challenges in solving an EIT inversion problem which is a nonlinear, ill-posed problem that is very intensive computationally. The basis of the EIDORS package is that it utilizes a finite element model for forward calculations and a regularized nonlinear solver to obtain a unique and stable inverse solution. The package is equipped with a mesh generator, several standardized EIT methods, a graphical output, and supports two and three-dimensional EIT systems. The program calculated the inverse solution iteratively by using a weighted image prior of the homogeneous solution.

A forward modeling was used to calculate the apparent resistivity values using Dipro software (version 4.0). This program operates mathematically based upon the smoothness-constrained least squares method (Loke and Barker, 1996). The smoothness-constrained least-squares method operates based on the following equation:

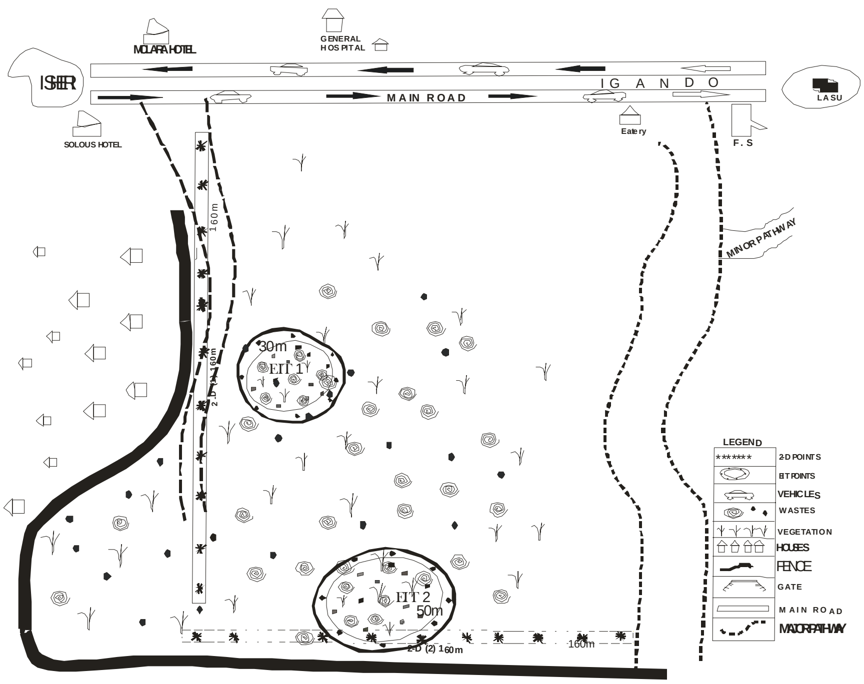


Fig. 7: Base map of abule-egba dumpsite

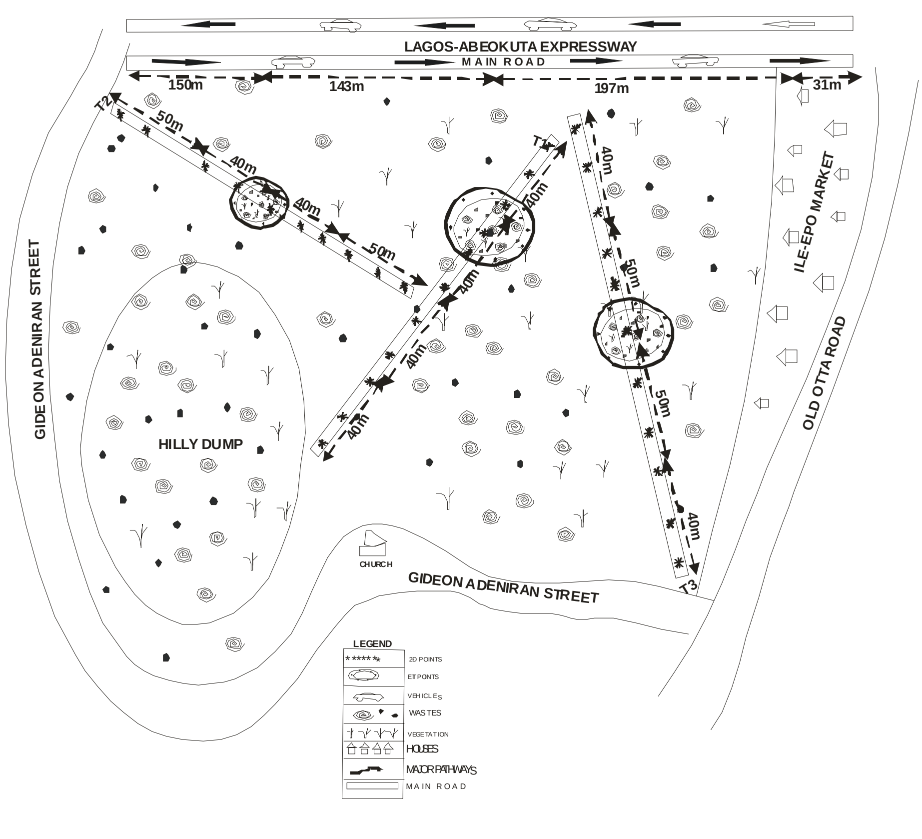


Fig. 8: Base map of solous 1

$$J^T g = (J^T J + \mu F)d$$

where, F is a function of the horizontal and vertical flatness filter, J is the matrix of partial derivatives, μ is the damping factor, d is the model perturbation vector and g is the discrepancy vector. The Dipro program amortises the bulk data into a series of horizontal and vertical rectangular blocks, with each containing a number of records. Resistivity of each block was then calculated to produce an apparent resistivity pseudo section.

RESULTS AND DISCUSSION

The scheme utilized in this work is a forward solution solved with a mesh of 768 finite elements with 205 nodes as shown in Fig. 9.

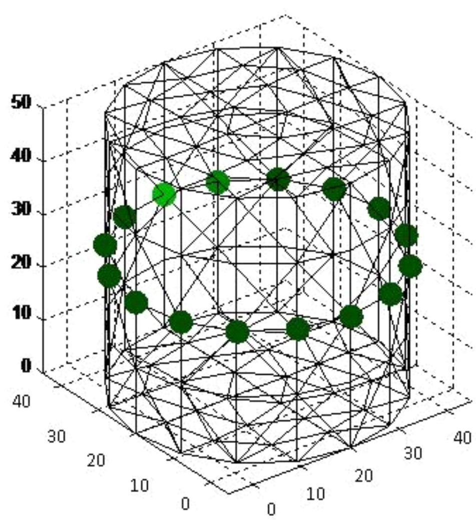
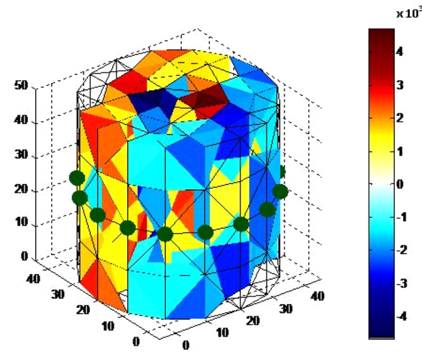


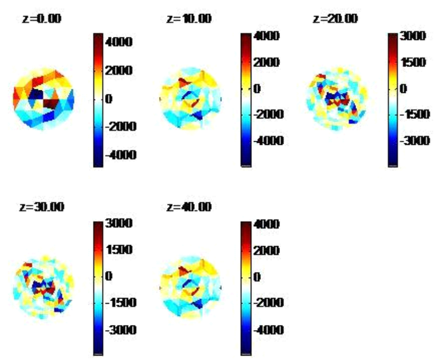
Fig. 9: Mesh diagram with 768 elements and 205 nodes

Abule- Egba results: Figure 10-15 shows the tomograms of electrical conductivity for the neighboring, opposite and cross methods of EIT at two separate locations on the site. The bs in these figures are extracted profiles at various depths from the inversion of the conductivity images. These tomograms, with conductivity ranging from 1, 000 to 4, 000 mS/m except for opposite method indicate the presence of highly conducting plumes. The negative conductivity values depict areas with very low conductivity.

Figure 10 shows the plume emanating from the western part of the landfill, in which waste is presently concentrated. The plume is relatively narrow (about 10m width) stretching from west to east to about 20m spread in the northeast. It then, spreads more widely downstream to



(a)

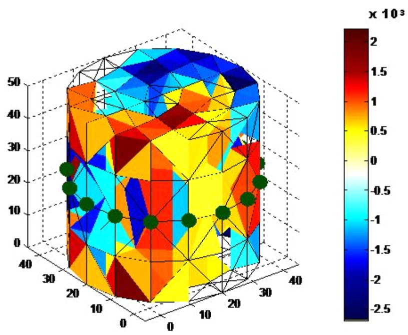


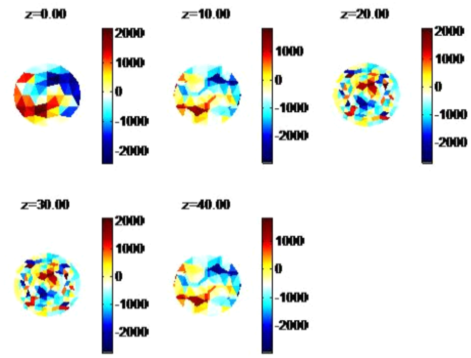
(b)

Fig. 10: (a) Neighboring method reconstructed conductivity images profile 1, (b) extracted images at different levels (in mS/m) for Abule-Egba

a depth of about 50m. This is characteristic of advective transport of contaminants. The high conductivity zones (identified as light yellow to deep red) with conductivity ranging from 1, 500 to 4, 000 mS/m were interpreted as leachate contaminant plumes which are most likely leachate from the decomposing waste materials containing dangerous pathogens, dissolved organic and inorganic constituents which were observed to have seeped from the surface to a depth of about 50m. This observed seepage is enhanced by the porous and permeable nature of the dominant sandy formations of the area. The colour scaling changing from light yellow to deep red reflects the changes in the concentration of the leachate as it seeps down due to infiltration.

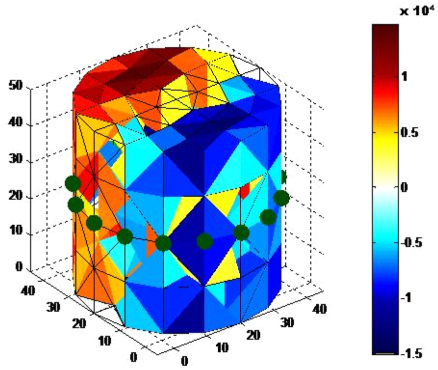
The trend of Fig. 11 (profile 2) at 25m from profile 1 looks similar to that of Fig. 10, but the contamination here has spread from the base of the dumpsite and to a depth of about 40m with conductivity values ranging from 1, 000 to 2, 000 mS/m indicative of leachate contaminant. The

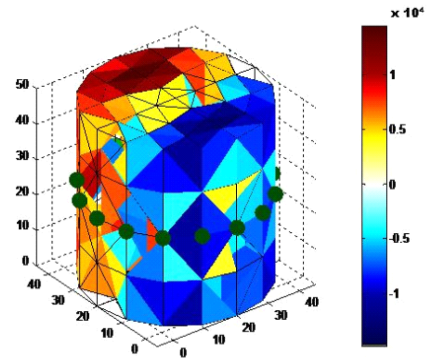




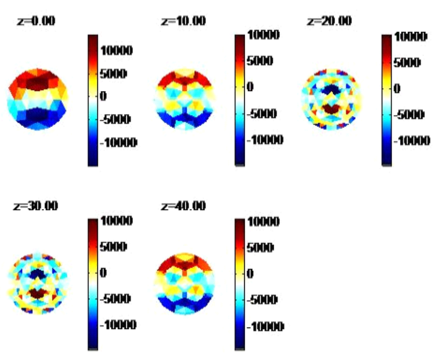
(a) (b)

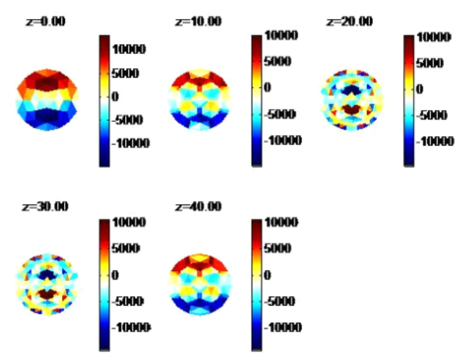
Fig. 11: (a) Neighboring method reconstructed conductivity images profile 2 (b) extracted images at different levels (in mS/m) for Abule-Egba





(a) (a)





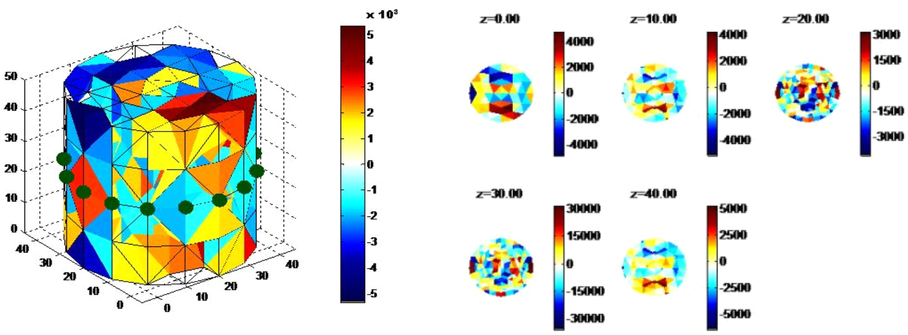
(b) (b)

Fig. 12: (a) Opposite method reconstructed conductivity images profile 1(b) extracted images at different levels (in mS/m) for Abule-Egba

Fig. 13: (a) Opposite method reconstructed conductivity images profile 2 (b) extracted images at different levels (in mS/m) for Abule-Egba

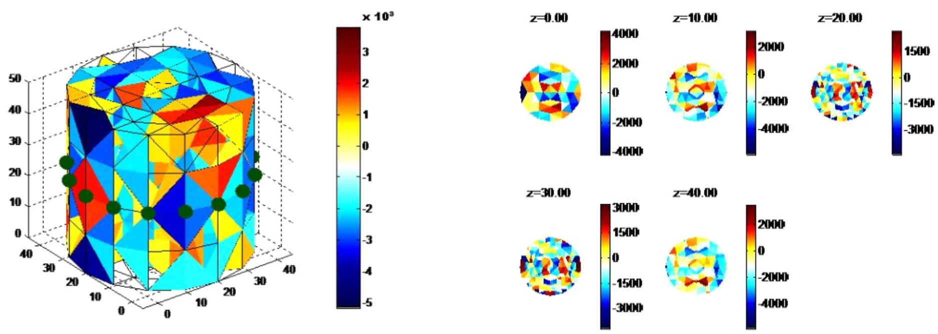
only portion of this tomogram with low conductivity can be seen at about 50m depth and is pronounced in the northeast of the site with some traces in the northwestern to a depth of about 20m.

The tomograms of Fig. 12 and 13 look similar. From the base of these tomograms, is a trend of migration of about 10m width downstream up to a depth of about 50m. This is observed only in the northwestern part of the



(a) (b)

Fig. 14: (a) Cross method reconstructed conductivity images profile 1, (b) extracted images at different levels (in mS/m) for Abule-Egba



(a) (b)

Fig. 15: (a) Cross method reconstructed conductivity images profile 2, (b) extracted images at different levels (in mS/m) for Abule-Egba

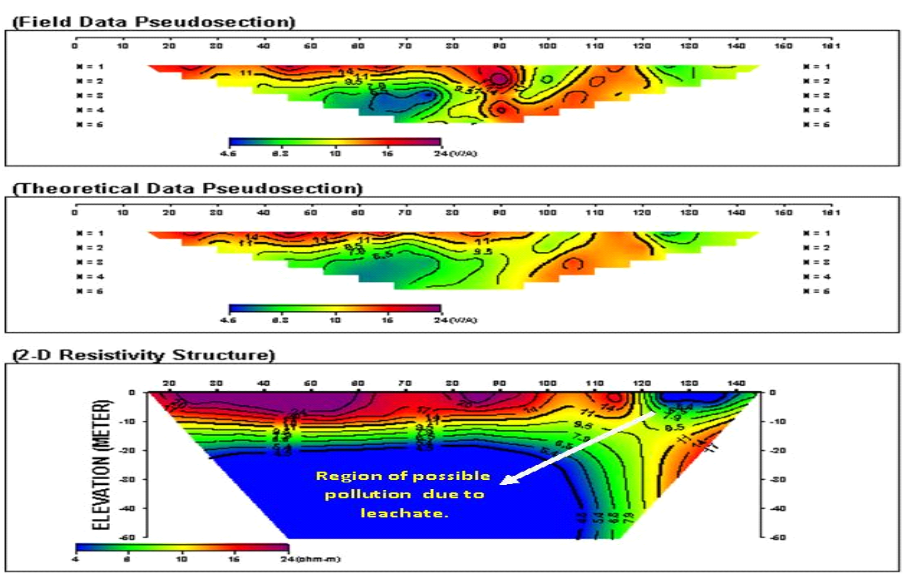


Fig. 16: 2D resistivity structure and pseudo section for Abule-Egba site

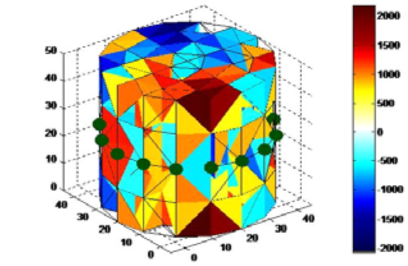
tomograms. The northeastern part of the tomograms is of very low conductivity but the trend of contamination could be seen migrating gradually to this section from a depth of about 10m. It was observed that a highly conducting anomaly of conductivity close to 10, 000 mS/m appeared on these tomograms. It is at about 50m depth northwest on both tomograms and is likely that this feature is a spurious artefact of the inversion process. It could also be as a result of buried metallic objects.

In Fig. 14 (Cross method, profile 1) the conducting plume can be largely seen at the base of the tomogram migrating through the northwestern side up to a depth of 30m and is seen to be concentrated at the northwestern part with conductivity as high as 4, 000 mS/m. This spread continues downstream with conductivity of 1,500 mS/m. The northwestern part, from a depth of 30 m down shows a low level of conductivity of various degrees down to about 50 m. This shows that this part of the dumpsite has not been contaminated and it was observed to be the edges of the site. This is similar to what was observed in Fig. 15 except that most part of the base of the tomograms is of low conductivity but the migration could be seen moving downstream.

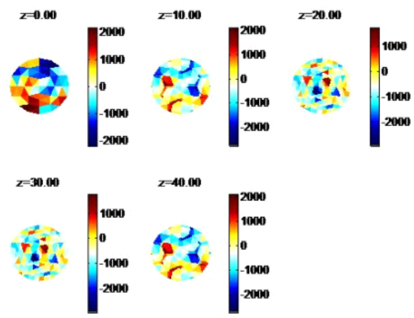
The 2D resistivity imaging taken at this site runs through the two EIT profiles. A depth of 50m was probed with resistivity value ranging from 0.5Ωm to 23.6Ωm (Fig. 16). In this profile, the leachate effect is mapped out in the regions with relatively low resistivity (0.5 to 6.6Ωm) which is mapped out in deep blue color code. The low resistivity variation is indicative of the degree of decomposition of the refuse materials and are indications of saturated zones starting from the ground surface. Below the first layer, the subsurface is characterized by materials with low resistivity (1.0 - 13. 6Ωm) within the lateral distance of 110 - 160m. Within the lateral distance of 0 - 115m, the subsurface indicates low resistivity value of between 1 - 13Ωm. This indicates the migration of leachate into the subsurface which is mapped within the depth of 20 - 50m on the section. This indicates that the water table in this area may have been polluted. This agrees fairly well with the EIT profiles.

Solous 1 result: The tomograms of Fig. 17 to 22 are the results of reconstructed conductivity profiles for Solous 1. All the profiles show considerate conductivity plume ranging from 1, 000 to 5, 000 mS/m depending on the concentration of the contaminant. The areas with high conductivity values potentially indicate areas of contaminant dispersion. The sections on the tomograms with very low conductivity, which indicate very high resistivity, may represent the basement of the dumpsite. It was observed that the profiles of cross (Fig. 21 and 22) have better sensitivity over the entire region with conductivity values ranging from 2, 000 - 5, 000 mS/m.

Other parts of the tomograms of both sites which indicate more resistive zone were mapped and identified as deep blue to light blue which represent the clay capping materials and unsaturated waste. This overlies much of the conducting feature. These low conductivity values indicate absence of leachate materials or could be

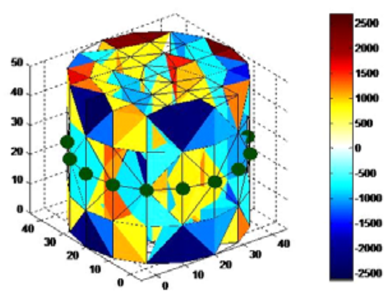


(a)

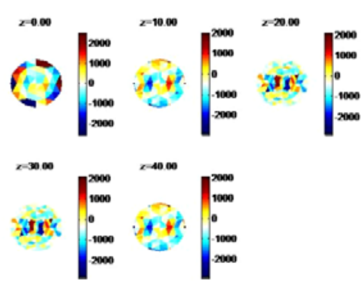


(b)

Fig. 17: (a) Neighboring method reconstructed conductivity images profile 1 (b) extracted images at different levels (in mS/m) for Solous 1

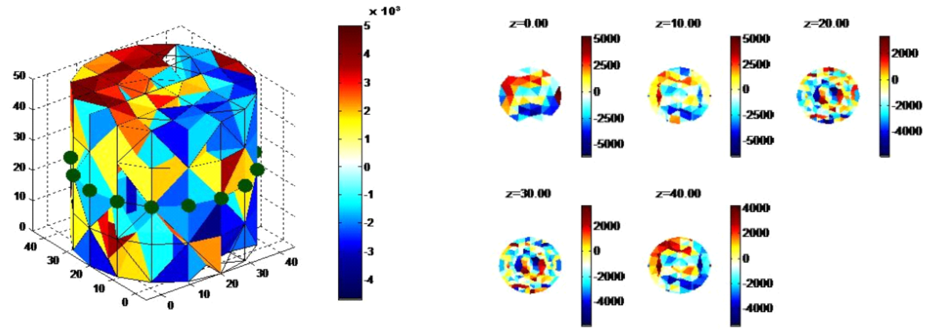


(a)



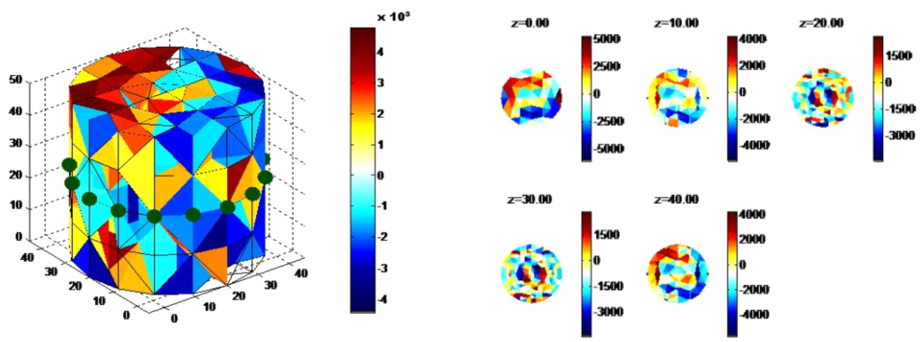
(b)

Fig. 18: (a) Neighboring method reconstructed conductivity images profile 2 (b) extracted images at different levels (in mS/m) for Solous 1



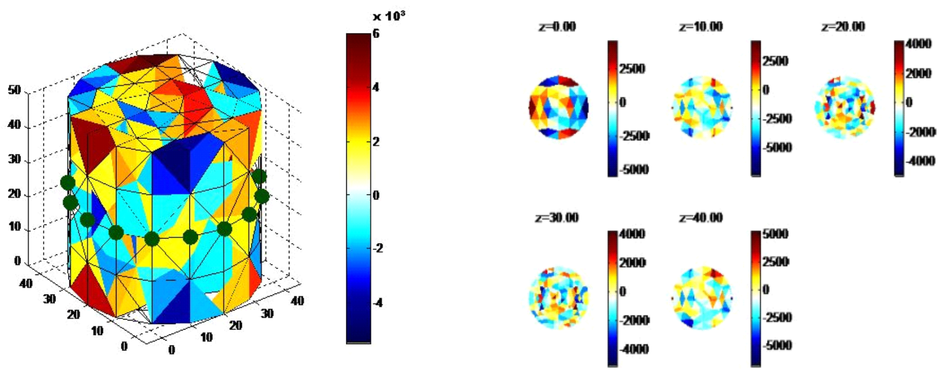
(a) (b)

Fig. 19: (a) opposite method reconstructed conductivity images profile 1, (b) extracted images at different levels (in mS/m) for Solous1



(a) (b)

Fig. 20: (a) opposite method reconstructed conductivity images profile 2, (b) extracted images at different levels (in mS/m) for Solous1

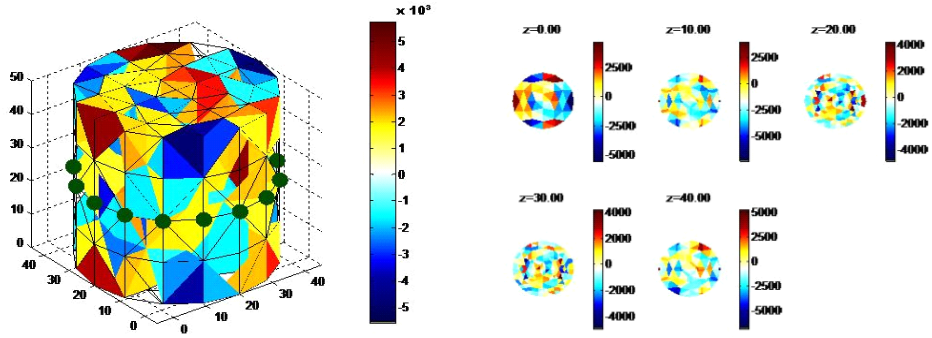


(a) (b)

Fig. 21: (a) cross method reconstructed conductivity images profile 1, (b) extracted images at different levels (in mS/m) for Solous 1

associated with the presence of landfill gases (ammonia, methane, sulphur (iv) oxide or carbon (iv) oxide) generated as a result of the anaerobic decomposition of the landfill municipal waste. These gases have been displaced to various degrees with respect to depth in the study sites due to their lower densities to the groundwater and pressure buildup within the landfill, and are migrating through the permeable and porous sandy formations.

An opaque volume was observed on some tomograms especially to a depth of 50m. This may be as a result of electrode position error since no information was obtained at such location. Moreover, some highly resistive sections



(a) (b)

Fig. 22: (a) cross method reconstructed conductivity images profile 2, (b) extracted images at different levels (in mS/m) for Solous 1

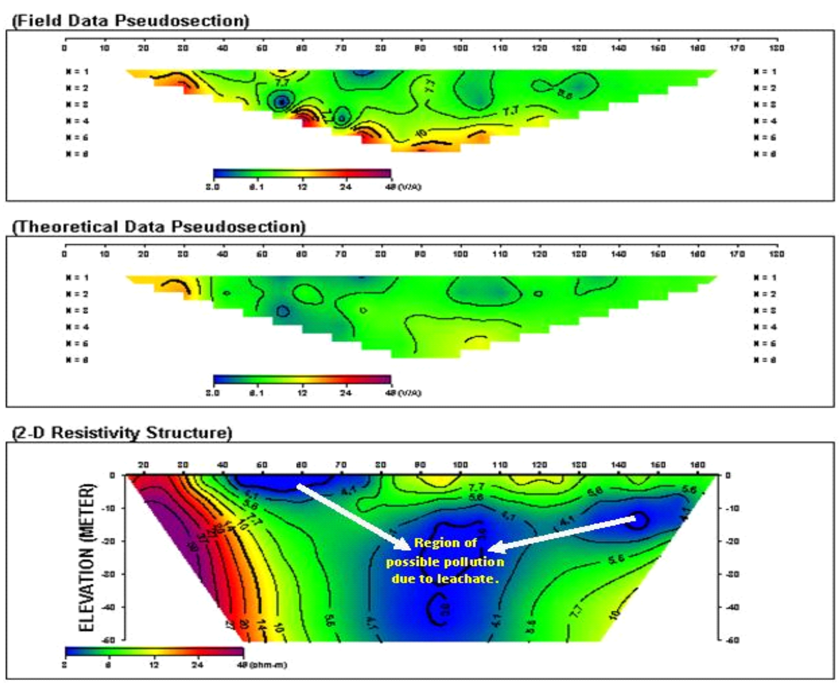


Fig. 23: 2D resistivity structure and pseudo section for Solous 1site

(of very low conductivity) were noticed on some tomograms especially for profile 2. This could be as a result of some highly resistive materials in the dump.

For the 2D resistivity structure on this site (Fig. 23), the topsoil is characterized with distribution of contaminants with resistivity values from 3Ωm to 9Ωm. The layer beneath the horizontal profile indicates segments having leachate effect which is found within a depth of about 20m with resistivity ranging from 3.6 - 4.0Ωm. The subsurface is characterized with relatively low resistivity at 140m spread showing regions of pollution as a result of infiltrated leachate. The lateral distance of 0 - 110m and the depth of 20 - 30m signify clay which does not permit infiltration by leachate effect.

CONCLUSION

Electrical Impedance Tomography has been presented and used to image and detect underground contaminants in landfill sites in Lagos State, Nigeria.From this work, it appears that EIT is a viable alternative to image and detect underground contaminants because it was found that the method can detect changes in the sub-surface conductivity distributions quickly and relatively accurately. It has proved a particularly useful technique in defining contaminants within the landfills because the inverted conductivity profiles offered a matching distribution of the contaminant concentration and has been effective in identifying leachate plumes emanating from the landfills.

With the aid of the tomograms, two distinct contaminant plumes had been mapped and identified within the study sites. They are; highly conductive leachate contaminant plumes seeping from the surface downstream and highly resistive (very low conductivity) gaseous contaminants that are probably due to landfill gases (ammonia, methane etc.) obtained as a result of the anaerobic decomposition of the landfill organic wastes.

The hydro geologic features of the study areas showed that contaminants derived from the waste disposal sites infiltrate through vulnerable sandy formation and hence to the groundwater flow. This suggests that the soil and the groundwater system had been contaminated beyond the depth of 50m in the study areas.

The integrated use of EIT and convectional site investigation information has led to a better understanding of the sites than could have been achieved using traditional sites investigation method alone.

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