GEOPHYSICS TECHNIQUES FOR THE STUDY OF GROUNDWATER POLLUTION: A REVIEW

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Abstract

Recently, there is increased popularity of application of geophysical methods to environmental study most especially in the area of groundwater contamination. This is made possible by the introduction of automatic data acquisition techniques and more importantly data interpretation, through the development of fast two dimensional (2D) or three-dimensional (3D) inversion software. This paper reviews the application of Geophysical techniques in the investigation of groundwater contamination due to municipal landfill leachate. Results of case studies are presented as discussed.

Keyword: *Leachate, plume, contamination, sanitary landfill and tomography*

Introduction

Groundwater forms a significant part of the water resources all over the world, particularly in the arid areas and favoured for domestic purposes partly because groundwater is of high treatment before use since, according to(Sampat,2001)fungi,bacteria and other biological pollutants are naturally filtered and diluted as the water percolates through the soil and partly because the provision of portable water via the water supply scheme is grossly inadequate for the needs of the people. But as a result of careless management and/or disposal of hazardous materials, fresh groundwater supplies would be greatly decreased. The problem of environmental contaminations, today, is one of the concerns of earth scientists and researchers from other related fields of science around the world. Fast industrial development and the uncontrolled growth of the urban population quality and requires little result in the production of toxic solid residues. Urban waste materials, mainly domestic garbage, are usually disposed off inadequately in land surface, shallow excavation, river and stream channels which place the under groundwater at high risk of being polluted. Pollution of groundwater happens mostly due to percolation of fluvial water and the infiltration of contaminants through the soil under waste disposal sites. The contaminant is a fluid that results from the decomposition of municipal solid wastes. Contamination takes place when this leaking aqueous liquid, called leachate reaches the groundwater table, thus affecting the quality of the groundwater.

Factors that Determine Groundwater Contamination by Leachate

1. Depth to water table

If the water table is low (far below the ground surface), the leachate will be partially filtered as it percolates downward through the soil. If the water table is high(close to the ground surface), the groundwater stands the risk of being contaminated by the leachate which has not been fully filtered by the time it gets in contact with the groundwater as shown in Figure 1.

2.Concentration of contaminants

A high concentration of contaminants in leachate will make groundwater pollution more likely.

3. Permeability of geologic strata

Highly permeable geologic strata allow leachate to quickly percolate through, receiving little filtration along the way as shown in Figure 2.

4. Hydrologic setting

Relative vulnerability to pollution by hydrologic setting becomes:

I. Extreme if (a) Bedrock aquifers crop out (especially in Karsts area); or bedrock aquifers are overlain by less than 3m of soil (b) Unconfined and gravel aquifers with unsaturated zone less than 3m thick

II. High if Bedrock aquifers are overlain by 3m sand and gravel, 3-10m sandy till, or 3-5m clay or clay- rich till.

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III. Moderate if unconfined aquifers are overlain by 10m sandy clay till, or 5-10m clay rich till, clay or peat.

IV. Low if confined aquifers low permeable rock such as shale are overlain by 10m clay-rich till or (George, 1992).

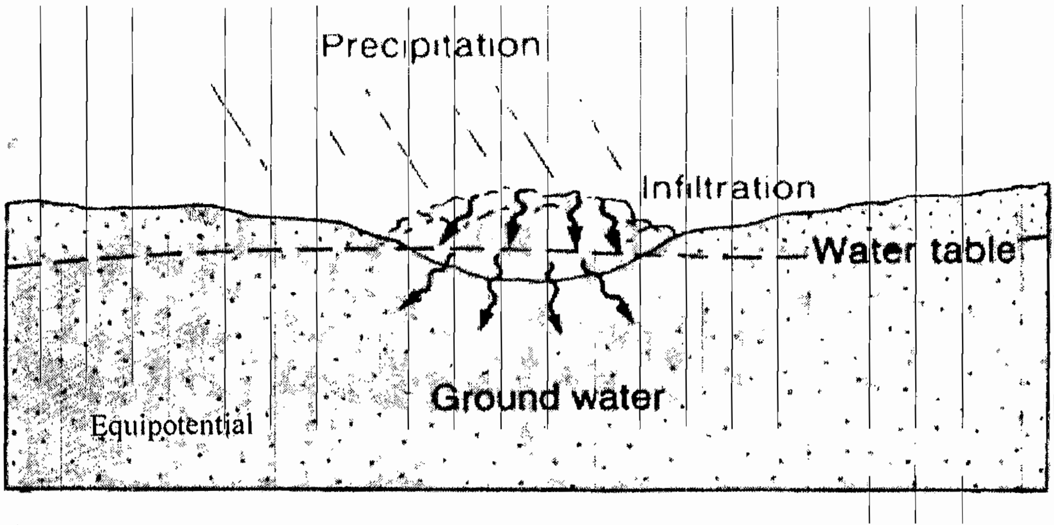

Fig. 1: water table intersect landfill (Montgomery, 2000)

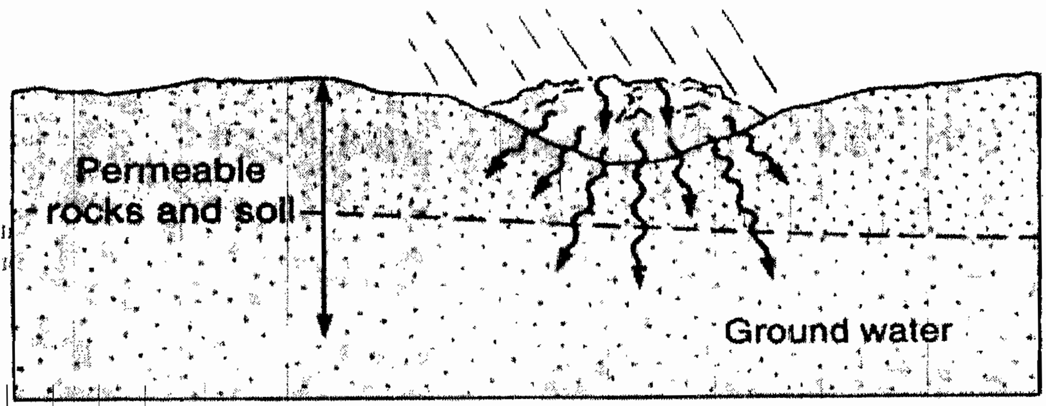

Fig. 2: leachate infiltrates to water table through permeable materials(Montgomery, 2000)

Landfill Leachate and Public Health

There is common misconception that since the materials placed on solid landfills are basically household materials, they are relatively safe and would not adversely affect groundwater quality and hence public health. Recent discovery of numerous toxic chemicals in well waters have proven this traditional belief to be false (Brown & Donnelly, 2005). One need only to consider the water that was used to clean a garbage can to understand that it is not desirable to have a drop of solid waste leachate in the water meant for drinking and domestic use. But this is what happens if landfill leachate contaminates groundwater. The nature of landfill leachate varies: its composition is a function of climatic conditions, hydrologic factors, waste type, quantity and age of the landfill (Fatta *et al.,* 2000). The studies by (Brown and Donnelly, 2004) and (ERA, 2003) have shown that in municipal landfill leachate:

* 32 organic chemicals cause cancer(e.g. vinyl chloride, benzene), 16 cause birth defects (e.g. endrin), and 22 cause genetic effects(e. *g.* 1,1,1-Trichloroethene)

* 10 inorganic chemicals cause diseases like skin discolouration(e.g. Silver),skeletal damage (e.g. Fluoride), nervous system effects

(e.g. Mercury), central nervous system effects(e.g. Lead), circulatory system effects (e.g. Barium), liver/kidney(e.g. Chromium, .cadmium) and cancer of the bladder(e.g. Arsenic).AIso the World Health Organization (WHO, fact sheet no 112, 1996) estimated in 1996 that every eight seconds a child died from a water-related disease and that each year more than five million people died from illnesses linked to unsafe drinking water or inadequate sanitation. WHO(Geneva,1996) also suggest that if sustainable safe drinking water and sanitation services were provided to all each year there would be 200 million fewer diarrhoeal episodes, 2.1 million fewer deaths caused by diarrhoea, 76,000 fewer dracunculiasis cases, 150 million fewer schistosomiasis cases and 75 million fewer trachoma cases.

Sanitary Landfill.

The long established method for solid waste disposal that demand a minimum of effort and expense has been the open dumpsite (Figure 3). Drawbacks to such facilities are fairly obvious,especially to those having the misfortune to live nearby. Apart from polluting the groundwater, open dumps are unsightly, unsanitary, and generally smelly. Landfills today in developed countries are built to avoid any hydraulic contact between the waste and the surrounding environment, particularly groundwater. Sanitary landfills are enclosed with special covers to prevent rainwater from entering to form leachate and liners to prevent leachate from exiting the landfill to pollute the groundwater. Modern landfills also use monitoring wells which are located at the edge of the landfill to detect any problems. Figure 4 shows a double composite sanitary landfill containment system.

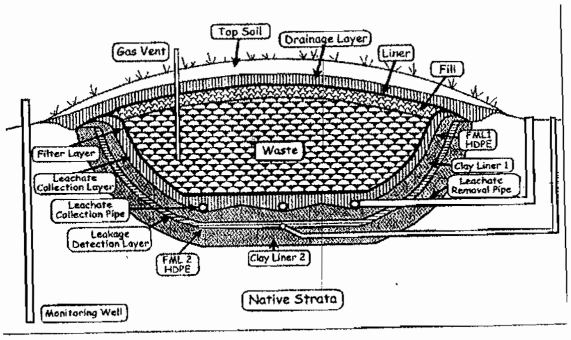

Fig.3: Typical open landfill

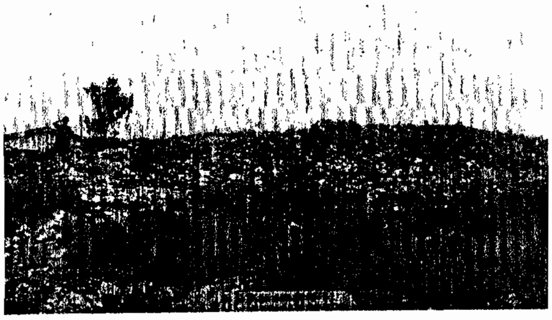

Fig.4: Sanitary landfill

Geophysical Methods Applied to Pollution Studies

Vast literature exists (Aristedemou *et al*,2001: Barker *et* al.,2001; Ali Kaya *et al.*,2007;Buselli *et al,* 1992; Dahlin, 2002; Porsani *et al.,* 2004) showing the application and limitations of the geophysical methods in environmental problems associated with groundwater contamination due to leachate movement. The use of various geophysical techniques for the investigation of groundwater pollution sites is a fairly recent development. The combination of more than one technique at a location in an integrated interpretation results in a reduction of the degree of ambiguity. The introduction of multi-electrode and computer

controlled system allow semi-automated surveys, allowing large data sets to be collected more quickly and at reduced cost (Dahlin, 2002). The success of geophysical exploration techniques depends on contrast in physical properties in the subsurface. The following geophysical techniques can be successfully applied in landfill investigation because dissolved plume (Leachate) can influence resistivity (ρ) or conductivity (σ), dielectric constant (ε), changeability (M) and magnetic susceptibility (k).

A. Goo-electrical technique

The DC Resistivity method is found suitable for this kind of environmental investigation due to the fact that, generally, ionic concentration of landfill leachate ismuch higher than that of natural groundwater and so when the leachate enters the aquifer, it results in a large contrast in electrical resistivity and the methods will identify theses zones as an anomaly which enables the leachate plume to be detected. Resistivity data has serious ambiguities in distinguishing between equally electrically conducting targets like electrolytic, metallic-ion contamination plumes from saline clay (Dahlin, 2002).To distinguish between these targets, Time-domain IP data is included in landfill investigation because it has the potential through its electrical changeability to distinguish between these targets. With the introduction of automated data acquiring equipment and fast computer interpretation software,

Tomography techniques are now employed in the field. Tomography is an imaging technique which generates a cross-sectional picture (tomogram) of an object by utilizing the objects response to non-invasive, non-destructive energy of an external source.

Theory of Geo-electric surveying

In simple terms, DC resistivity measurements are performed by applying current I, which is introduced into the earth between two electrodes A and B. A potential difference (V) can then be measured by electrodes M and N, situated between A and B (Figure 5).The resistivity of earth depends on the method of measurement (Sounding or profiling) and is formulated as apparent resistivity (ρ) which is afunction of true layer resistivity, their boundaries and location of electrodes;

$$\rho_a = \frac{\Delta V}{I} K \qquad (1)$$

where K is a geometrical factor, which depends on the geometry of the array used and expressed as:

$$K = 2\pi \frac{1}{r_A - r_M} - \frac{1}{r_A - r_N} - \frac{1}{r_B - r_M} - \frac{1}{r_B - r_N} \qquad (2)$$

r_A and r_B are positions of current electrode Tm and r_N are positions of potential electrode(Figure 5). Some of the field electrode arrays are the Wenner, Schlumberger, pole-pole, pole-dipole and dipole-dipole array. Traditionally, resistivity technique employs the vertical electrical sounding (VES) which measure resistivity variations with depth but since the 1980's, the development of the continuous vertical electrical sounding (VCES), a new technique that combines both sounding and profiling so that a 2D data coverage along a profile is obtained has taken place, Figure 6 (van Overmeeren & Ritsema 1988; Dahlin 1996). One of the more recent developments in the instrumentation for electrical imaging surveys have been the addition of Induced Polarization (IP) capability in the multi-electrode resistivity meter system. Same electrode array used for collecting data is used for the IP survey which can be measured in Time-domain or Frequency-time domain given by the

$$M = \frac{1}{V_O\left[t_{i+1} - t_i\right]} \int_{t_i}^{t_{i+1}} V(t)\,dt \qquad (3)$$

where M = changeability in msec, time- domain unit,

V_0 = observed voltage

V = over voltage (residual voltage), $t_{i+1} - t_i$= window interval time, and

$$PFE = \frac{\rho(\omega_L) - \rho(\omega_H)}{\rho(\omega_H)}.100 \qquad (4)$$

Where $\rho(\omega_L)$ is the resistivity measured at low frequency and $\rho(\omega_H)$ is the resistivity measured at low frequency.

The Geo-electrical techniques are used in landfill investigation:

- to determine geo-electric formations
- to detect and map contaminated zones
- to map vertical and lateral extent of the Contamination
- to distinguish between equally electrically conductive targets

to detect and map subsurface structures (faults fractures and loose ground).

(B) Electromagnetic methods

Electromagnetic methods measure electrical conductivities by low-frequency induction (Benson *et al,* 1984). Electrical conductivity is a function of the type of soil and rock, its porosity, degree of saturation, and the electrochemistry of the fluids that fill the pore space. In most cases, the electrical conductivity (measured in milliSiemens per meter, mS/m) of the pore fluids dominate the measurements, and dissolved species in contaminated water will alter its conductance compared with natural groundwater. Consequent^, EM is an excellent technique for mapping subsurface features with contrasting electrical properties. EM measurements can be made in the Frequency or Time-domain. Frequency-domain electromagnetic Induction is the most commonly used geophysical method for detection of conductive contaminant plumes, but Time-domain Electromagnetic method has gained increasing popularity in groundwater studies because of its higher resolution and greater depth of penetration. Other EM methods

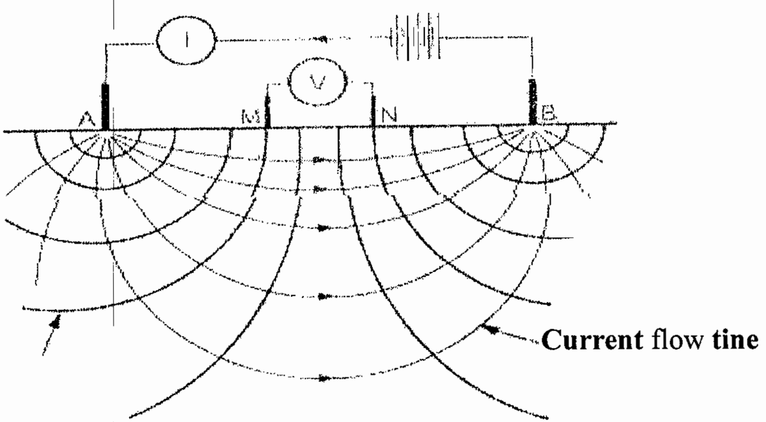

Figure.5 Simplified current flow lines and equipotential surfaces arising from a set of current electrodes (a current source and sink).

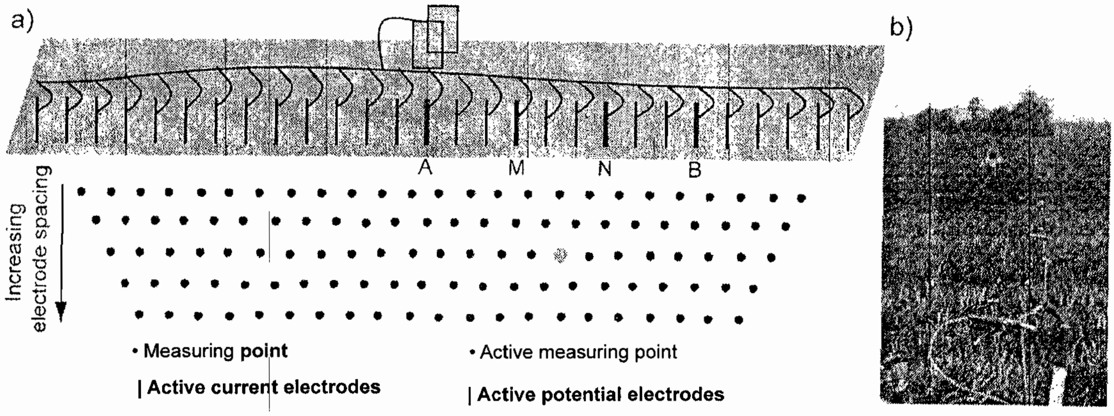

Figure.6: a) A sketch of a field setup for CVES and data density for a profile acquired in Wenner configuration b) Photo of the CVES system in the field (van Overmeeran & Ritsema (1998)

applied to contaminated site are Very-low-frequency (VLF) resistivity methods for detection of conductive Contaminant plumes and Metal Detection (using EMI instruments designed specifically to detect buried pipelines and metallic waste).

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Theory of EM method

Electromagnetic (EM) methods make use of the response of the ground to the propagation of the electromagnetic fields which are composed of alternating electric intensity (**E**) and magnetic force (**H**) in a plane perpendicular to the direction of travel (Reynolds, 1999). An electromagnetic field may be defined in terms of four vector functions **E**, **D**, **H** and **B**, where: ***E*** *is* the electrical field in V/m. *H is* the magnetic field intensity in A/m.

B *is* the magnetic induction in Tesla.

D is the dielectric displacement in Coulomb/m^2. Experimental evidence shows that all electromagnetic phenomena obey the following four Maxwell equations.

$$E=-\partial B/\partial t \qquad (5)$$

$$H=J+\partial D/\partial t \qquad (6)$$

$$B=0 \qquad (7)$$

$$D=q \qquad (8)$$

Equation *(5)* is Faraday's law while equation (6) is Amperes law. Equation (7) infers that lines of magnetic induction are continuous and there are no single magnetic poles and equation(8) assumes that electrical fields can begin and end on electrical charges. By using the following subsidiary equations, $D=\varepsilon E$, $B=\mu H$ and $J=\sigma E$

Where,

J = electrical current density in A/m^2

q = electric charge in Coulomb/m^2

ε = electric permittivity

= magnetic permeability

σ = electric conductivity and the four Maxwell equations the, electromagnetic wave equation can be derived. Such waves, with low attenuation and their relationship are shown in Figure 7. EM methods are applied at contaminated sites:

I. To detect and map contaminated zones;

II. To map vertical and lateral extent of the contamination.

III. To detect and map fracture and fault zones

IV. In characterization of waste.

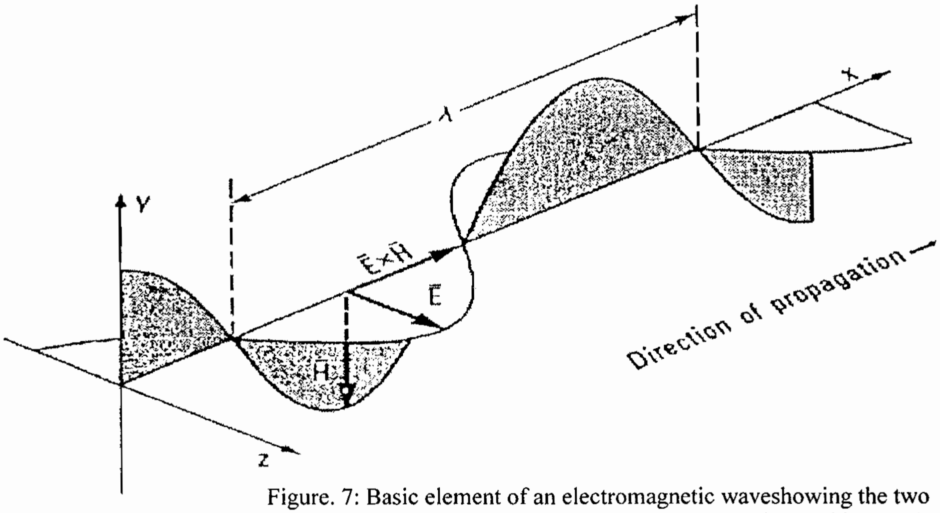

Figure. 7: Basic element of an electromagnetic waveshowing the two principal electric(E) and magnetic (H)components (Reynolds, 1999)

C) Seismic refraction method

Seismic refraction method has been commonly used in groundwater and contaminated site investigation because of its relative simplicity and adaptability for shallow zone investigation. Since seismic refraction can only measure physical contrasts, it is unable to directly detect contaminant plumes or subsurface contaminants. However, with the introduction of tomography technique, the geologic information gained from a seismic investigation can be used in the hydrogeologic assessment of a groundwater pollution site and its surrounding.

Seismic refraction theory

The foundation of seismic refraction theory is Snail's law, which governs the refraction of a sound or light ray across the boundary between layers of different physical properties (Reynolds,1999). As sound waves travel from a medium of low seismic velocity into a medium of higher seismic velocity, some are refracted toward the lower velocity medium, and some are reflected back into the first medium. As the angle of incidence of the sound ray approaches the critical angle (an angle where the refracted ray grazes the surface of the contact between the two media), most of the compressional energy is transmitted along the surface of the second layer, at the velocity of sound in the second layer. As this energy propagates along the surface, it generates new sound waves in the upper medium that in turn propagate back to the surface at the critical angle and at the seismic velocity of layer one. For seismic refraction to work, therefore, the velocity of sound in each deeper layer must be greater than in the layer above it. When this condition is met, the refracted wave arrives at the Earth's surface where it can be detected by a geophone which generates an electrical signal and sends the signal to a seismograph (Figure 8). Since travel time equations can be derived as a function of velocity, equation (9), depth to a refractor such as bedrock can be determined in a seismic refraction survey.

$$z = \frac{1}{2}\sqrt{\frac{v_2 - v_1}{v_2 + v_1}} \cdot x_{CROS} \qquad (9)$$

where v_1 and v_2 are the speed of sound in layer 1 and 2, respectively, $\mathcal{X}_{cros}$ is the cross-over distance. Seismic refraction tomography data are commonly used to:

*Categorize geologic strata
*Determine thickness of geologic strata,
* Determine depth to water table.

Also due to the dependence of seismic velocity on the elasticity and density of the material through which the energy is passing, seismic tomography data is used to:

* Detect and map fracture and fault zones.

Although seismic refraction technique has generally lower resolution than seismic reflection, it is generally preferred to seismic reflection technique in shallow hydrological investigations for a number of reasons (Reynolds, 1998):

- Most landfills are shallow for reflection seismology to be of much use.Landfill material is highly (ranging from around 10MHz to attenuating and thus is difficult 1,000MHz) into the subsurface and to put much energy into the each pulse interacts with subsurface
material and detect any materials in a variety of ways. These significant signals
- The cost of seismic reflection surveys is much greater than that of refraction surveys.

include attenuation, reflection, refraction, diffraction, scattering, which are recorded by a receiving antenna. The dielectric and conductivity of the substrata are the most important factor determining the rate of signal attenuation.Materials with high conductivities (e.g. landfill leachate) will cause rapid dissemination of the transmitted pulse through the transformation of the EM energy into heat, as ions within the medium become excited (Reynolds, 1998), hence GPR is a very useful tool for characterization of subsurface contamination plumes. The radar frequency selected for a particular study is chosen to provide an acceptable compromise between deeper penetration and higher resolution. High-frequency radar signals produce greater penetration but are limited in depth penetration (Davis and Annan, 1989). Dragging the antenna along the ground surface creates a continuous profile that gives the greatest resolution of all **the** geophysical techniques discussed (ERA, 1993).

Theory of GPR surveying

The GPR technique is similar to seismic reflection techniques (Benson, *et al,* 1984). Pulse -mode GPR systems radiate short pulses of high frequency (10-1000MHz) electromagnetic energy into the ground from a

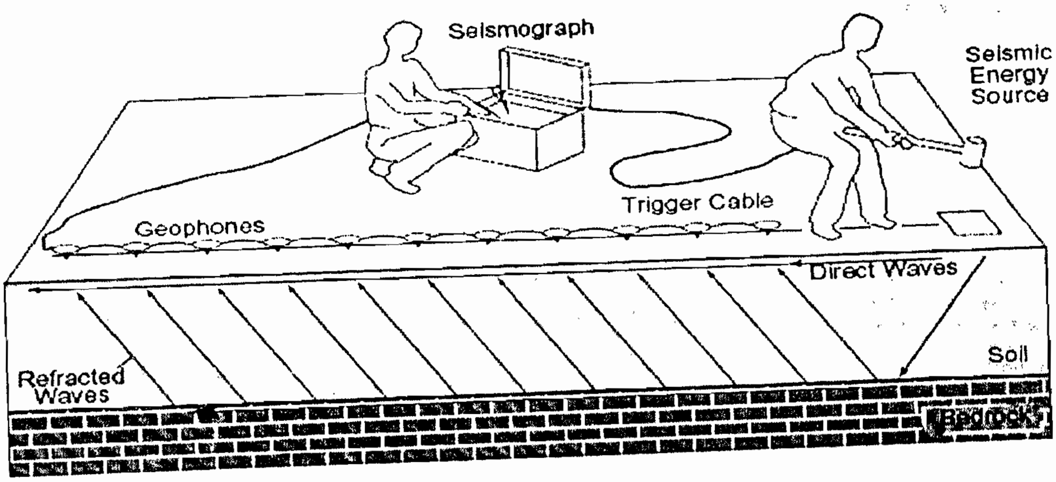

Fig.8: Field lay out showing the path of directed and refracted seismic waves Benson *et al.*, 1984)

(D)Ground penetrating radar (GPR)

Ground penetrating radar involves use of small antenna to radiate short pulses of high-frequency radio waves (ranging from around 10MHz to, 1,000MHz) into the subsurface and to each pulse interacts with subsurface material in a variety of ways.These

transmitting antenna. When the radiated energy encounter an inhomogeneity in the electrical properties of the subsurface, part of the incident energy is reflected back to the antenna and part is transmitted into and possibly through the inhomogeneity. If the propagation velocity of the electromagnetic pulse is known, the depth to the reflector can be determined from:

$$d_r = \frac{vt_r}{2} \quad (10)$$

where d_r is the depth to the reflector and t_r is two-way travel time and v is the velocity. For low-loss media, the propagation is related to the relative dielectric constant by:

$$v = \frac{c}{\sqrt{\varepsilon_r}} \quad (11)$$

where c is the velocity of light in free space ε is the dielectric constant. Thus in low-loss medium, the depth of reflector is:

$$d_r = \frac{ct_r}{2\sqrt{\varepsilon_r}} \,. \quad (12)$$

GPR is used in landfill investigation:

*to locate and map contamination plumes, since landfill leachate will cause attenuation of EM energy due to its high conductivity.

*to investigate closed landfills

*to characterize buried waste as either homogenous or heterogeneous , because such material gives a radargram showing many diffraction hyperbolas and limited reflections of regular pattern (Orlando *et al*, 2001)

*to determine depth to water table, a zone characterized by a smooth strong reflector of high amplitude due to the large contrast in dielectric constant between dry and saturated sand(Overmeeran, 1994)

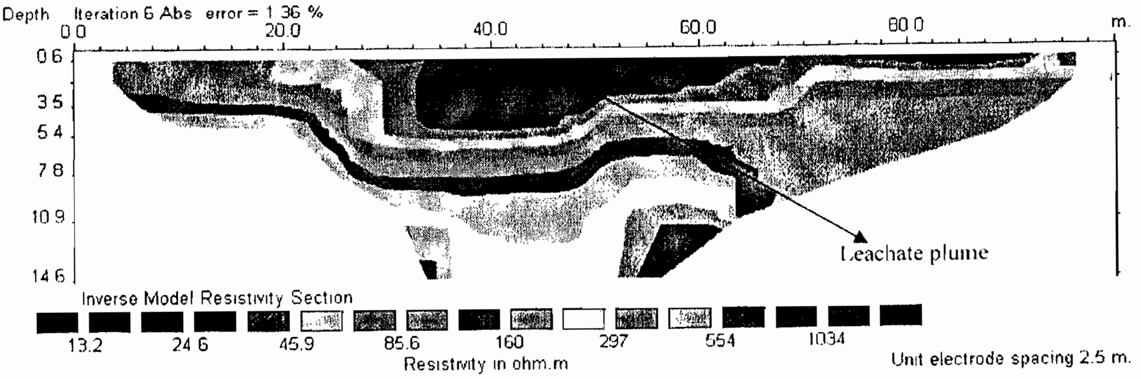

Fig ,8a: Resistivity model near solid waste facility in Kaduna, Nigeria

Results from Case Studies

Results of the application of 2D resistivity/ induced polarisation, Electromagnetic Induction, VLF and Ground penetrating radar investigations at waste facilities are presented as discussed.Also presented is the result of seismic tomography data. Figure 8(a) shows the result of 2D resistivity model from the data collected at a dumpsite in Unguwan Dosa (Fig3), Kaduna North, Kaduna State, Nigeria which is part of the ongoing research of the second author at Advanced Geophysical Research Laboratories, Physics Department, Ahmadu Bello University, Zaria, Nigeria. The data were collected with ABEM LUND imaging equipment using Wenner 32SX protocol and processed with RES2INV package. At positions 32.5-65 m and 77.5-92.5 m there are indications of saturated zones represented by low resistivities (13.2 - 24.6 ohm-m), starting at the ground surface down to 5m depth. This low resistivity reflects the positions of the central electrodes and those at take-outs 18, 19, 23, and 24 that were located at evacuated portion of the dump and is believed to be due to accumulation of leachate.Figure 8(b) is the corresponding chargeability model. The chargeability model do not show IP anomalies at the profile positions 32.5 - 65 m which correspond to the low resistivity zones in the resistivity model because, saline water does not produce appreciable chargeability anomaly in the absence of clay (Loke, personal communication),The inverse model shows high chargeabilities (16-40msec) from the ground surface down to 5 m depth at profile positions 35-40m.There was not such anomaly in the resistivity model as clearly as in the chargeability model. One possible explanation of this inconsistency is that chargeability assists in distinguishing IP effects due to predominantly electrolytic controls from effects due to structural (primarily clay control) variation better than resistivity measurement. The high chargeability >16msec is due to the presence of disseminated organic waste and not clay

(Aristedemou *et al.*, 2001).Figure 9a shows the result of EM apparent resistivity map from a waste facility in Southern Sweden (Bernstone & Dahlin, 1996). A number of low resistivity areas (10 ohm-m) corresponding to contamination plume are clearly visible.Figure 9b is the result of VLF-EM data collected at Isparta, Turkey open waste disposal site (Karlik and Kaya, 2001). The observed VLF-EM maps processed with VLFMOD interpreting package shows the in-phase component exhibiting negative sign while the Quadrature components show positive sign over the conductive body (leachate plume). Figure 10 is the results of GPR data obtained from the solid waste facility of Nagpur, India (Pujari *et* al., 2007).The bright zone in the figure(circled) is an indicative of strong reflection arising due to conductivity contrasts associated with fractures in the subsurface. The figure also shows strong absorbance zone in the top few meters up to 4.5m, This absorbance

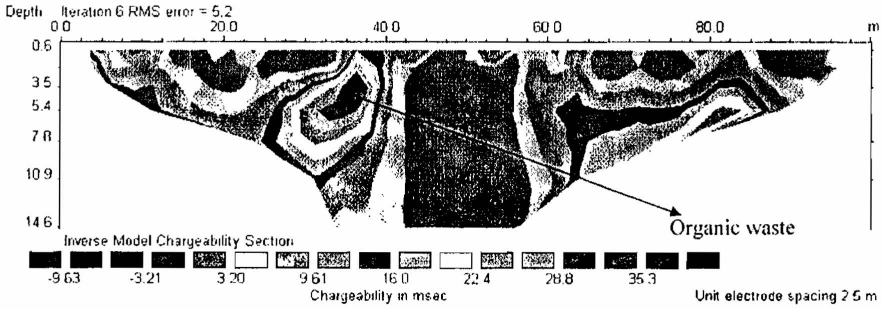

Fig. 8b: Chargeability model near solid waste facility in Kaduna, Nigeria

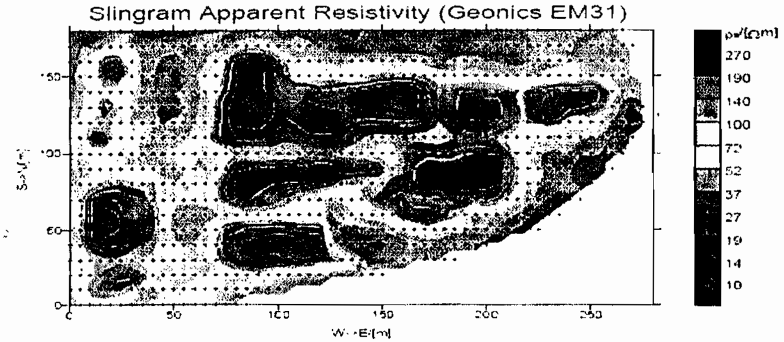

Fig. 9(a): EM Inductive map of waste sit in Southern Sweden (Bernstone & Dahlin, 1999)

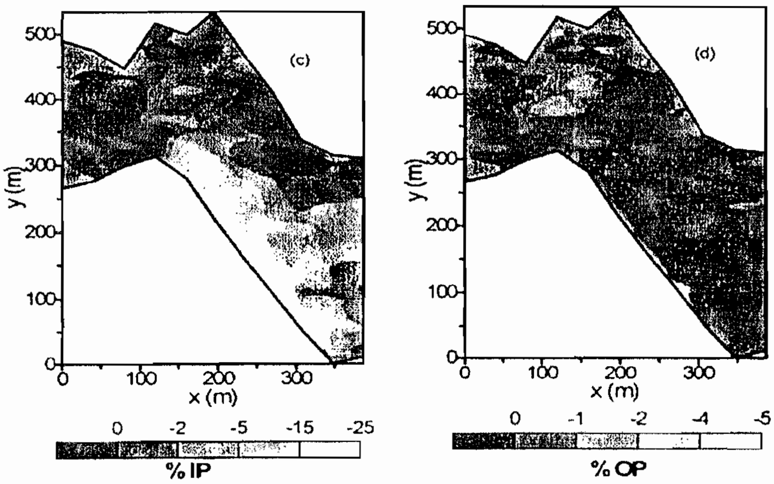

Fig. 9(b): VLF-EM maps near open waste disposal site, Sparta, Turkey (Karlik&Kaya,2001

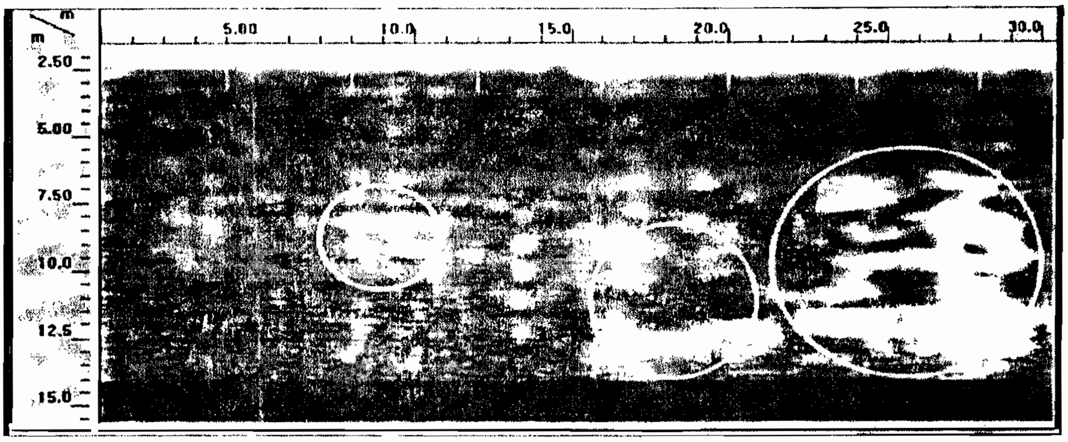

Fig. 10: GPR result from Nagpur dumpsite, India (Pujari *et al.*, 2006)

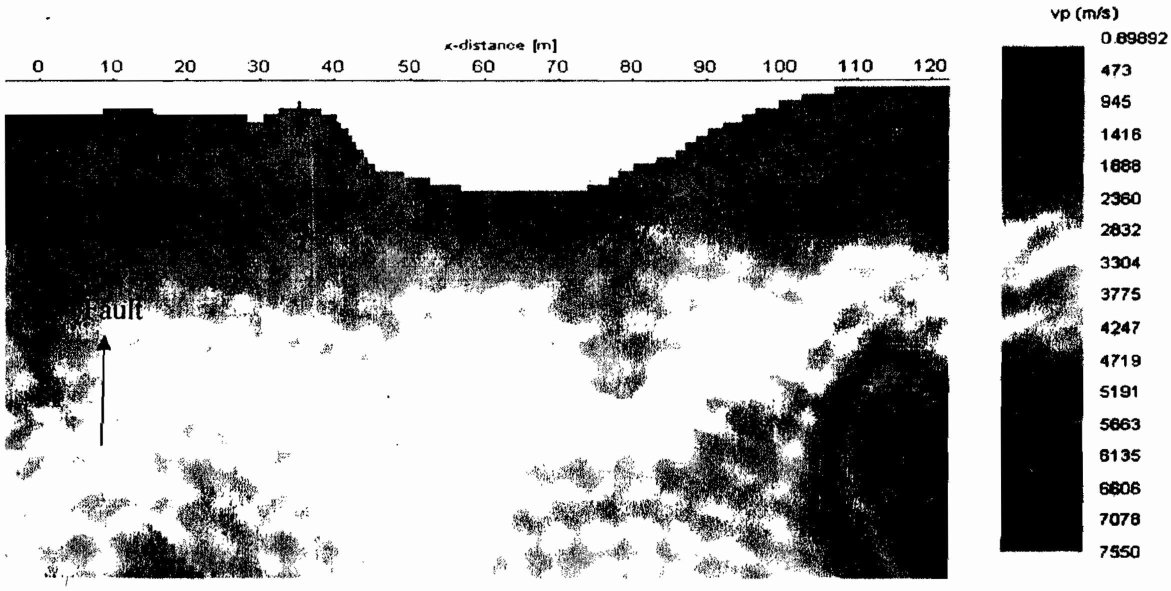

Fig. 11; Seismic Refraction tomography result at Jikwoyi Karshi, Abuja, Nigeria (Osazuwa, era/., 2006)

zone can be associated with plumes or heterogeneous dumped material. Fig 11 is the result of seismic refraction tomography data (Osazuwa *et* a/., 2006) at Jikwoyi Karshi, Federal Capital Terrority Abuja, Nigeria. The figure reveals the presence of displacement at profile positions 5m at a depth of 26m which is interpreted as a fault.This subsurface structure is one of the means of the transportation pathways for leachate outside the dump site.

Conclusion

The use of various geophysical techniques in environmental study isa cost-effective means of preliminary evaluation. Various geophysical techniques reveal physical properties of the subsurface, which can be used to determine hydrostratigraphic framework, extent of groundwater contamination plumes, location of faults or fractures, which are the mechanisms responsible for the transportation of the contamination plume outside the waste disposal site. This review has shown the results of various geophysical techniques that can be used successfully in areas with moderately complex geology (i.e. contamination plumes) where the conventional (1-D) survey methods do not give sufficiently accurate results. A three-dimensional (3D) survey should give even more accurate results but at a much greater cost. Information gained from Geophysics survey can be used to choose optimal locations for placement of boreholes, for subsurface sampling and remediation.

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