Geoelectrical Resistivity Imaging in Environmental Studies

A.P. Aizebeokhai

Abstract The presence of contaminants in the environment requires a precise characterization of the nature and extent of contamination for effective remediation. Conventional environmental monitoring has focused largely on point sampling, which involves intrusive processes such as grid drilling. This approach is expensive and provides information only on effects at the sample sites, and hence may not be a true representation of the complex and subtle subsurface geology associated with environmental investigations. Alternative methods that have been used in environmental studies are geophysical methods such as geoelectrical resistivity techniques. Geoelectrical resistivity imaging is used in estimating the resistivity distributions of the subsurface based on several measurements of discrete voltage and current. This paper evaluates the effectiveness of geoelectrical resistivity imaging in environmental applications.

Keywords Environmental studies · non-invasive techniques · geoelectrical imaging · resistivity

1 Introduction

The presence of contaminants in the environment requires precise characterization of the nature and extent of contamination for effective remediation. Conventional environmental monitoring has focused largely on point sampling, which usually

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involves intrusive processes such as drilling. This approach is expensive and provides information only on effects at the sample site (Granato and Smith 1999). Intrusive processes can be very dangerous and may not be a true representation of the complex subsurface geology (Ogilvy et al. 1999). Non-invasive techniques, such as geophysical methods, are alternative methods that have been used in environmental monitoring applications.

Many environmental problems amenable to solution by geophysical methods are related to the protection of groundwater from various sources of contamination. The most important sources of subsurface contaminants are hazardous waste disposal sites, landfills, saline water intrusion, and saline water disposal basins and buried hazardous wastes. Other contributors are hydrocarbon spills commonly from exploration and production sites, and buried storage tanks at gas stations, refineries and industrial plants. The escape of leachates from these contaminant sources can lead to serious environmental problems (Simmons et al. 2002). The presence of contaminants in porous rocks significantly alters the physical properties of the rock formations. The degree of alteration depends on the nature, constituents and concentration of the contaminants, as well as the duration of the contamination. Many contaminants decrease pore water resistivity; thus they can be detected and mapped by geoelectrical resistivity imaging methods. This paper attempts to evaluate the effectiveness of geoelectrical resistivity imaging techniques in environmental applications, which is commonly characterized with heterogeneous, subtle, complex and multi-scale subsurface geology.

Subsurface resistivity is related to several geological parameters such as mineral matrix, fluid content, porosity, permeability and degree of water saturation. Other contributing factors include groundwater salinity, volumetric clay content, cation exchange capacity, temperature of pore water, concentration of dissolved salts and contaminants (Shevnin et al. 2006; Lagmanson 2005; Loke 2001). The distributions of subsurface resistivity can be converted to geological images by integrating the knowledge of typical resistivity values for different subsurface materials with the local geology. Electrical conduction in the subsurface is mainly electrolytic because most mineral grains are insulators. Thus, the conduction of electricity is through the interstitial water (or other fluids) in the pores and fissures. Groundwater that fills the pore spaces of rocks is a natural electrolyte. The range of resistivity values for common earth's materials and chemicals (common subsurface contaminants) are given in Table 1 (Palacky 1987; Sharma 1997; Loke 2001; Lagmanson 2005). Igneous and metamorphic rocks typically have high resistivity values. However, geological processes such as dissolution, faulting, shearing and weathering can significantly increase their porosity and fluid permeability thereby increasing their conductivity. Processes such as hardening by compaction or metamorphism, and precipitation of carbonates or silica reduce the porosity and fluid permeability of rocks and hence reduces the conductivity. Sedimentary rocks are generally more porous and permeable than igneous and metamorphic rocks. The resistivity of sedimentary rocks is highly variable, low and depends on its formation factor (Archie 1942).

Table 1 Resistivity values of common earth's materials and chemicals

Materials	Resistivity (Ωm)
Igneous and metamorphic rocks	
Granite	$5 \times 10^3 - 10^6$
Basalt	$10^3 - 10^6$
Slate	$6 \times 10^2 - 4 \times 10^7$
Marble	$10^2 - 2.5 \times 10^8$
Quartzite	$10^2 - 2 \times 10^8$
Sedimentary rocks	
Sandstone	$8 - 4 \times 10^3$
Shale	$20 - 2 \times 10^3$
Limestone	$50 - 4 \times 10^2$
Soils and water	
Clay	1 – 100
Alluvium	10 – 800
Groundwater (fresh)	10 – 100
Sea water	0.2
Permafrost	$6.5 \times 10^2 - 10^5$
Chemicals	
Iron	9.074×10^{-8}
0.01 M potassium chloride	0.708
0.01 M sodium chloride	0.843
0.01 M acetic acid	6.13
Xylene	6.998×10^{16}

2 Geoelectrical Resistivity Surveys

The goal of geoelectrical resistivity surveys is to determine subsurface resistivity distributions by taking measurements of the apparent resistivity on the ground surface. Estimate of the true resistivity is made from these measurements by carrying out inversion on the observed apparent resistivity values and anomalous conditions or heterogeneities are inferred. Traditional applications of geoelectrical resistivity surveys include groundwater prospecting, mining and geotechnical investigations. More recently, the technique have been applied in mapping of contaminant transport (Newmark et al. 1998), hydraulic barriers (Daily and Ramirez 2000), fracture flow paths (Slater et al. 1997), contaminated zone (Amidu and Olayinka 2006; Olayinka and Olayiwola 2000), seepage pathways in embankment dams (Cho and Yeom 2007) and hydrocarbon contaminant plume (Osella et al. 2002).

The use of resistivity to determine the thicknesses and resistivities of layered media has its origin in the work of Conrad Schlumberger who conducted the first experiment in the fields of Normandy in 1912; and about the same time Wenner developed the same idea in the USA (Kunetz 1966). The technique has become an important tool in environmental and engineering applications. The conventional methods of geoelectrical resistivity surveys have undergone significant changes in the last 10–20 years. The traditional horizontal layering (1D) model of interpretation of geoelectrical resistivity data has been replaced with 2D and 3D models of interpretation in complex and highly heterogeneous media. Field techniques has been transformed from measurements made in separate and independent points, with current electrodes spacing growing in logarithmic scale to measuring systems with multi-electrode array along profiles (Dahlin 2001). Data acquisition was more or less carried manually till the 1980s, and this is tedious and slow. The survey was limited to either delineating the variation of apparent resistivity over a surface or compiling quasi-2D sections from a rather limited numbers of vertical electrical soundings (VES). This, however, is still the case in most developing countries, especially in Africa. The use of multi-electrode systems for data acquisition has led to a dramatic increase in field productivity so that one person rather than three or more can conveniently carry out electrical resistivity survey with limited layout.

2.1 Conventional Geoelectrical Resistivity Surveys (1D Interpretation Model)

Two procedures are adopted in convention geoelectrical resistivity surveys. The first is vertical electrical sounding (VES) or drilling (Keofoed 1979) where the mid-point of the electrode array remains fixed, but the electrode spread is increased about the centre. This yields the vertical variations in the subsurface resistivity distribution about the mid-point of the entire electrode spread. The subsurface is assumed to consist of horizontal layers in which resistivity vary only with depth. The apparent resistivity values are usually plotted in a log-log graph. Thus, the one-dimensional model of interpretation of VES is insensitive to lateral variations in the subsurface resistivity, which might lead to changes in apparent resistivity values. This is often misinterpreted as changes in resistivity with depth; however, useful results have been obtained for geological situations such as depth to bedrock and water table where the 1D model is approximately true.

The second approach employed is the constant separation traversing (CST) or profiling method where electrodes separation remains fixed but the entire array is progressively moved along a straight line. This yields information about lateral variations in the subsurface resistivity and is incapable of detecting vertical variations. Data obtained from profiling are mainly interpreted qualitatively. In environmental investigations, the subsurface geology is usually complex, subtle and multi-scale such that both lateral and vertical variations in the resistivity can be very rapid. Thus, the conventional approaches for geoelectrical resistivity surveys are inadequate for environmental applications.

2.2 Geoelectrical Resistivity Imaging (2D and 3D) Surveys

2D geoelectrical resistivity imaging has been used to map areas with moderately complex geology (Griffiths and Barker 1993; Dahlin and Loke 1998). The resistivity of the two-dimensional model changes both vertically and laterally along the survey line but constant in the direction perpendicular to the survey line. The 2D geoelectrical resistivity imaging can yield useful information that is complementary to those obtained using other geophysical methods in many geological situations. For instance, seismic methods can clearly delineate undulating interfaces but may not be able map discrete bodies such as boulders, cavities and contaminated plumes. Similarly, ground-penetrating radar can give detail information of the subsurface but have limited depth of penetration especially in areas with conductive unconsolidated sediments such as clay soils. 2D geoelectrical resistivity imaging surveys are usually carried out using large numbers of electrodes, 25 or more, connected to a multi-core cable.

To obtain a good 2D electrical resistivity image of the subsurface, the coverage of measurements should be two-dimensional. This is done in a systematic manner so that all possible measurements that will yield the best results from the inversion of the apparent resistivity values are made (Dahlin and Loke 1998). If a system has limited number of electrodes the area covered by the survey can be extended horizontally using a technique known as the roll-along method. This can be achieved by moving the cable past one end of the line by several unit electrode spacing, after completing a sequence of measurements. The observed apparent resistivity values are presented in pictorial form using pseudo-section contouring to obtain an approximate picture of the subsurface resistivity. However, the shape of the contours depends on the type of array used as well as the true subsurface resistivity. The pseudo-section plot is a useful guide for detail quantitative interpretation. Poor apparent resistivity data can easily be identified from the pseudo-section plot. The major limitation of the 2D geoelectrical resistivity imaging is that measurements made with large electrode spacing are often affected by the deeper sections of the subsurface as well as structures at a larger horizontal distance from the survey line. This is most pronounced when the survey line is placed near a steep contact with the line parallel to the contact (Loke 2001).

Geological structures encountered in environmental and engineering investigations are inherently three-dimensional in nature. Images resulting from 2D geoelectrical resistivity surveys often contain spurious features due to 3D effects and this usually leads to misinterpretation of the observed anomalies in terms of magnitude and location. Geometrically complex heterogeneous subsurface can therefore not be adequately characterized with 2D geoelectrical resistivity imaging. Due to out-of-plane resistivity anomalies and violation of the 2D assumption, the 2D resistivity imaging will produce misleading images (Bentley and Gharibi 2004). Hence, a 3D geoelectrical resistivity survey with a 3D interpretation model should give the most accurate and reliable results especially in subtle heterogeneous subsurface.

3D geoelectrical resistivity imaging have been used: to map an epithermal area associated with mineral deposits (Li and Oldenburg 1994), track fluid infiltration in vadose zone (Park 1998), delineate soil contaminated with oil and tar (Chambers et al. 1999), investigate an old quarry site used as landfill (Ogilvy et al. 1999), investigate the integrity of a permeable reactive barriers (Slater and Binley 2003) and study a decommissioned sour gas processing plants as part of its remediation programme (Bentley and Gharibi 2004). The 3D surveys were conducted because the heterogeneity of the sites precluded the use of conventional methods or the 2D geoelectrical resistivity imaging technique. The investigations show that 3D geoelectrical resistivity images are superior to the 2D images or the quasi-3D images produced from 2D inversions. Consequently, the 3D geoelectrical resistivity imaging is a better option to properly map the subsurface and its spatial distributions of petrophysical properties or contaminants in environmental and engineering investigations. However, 3D geoelectrical resistivity imaging is far more expensive than the 2D geoelectrical resistivity imaging. In addition, active researches in the field geometry and inversion code for 3D geoelectrical resistivity imaging are on going. Thus 2D geoelectrical resistivity imaging is still widely used in subsurface resistivity mapping even in complex and highly heterogeneous sites.

2.3 Arrays Used in 2D and 3D Geoelectrical Resistivity Surveys

A number of arrays have been used in 2D and 3D geoelectrical resistivity imaging surveys, each suitable for a particular geological situation. The most commonly used arrays include Wenner, Wenner-Schlumberger, dipole-dipole, pole-pole, pole-dipole and gradient arrays. The pseudosections produce by the different arrays over the same structure can be very different. The choice of an array type depends on the geological structures to be delineated, sensitivity of the resistivity meter, the background noise level, sensitivity of the array to vertical and lateral variations in the subsurface resistivity, depth of investigation, horizontal data coverage and signal strength (Loke 2001). The sensitivity function of an array shows the degree to which variations in resistivity of a section of the subsurface will influence the potential measured by the array. Higher values of the sensitivity function indicate greater influence of the subsurface region on the measurements which is mathematically given by the Frechet derivative (McGillivray and Oldenburg 1990).

Most of the pioneering works in 2D geoelectrical resistivity imaging surveys were carried out using the Wenner array (Griffiths and Turnbull 1985; Griffiths et al. 1990). The Wenner array is relatively sensitive to vertical variations in the subsurface resistivity below the centre of the spread but less sensitive to horizontal variations. It has moderate depth of investigation and its signal strength is inversely proportional to the geometric factor. It has the strongest signal strength but the smallest geometric factors, among the common arrays. The major limitation of Wenner array is its relatively poor horizontal coverage with increased electrode spacing. The dipole-dipole array has low electromagnetic coupling between the current and potential electrodes. It is most sensitive to resistivity variations between the electrodes in each dipole pair, and very sensitive to horizontal variations but relatively insensitive to vertical variations of subsurface resistivities. Thus, dipole-dipole array is useful in mapping vertical structures like dykes and cavities, but poor in mapping horizontal structures such as sills or horizontal layers. The depth of investigation is generally shallower than that of Wenner array but has better horizontal data coverage. The major disadvantage of dipole-dipole array is the decrease in signal strength with increasing distance between the dipole pair.

Wenner-Schlumberger array (Pazdirek and Blaha 1996) is a modified form of the classical Schlumberger array, and is moderately sensitive to both horizontal and vertical structures. The array is a good compromise between the Wenner and dipole-dipole array. Its depth of investigation is about 10 times greater than that of Wenner array for the same current electrodes separation. However, its signal strength is smaller than that of the Wenner array, but higher than that for Schlumberger array. Each deeper data level has two data points less than the previous data level unlike the loss of three data points with each deeper level in Wenner array. Thus, its horizontal coverage is slightly better than that for the Wenner.

The pole-pole array, in practice, consists of one current and one potential electrode with the second current and potential electrodes at an infinite distance. Finding suitable locations for these infinite electrodes so as to satisfy this requirement is sometimes difficult. In addition, pole-pole array is often associated with large amount of telluric noise capable of degrading the quality of the measurements. However, this array has the widest horizontal coverage and the deepest depth of investigation but the poorest resolution. Pole-dipole array is an asymmetrical array with asymmetrical apparent resistivity anomalies in the pseudosections over a symmetrical structure. The second current electrode is placed at an infinite distance. It has relatively good coverage but higher signal strength compared with dipole-dipole array. It is insensitive to telluric noise. Repeating measurements with the electrodes arranged in the reverse order can eliminate the asymmetrical effect. The signal strength of the pole-dipole array is lower than that of Wenner and Wenner-Schlumberger arrays.

3 Conclusions

Geoelectrical resistivity surveys have become an important tool in environmental applications where the subsurface geology is usually complex, subtle, multi-scale and highly heterogeneous such that both lateral and vertical variations in the resistivity can be very rapid. The conventional methods for geoelectrical resistivity surveys, which used one-dimensional model for interpretation, are inadequate for environmental studies. 2D geoelectrical resistivity imaging has been used to map areas with moderately complex geology resistivity values. However, images resulting from 2D geoelectrical resistivity surveys can contain spurious features due to 3D effects and this usually leads to misinterpretation of the observed anomalies in terms of magnitude and location. A 3D geoelectrical resistivity survey with a 3D interpretation model gives the most accurate and reliable results especially in subtle heterogeneous subsurface associated with environmental investigation sites.

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