Abstract: Oil contamination of soil and groundwater is a very important and expensive environmental problem. Therefore detection and monitoring of LNAPL contaminated sites using effective and economical geophysical methods are of extreme importance in management of these sites. According to the results of hydrodynamic simulation of the soil and groundwater pollution, a suspected pollution front in the transverse direction of plume movement was selected for the application of geophysical methods. The main goal was to create a novel economic and efficient non-intrusive method to delineate the plume boundaries and to increase the accuracy of interpolation and extrapolation schemes both in the hydrodynamic and geophysical techniques. VLF and Resistivity methods were used in three parallel profiles from west to east in north-south direction 30 m apart.

In this study it was verified that a region of low resistivity adjacent to a region of considerably higher resistivity in suspected polluted sites could be associated with the lateral boundary of the core of a free phase pollution plume (at about 12 to 22 m in the depth). It could also be suggested that applying geophysical techniques in conjunction with other methods provides a fast, economical and non-intrusive pollution assessment methodology.

Key-Words: LNAPL Contamination, Biodegradation, VLF, Resistivity, Schlumberger array, Silty-Clayish Subsurface

1 Introduction

Oil pollution is one of the most expensive and troublesome environmental problems for soil and water resources in the surrounding areas of the industrial facilities. Extensive geophysical studies have been conducted on LNAPL pollution, pollution extent, microbial biodegradation activities, source location etc in the past two decades. Some of these works and applications are listed here: Resistivity Soundings [1], RS application in determination of petrophysical parameters of soil for differentiation between the polluted and non-polluted zones [2-4], 2-D resistivity measurements [5,6], joint inversion of 2-D resistivity arrays in better and more accurate interpretation and analysis of the data [7], application of well logging for special resistivity measurements [8], Using Time Domain method in IP measurement [9, 10] and IP measurement through application of Frequency Domain [1112], Spectral Induced Polarization [13], Ground Penetrating Radar technique [8, 14, 15], electromagnetic methods such as VLF [16] and RMT [17], SP method [18,19], Time Domain Reflectometry [20] etc.

In some references hydrocarbon polluted soils are characterized by high resistivity [1, 5, 7, 14] however, it should be emphasized that these have been limited either to laboratory studies conducted by geophysicists like Darayan [1998] [20] or to studies conducted on newly polluted sites [5]. In cases of aged pollutions, high resistivity have been attributed to factors such as existence of clayey layers which had hindered microbial activity [17]. In older polluted sites (few weeks to few years based on other surrounding factors) where pollution can be classified as mature we encounter lower resistivity, i.e., higher electrical conductivity [21-27]. Benson [16] has shown that hydrocarbon contamination could create zones of high resistivity values. But Sauck [2000] [8] described a model which correctly suggests that aged hydrocarbon contaminated sites could develop anomalies of relatively low resistivity due to increase in dissolved solids as a results of weathering minerals with production of organic and carbonic acids. He also
concluded that very high resistivity values shown in the past studies were due to short term monitoring of sites where geochemical alteration due to LNAPL biodegradation had not occurred. According to Estella A. Atekwana [21-27] and Eliot A. Atekwana [28, 29], Sauck’s findings were further verified. These studies, however, showed that the low resistivity anomalies were not solely because of organic and carbonic acid production. Atekwana [24-27] suggests that very low resistivity anomaly in the contaminated media could not be just as a result of increase in electrolytic conductance. They document that biosurfactant production also contributed to low resistivity.

2 Methodology
According to the results of hydrodynamic simulation of the soil and groundwater pollution, a suspected pollution front in the transverse direction of plume movement was selected for the application of geophysical methods. The main goal was to create a novel economic and efficient non-intrusive method to delineate the plume boundaries and to increase the accuracy of interpolation and extrapolation schemes both in the hydrodynamic and geophysical techniques. Sauck [2000] [8] suggests that application of geophysical methods results in more accurate interpretations in the transverse direction rather than in the longitudinal direction of the plume movement. It is important to note that in the principal direction of plume movement, i.e. the direction of the highest hydraulic gradient, due to dominance of advection mechanism a thin free phase layer is created. This thin layer is followed by a longer dissolved phase zone. Low difference in special resistivity between the free and dissolved phases of the plume makes it difficult to distinctly pinpoint the actual location of the plume front using the geophysical methods. While in the transverse direction, due to the dominance of diffusive mechanisms and very slow movement of the peripheral front, this distinction is much easier.

VLF and Resistivity methods were used in three parallel profiles from west to east in north-south direction 30 m apart. Distance between successive soundings in the VLF profiles was 5m and in the resistivity profiles10m. Resistivity and VLF data were interpreted with IPI2WIN and RAMAG2 programs respectively. Resistivity method was used through application of Schlumberger array with sounding space of 10m. The antenna used for the VLF method had a frequency of 23.4 kHz(NPM station).

3 Example
Tehran Oil Refining Company (TORC) is one of the largest and oldest petroleum contaminated sites in the world. Contamination has continued within the past forty years with contaminants consisting of gasoline, gas oil, jet fuel and crude oil.

Geology of this site contains successive silty-clayish layers with presence of pebbles and wide range of grain size from clay to gravel. Water table at this site is approximately 16m below the ground surface. While there are areas, in the center of plumes, in which the thickness of free phase layer exceeds 18 meters, however the peripheral area of interest for our studies has 90 cm of free phase on the top of the water table.

As can be observed in Fig.1, the apparent in-phase current density cross sections can be approximately indicative of existence of conductive masses in the depth associated with the actual pollution. This in part is due to the low differential conductivity between the free and dissolved phases of the contamination and also due to the high conductivity nature of the silty-clayish host environment. On the other hand the results of resistivity measurements in the polluted site, figures 2, 3 and 4 clearly indicate the existence of a low resistivity zone associated with the depth of the actual pollution that could be verified with a collection well close to the line 1

4 Conclusion
It was concluded that measured resistivity in this area showed a reduction to almost 50% of the original background values. In this study it was verified that a region of low resistivity adjacent to a region of considerably higher resistivity in suspected polluted sites could be associated with the lateral boundary of the core of a free phase pollution plume. It was also observed that the use of VLF method with other geophysical technique can be helpful; in detecting LNAPL plume. It could also be suggested that applying geophysical techniques in conjunction with other methods provides a fast, economical and non-intrusive pollution assessment methodology.
**Fig. 1** The apparent In-Phase cross-section of VLF data corresponding to line 2

**Fig. 2** Top: Resistivity pseudo cross-section, bottom: Resistivity cross-section for line 1

**Fig. 3** Top: Resistivity pseudo cross-section, bottom: Resistivity cross-section for line 2
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