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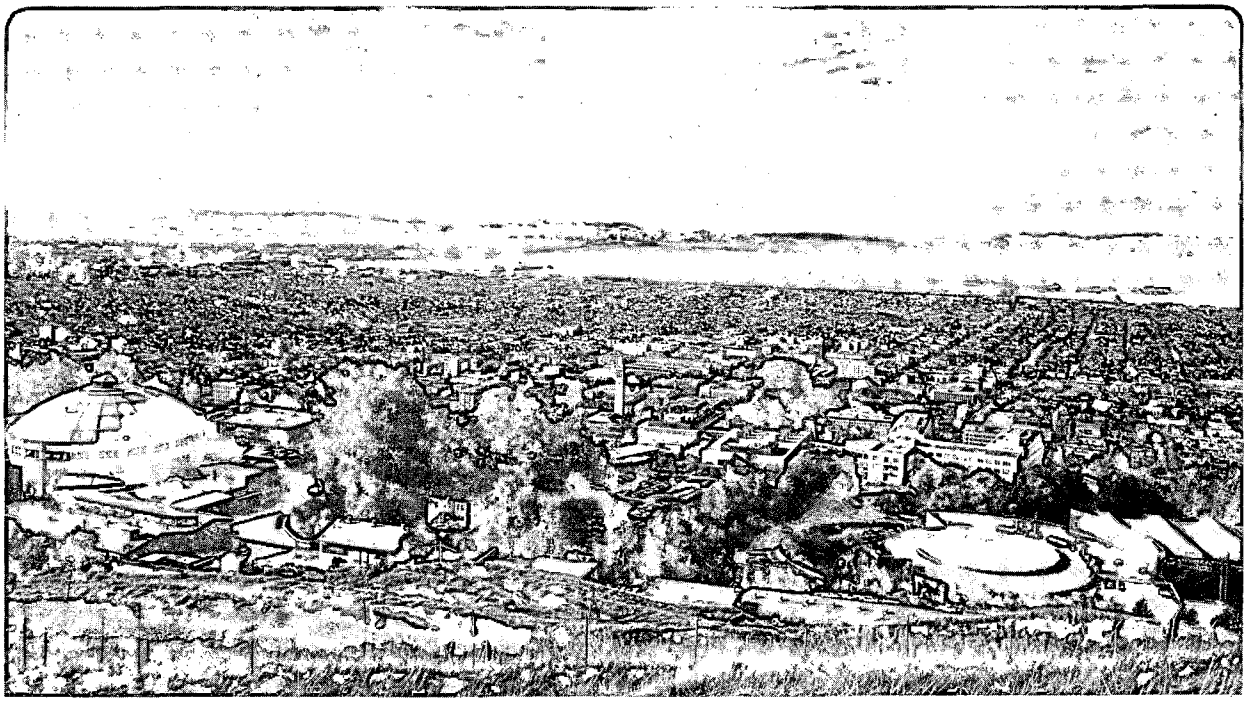
Electrical Resistivity for Detecting Subsurface Non-Aqueous Phase Liquids: A Progress Report

K.H. Lee, C. Shan, and I. Javandel

June 1995



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Electrical Resistivity for Detecting Subsurface Non-Aqueous Phase Liquids: A Progress Report

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Electrical Resistivity for Detecting Subsurface Non-Aqueous Phase Liquids: A Progress Report

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Objective

The objective of this study is to characterize the functional relationship between the bulk electrical resistivity of soils/rocks and their saturation with non-aqueous phase liquids (NAPLs). This functional relationship will be the basis for developing a field technique for locating subsurface NAPLs.

Introduction

Soils and groundwater have been contaminated by hazardous substances at many places in the United Sates and many other countries. The contaminants are commonly either petroleum products or industrial solvents with very low solubility in water. These contaminants are usually called non-aqueous phase liquids (NAPLs). The cost of cleaning up the affected sites in the United States is estimated to be of the order of 100 billion dollars. In spite of the expenditure of several billion dollars during the last 15 years, to date, very few, if any major contaminated site has been restored (National Research Council, 1994).

The presence of NAPL pools in the subsurface is believed to be the main cause for the failure of previous cleanup activities. Due to their relatively low water solubility, and depending on their volume, it takes tens or even hundreds of years to deplete the NAPL sources if they are not removed from the subsurface. However, there is no effective method in detecting and locating the subsurface NAPL pools *in situ* . Without some good knowledge about the spatial distribution of the NAPL pool, any drilling activities on a NAPL site could accidentally penetrate through the formation supporting the NAPL pool and provide a fast pathway for the spreading of contamination. In fact, this is the biggest concern for NAPL site investigation and remediation. Once such pools are located, they can be easily removed by means of appropriately positioned wells.

The electrical resistivity technique has been used routinely to locate the subsurface ore deposits. The significant difference in electrical resistivity between ore and other geological materials makes such prospecting successful. This technique has also been used to help monitor the process of underground injection of steam (Ramirez, et al., 1993) and salt water (Bevc and Morrison, 1991).

The electrical conductivity of rocks and unconsolidated sediments in the upper parts of the earth's crust is governed by the water content and nature of the water connections in the rock/soil formation. When an electrical potential gradient is applied to a rock/soil saturated with water, the electrical current is basically carried by the ions in groundwater. The electrical current through a rock/soil is therefore dependent on the ionic concentration

and mobility, as well as the magnitude of water saturation and the nature of pore connections. The reciprocal of the electrical conductivity is called the *electrical resistivity.*

The intrinsic electrical resistivity of most NAPLs is typically in the range of 10^7 to 10^{12} Ω-m, which is several orders of magnitude higher than that of groundwater containing dissolved solids (usually in the range of a few Ω-m to a few thousand Ω-m). Although a dry soil is very resistive, the electrical resistivity of a wet soil is on the order of 100 Ω-m and is dependent on the extent of water saturation. For a given soil, the electrical resistivity increases with decrease of water saturation. Therefore, if part of the pore water is replaced by a NAPL, the electrical resistivity will increase. At many NAPL sites, both the vadose and phreatic zones can be partially occupied by NAPL pools. It is the great contrast in electrical resistivity between the NAPLs and groundwater that may render the method to be effective in detecting subsurface NAPLs at contaminated sites. The following experiments were conducted to investigate the change of the electrical resistivity of porous media when diesel fuel (NAPL) replaces part of the water.

Laboratory Experiment

We started designing our laboratory resistivity experiments in June, 1993. The experimental apparatus consists of a vertical soil column in a glass container supported by a porous plate (or filter), four electrodes (two electrodes on each side), a bottom reservoir, and a cover with filter (Figure 1). The fluid (water or NAPL) can be introduced from either the top or the bottom. An alternating-current (AC) was applied to the soil column (14 cm high and 10 cm in diameter) during the experiments, the electrical potential and current, respectively, were measured using the two pairs of electrodes. Values of current and potential were measured at a selected time interval and recorded electronically. The apparent electrical resistivity of the medium is proportional to the ratio of the potential (P) to the current (C). Further details follow.

a) Power: A 350 Hz AC power source was used to limit polarization. In case of high resistivity materials, to apply the same level of current, we used lower frequency (35 Hz). The wave form was generated using the Waveteck function generator. The typical current strength throughout the experiments was on the order of a few mA, and the potential of a few mV.

b) Electrodes: To limit the polarization and to minimize contact resistance, we used a #80 platinum planar mesh, 3 cm by 1.5 cm in size, for the electrodes. To minimize any undesirable chemical reactions, the platinum mesh electrode was welded to a titanium wire that was connected to external power source.

c) Recording: Measurements were recorded using a desktop PC (COMPAQ Deskpro 386/20). The P/C ratio represents the resistance which is a function of the electrical resistivity and a geometrical factor. Since the geometrical factor remains the same for all measurements, the P/C ratio can be considered as the normalized electrical resistivity. The

measurement interval for the experiments was in the range of 5 to 20 seconds. Two different column tests have been conducted to date.

1. Sand Loam Column Test

A sandy loam consisting of 70% sand, 20% silt and 10% clay (by weight) was used for preparing the soil column. A layering and vibrating technique was applied to pack the soil column, resulting in a porosity of 0.36. After several unsuccessful trials, we obtained reasonable experimental data in August, 1994. In this experiment, the current was supplied through electrodes 1 and 2, and the potential was measured between electrodes 3 and 4 (see Figure 1).

The soil column was initially saturated with water, and then drained to 80% average water saturation. Both the electrical potential and the current were measured and the P/C ratio of the medium was calculated. Later on, diesel fuel was injected to the soil column through a helical shaped PVC tube of small diameter (3/16") buried at the middle of the soil column. The densely perforated PVC tube helped diesel fuel to enter the soil column with a uniform distribution. The diesel fuel injection was carried out six times, with a 10 ml uniformly injected each time. After each injection, the P/C ratio was measured and recorded continuously until a steady-state condition was reached (typically, in about two hours).

The steady-state P/C ratio obtained after each injection was first normalized with respect to the P/C ratio obtained from the 80% water saturation. The increase of the normalized P/C ratio is shown in Figure 2, where the electrical resistivity of the soil column increases with the addition of diesel fuel up to 13% diesel saturation. Addition of diesel fuel beyond 13% of the pore volume showed a decrease in the value of P/C. The mechanisms causing such kind of phenomenon are still under investigation. Several factors such as temperature and pressure of the medium as well as the degree of interconnection of different fluids could affect the bulk electrical resistivity.

2. Sand Column Test

A sand column test was subsequently conducted. To obtain a larger coverage of soil volume, in this test, the current was supplied through electrodes 1 and 4, and the potential was measured between electrodes 2 and 3 (Figure 1). The column was packed with a coarse sand (the porosity was equal to 0.41), and initially saturated with groundwater containing 600 ppm total dissolved solids and having an electrical resistivity of about 11.5 Ω-m. The measured P/C ratio of the water saturated sand column was about 7.5 Ω. The column was then drained to an average water saturation of 24%. Efforts to measure the P/C ratio after the drainage were unsuccessful, however, because the sand at the measurement points was so dry that the contact resistance became too high to be measured. The 24% water saturation was calculated using the weight of the residual water in the container. Next, diesel fuel was introduced to the sand column from the bottom. After the column was fully saturated with residual water and diesel fuel, the P/C ratio was measured and at steady-state, it was about 1140 Ω. A comparison between the two measured numbers reveals that the bulk electrical resistivity increased about two orders of magnitude when

diesel saturation changed from zero to about 76%. Part of the data for P/C ratio from the two measurements is shown in Figure 3.

Discussions of Results and Future Plans

Results from the first experiment (sand loam column) revealed that for a small diesel saturation the contrast between bulk resistivity of two media is of the order of 10 to 15 percent. However, the result from the second experiment (sand column) is very exciting. A contrast of more than two orders of magnitude is very promising. Although experiments were conducted using diesel fuel only, we anticipate that the existence of other highly resistive NAPLs in soil will demonstrate a similar effect as that of diesel fuel. We plan to conduct the test with other NAPLs such as Freon 113 and 1,1,1-TCA. A relatively large-scale laboratory sand box test and a controlled field test are planned following the successful completion of the column tests. The final field test will be a demonstration of the applicability and efficiency of the electrical method in detecting and locating the subsurface NAPLs.

Acknowledgment

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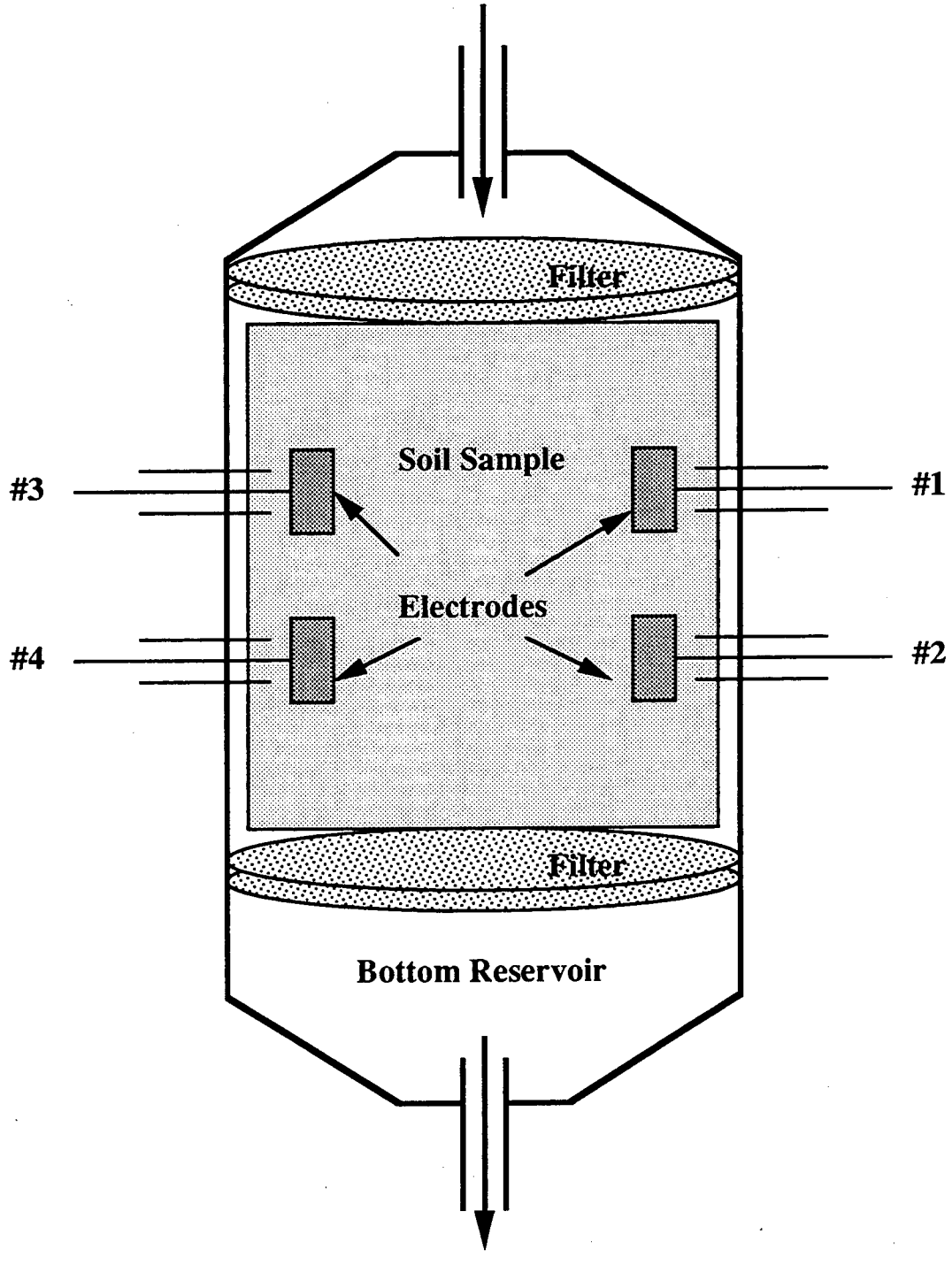

Figure 1. Schematic of Resistivity Experiment Using Soil Column

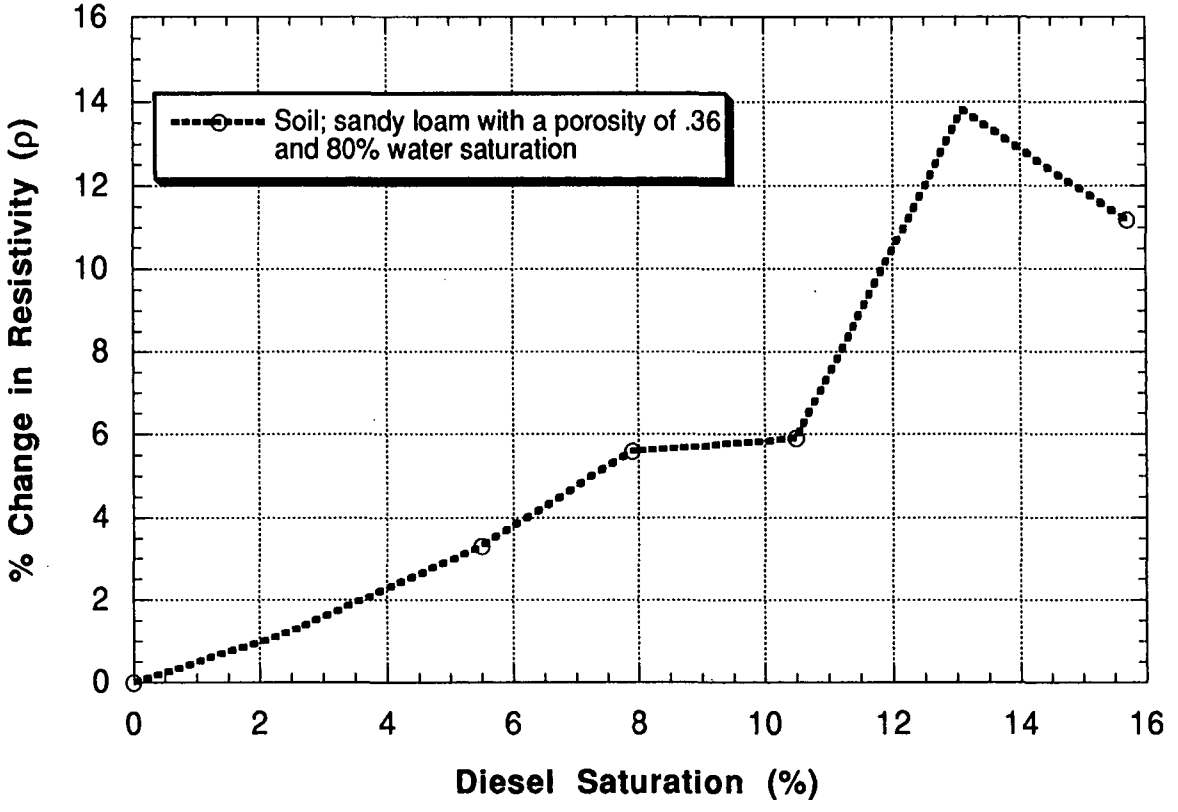

Figure 2. Resistivity Change as a Function of Diesel Saturation

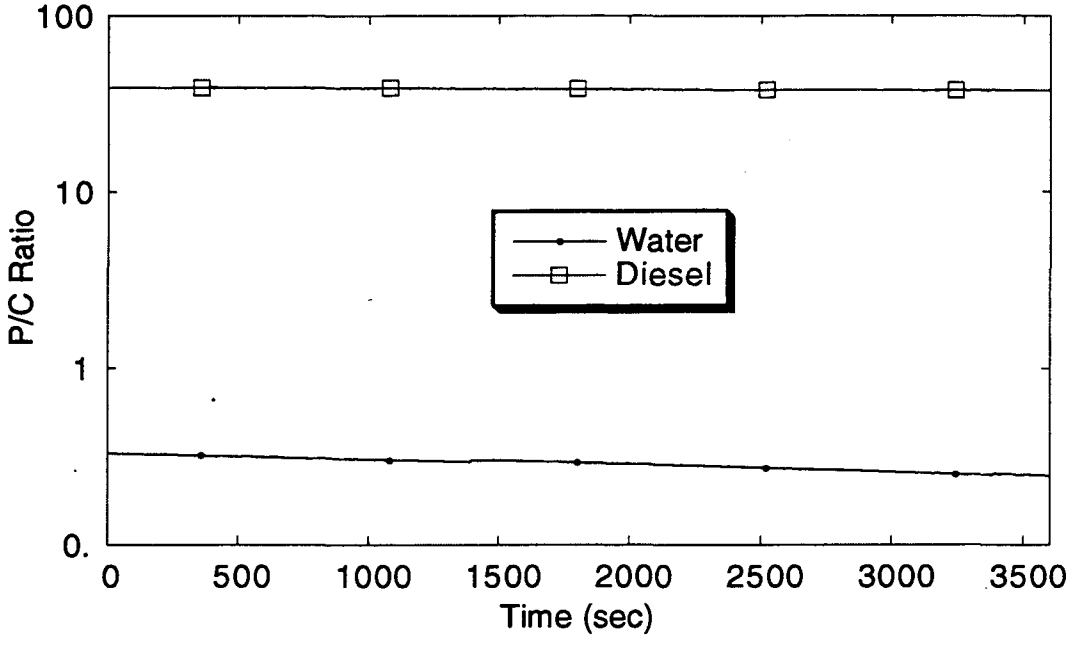

Figure 3. Comparison of P/C ratio for two different fluids and for the coarse sand

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