Experimental study of the complex resistivity and dielectric constant of chrome-contaminated soil

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ABSTRACT

Heavy metals such as arsenic and chromium often contaminate soils near industrialized areas. Soil samples, made with different water content and chromate pollutant concentrations, are often needed to test soil quality. Because complex resistivity and complex dielectric characteristics of these samples need to be measured, the relationship between these measurement results and chromium concentration as well as water content was studied. Based on soil sample observations, the amplitude of the sample complex resistivity decreased with an increase of contamination concentration and water content. The phase of complex resistivity takes on a tendency of initially decrease, and then increase with the increasing of contamination concentration and water content. For a soil sample with the same resistivity, the higher the amplitude of complex resistivity, the lower the water content and the higher the contamination concentration. The real and imaginary parts of the complex dielectric constant increase with an increase in contamination concentration and water content. Note that resistivity and complex resistivity methods are necessary to adequately evaluate pollution at various sites.

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1. Introduction

Soil pollution has become an increasingly serious problem in China. The threats posed to human health by heavy metals such as arsenic and chromium (Cr) in soil severely challenge the nation's ability to maintain a healthy environment along with food safety while sustainably using cultivated land resources (Liu et al., 2009). Numerous sites (more than 70) contaminated with large amounts of Cr (up to 6 million tons of Cr residues in open air storage), have severely contaminated the soil, rivers and underground water resources; this makes it imperative to conduct an evaluation of sites contaminated with Cr residues and to restore the contaminated soils and underground water resources (Li et al., 2006). The initial stage of contaminated site mitigation is to identify the level, scope, and characteristics of pollution including the geological conditions of each site. However, traditional time-consuming and expensive detection methods for contaminated sites mainly employ sample drilling combined with indoor chemical analysis (Liu et al., 2010b). Because funds are always limited, surveys for most sites contaminated with Cr residue cannot be conducted. Detection technology is developing in the direction of environmental geophysics for contaminated sites because this technology allows the rapid and accurate measurement of the differences among parameters of electrical properties (Dannowski and Yaramanci, 1999; Luo et al., 2010). This provides an ideal method

of detecting heavy metals (including Cr) at contaminated sites based on differences in their electrical properties.

The electrical method provides an important geophysical technique that can be used to investigate and monitor an abnormality in a geological body such as soil (Li, 1999). This method, in the broad sense includes methods that analyze electrical resistivity and complex resistivity as well as electromagnetic detection (Lazaro-Mancilla and Gomez-Trevino, 2000). The resistivity method is based on differences in conductivity. The complex resistivity method reveals spectral induced polarization properties (Kruschwitz and Yaramanci, 2004). Electromagnetic detection is based on dielectric dispersal characteristics (Robert, 1998; Sakellis et al., 2014; Pettinelli et al., 2014).

The Cole–Cole model is often used with the complex resistivity method to determine the relationship between measurement results and the physical characteristics of samples (Liu et al., 2010a; Orbert and Georg, 2009; Pelton et al., 1978). Dielectric dispersion characteristics are often present that relate the sensor frequency to the permittivity of a medium (Kelleners et al., 2004). Some successful examples of the use of the surface ERT to monitor a tracer test in a complex environment have been tested (Monego et al., 2010; Wilczek et al., 2012).

It does matter if a soil sample is tested or material comes from a contaminated site, the measurement results could be affected by water, contaminants and the density of the sample, etc. In a given set of conditions, it is often difficult to distinguish the effects of salt contamination and water content on the measurements. For this reason, a series of experimental studies have been conducted to study the relationship between conductivity, spectral induced polarization properties and the

dielectric characteristics of a sample compared with the concentration of Cr pollutants and water content; in addition, some practical and meaningful results have been achieved.

2. The methodology for the analysis of the laboratory measurements

2.1. Equipment

The instruments include model ZL5 Intelligent Impedance Analyzer (Shanghai, China), a model OI-859CF digital multimeter and HP8753C microwave vector network analyzer (Aligent, Palo Alto, CA, USA). A cylindrical organic glass tube (inner diameter 70 mm, height 70 mm) held the soil sample. The ambient temperature was set at 27 °C to eliminate the effects temperature during the experiment (Rosenbaum et al., 2011).

Crushed soil was collected from the yard of the China Environmental Science Research Institute. First, each soil sample was placed on a tray in a drying oven and dried for 48 h at 100 °C to remove moisture. A Na_2CrO_4 solution was prepared with various concentrations (based on the Cr concentration), ranging from 0 mg/kg to 4000 mg/kg at intervals of 500 mg/kg. Then, saline solution was used to prepare three soil samples with different volumetric water content (V_{wc}): 10%, 20% and 30%. The Vwc = soil moisture content in soil/soil volume following Ansoult et al. (1985). Each sample was placed into a glass tube, sealed and set aside for 48 h to allow the solution and soil to equilibrate. The concentrations of chloride and sulfate ions in the control soil sample were 2.11 mmol/L and 1.56 mmol/L, respectively. Tables 1 and 2 show the physical properties of the control soil sample and the analysis on metallic elements in that sample.

2.2. Experiment principle

The four-phase electrode method was used to determine complex resistivity, while the coaxial terminal open circuit reflection method was used to determine complex dielectric constant. Resistivity was also measured.

2.2.1. Resistivity

In this experiment, the multimeter was used to measure the voltage (U) between the measuring terminals (MN) and another multimeter was used to read the circuit current (I). The formula $\rho = (U / I) \times (S / l)$ was used to calculate the resistivity of the sample where, ρ is the resistivity of soil, U and I are the voltage drop and circuit current of the measured soil sample, respectively, and S and l are the sectional area and length of the measured soil sample, respectively. Figs. 1 and 2 illustrate the experimental device and circuit connection, where AB is the power supply with DC and AC signals, MN are the input terminals of the measured signals, ACE1 and ACE2 are Ag/AgCl electrodes, and CE1 and CE2 are copper electrodes.

2.2.2. Complex resistivity

A ZL5 intelligent impedance analyzer was used to determine the complex resistivity of the soil sample at ten frequency points (from 12 Hz to 100 KHz as follows: 12 Hz, 30 Hz, 100 Hz, 500 Hz, 1 kHz, 5 kHz, 10 kHz, 20 kHz, 50 kHz and 100 kHz). The complex resistivity was defined using Eq. (1):

$$Z^*(\omega) = U \cdot / I \cdot = |Z^*(\omega)|e^{i\phi(\omega)} \tag{1}$$

where, ($i^2 = -1$), $|Z^*(\omega)|$ and $\phi(\omega)$ are the module and phase of

Table 1
Physical properties of the control soil sample.

pH	Sand/%	Sandy soil/%	Clay/%	Density	Ecp(dS/m)	Temp/°C
7.61	30.7	53.2	16.1	1.18	0.028	27

Table 2
Metal content of the soil sample (unit: μg/g).

Na	Mg	K	Ca	Fe
12.9	26	16.9	20.5	0.2

complex impedance, respectively. The existence of a polarization process in the soil samples, namely, the so-called induced polarization effect, resulted in the occurrence of phase $\phi(\omega)$. The formula of complex resistivity is seen in Eq. (2):

$$\rho(\omega) = |Z^*(\omega)| \times (S/l)e^{i\phi(\omega)} \tag{2}$$

where, $|Z^*(\omega)| \times (S/l)$ is the amplitude (module) of complex resistivity, and $\phi(\omega)$ is the phase of complex resistivity.

2.2.3. Complex dielectric constant

The coaxial terminal open circuit reflection method was used to determine the complex dielectric constant within a frequency range of 10 MHz to 1 GHz (Sakellis et al., 2014; Scudiero et al., 2012). Fig. 4 illustrates the measuring system (Ke et al., 1999; Francisca and Montoro, 2012).

When the coaxial line length of the filling medium is much less than wavelength, the lumped parameter may be used as the equivalency (Fig. 3, where C_f stands for the equivalent capacitance of the interior coaxial line of the filling medium and $C_0(\varepsilon)$ and $G(\varepsilon)$ are the capacitance and conductance generated by axial open terminal edge and terminal medium, respectively. According to the transmission-line theory, when the open terminal is free space, the real part G_0 of input admittance is much less than the imaginary part $\omega(C_0 + C_f)$. The input admittance of terminal open coaxial can be written using Eq. (3):

$$Y/Y_0 = j\omega C_f Z_0 + j\omega C_0 Z_0 \tilde{\varepsilon} + G_0 Z_0 \tilde{\varepsilon}^{5/2} \tag{3}$$

where, $Z_0 = 1/Y_0$ is a coaxial specific impedance, and $\tilde{\varepsilon}$ is a complex dielectric constant of the medium. Make one side of the core sample cling to the coaxial open terminal. When the core sample is finished measuring, the signal passes the reflection coefficient of coaxial line at the terminal surface. Eq. (3) may be used to calculate ε. If G_0 is negligible, the simplified equation to calculate complex dielectric constant of terminal medium may be obtained using Eqs. (4) and (5) (Reppert et al., 2000):

$$\varepsilon' = \frac{-2\Gamma \sin\phi}{\omega C_0 Z_0 \left(1 + 2\Gamma Coo\phi + \Gamma^2\right)} - \frac{C_f}{C_0} \tag{4}$$
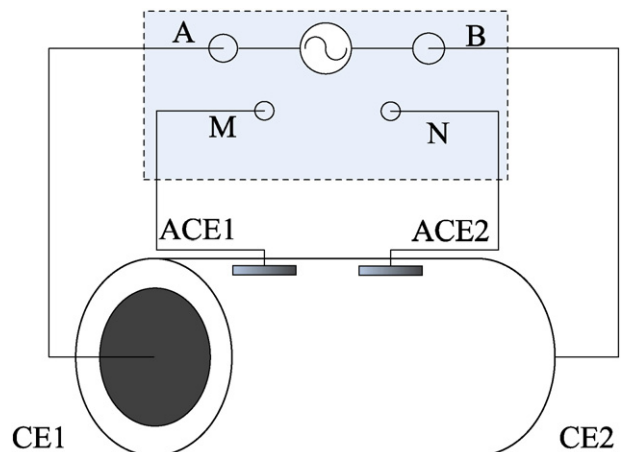

Fig. 1. The experimental device used for the circuit connection of the four-phase electrode method.