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A critical analysis of the performance of plate- and point-electrodes for determination of electrical properties of the soil mass

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ABSTRACT

In the recent past, researchers have started utilizing electrical properties of the soil mass for its characterization by employing either plate- or point electrodes. Though, plate-electrodes are easy to use for laboratory experiments, and quantification of geometrical characteristics of the electric field generated within them is easy to quantify, their application for in-situ experiments and for samples of cylindrical shape becomes difficult. On the other hand, usage of point-electrodes which are cylindrical in shape, are used for moisture content determination of the soil or migration of contaminants in it, for coarse-grained soils and fine-grained soils might yield erroneous results, due to the presence of inter particle voids and presence of cavities & anomalies, respectively. Furthermore, quantification of geometrical parameters of the electric field of point-electrodes is quite difficult which results erroneous measurements in determination of electrical properties of the material, in which they are installed. Hence, establishment of the uniqueness of electrical properties obtained from the plate- and point-electrodes, for identical samples becomes utmost important. With this in view, COMSOL Multiphysics® was employed to simulate the electrical response of various geomaterials in their uncontaminated and contaminated states and results were critically evaluated vis-à-vis those obtained from the impedance analysis (1 Hz to 40 MHz). Efforts have also been made to relate the geometrical dimensions of electrodes and electric field generated across the point electrodes, which would facilitate proper design and installation of sensors in a material to achieve the desired output. This study demonstrates the suitability and versatility of the point-electrodes for various (field and laboratory) applications where in moisture profiling and contaminant transport is to be established.

1. Introduction

Electrical properties of the soil mass such as dielectric constant [1–3], electrical conductivity [4–6], electrical dispersion [7,8] and impedance [9,10] have been utilized for determining its volumetric moisture content [1,3], degree of saturation [11,12], degree of compaction [13], porosity [14], permeability [15,16] and fabric structure [7,9,17]. A few other real life applications wherein these properties play an important role are: detection of the ground water contamination [18], subsurface water profiling [19,20], detection of frozen soils [21] and estimation of soil salinity and conductivity [6,22].

The dielectric constant, k, a measure of the ability of a material to store electrical charges under the influence of an electric field, is influenced by both ion concentration and types of ions present in it. Hence, its effect on the soil behavior, especially soil-water system has utmost importance [2,23,24]. Incidentally, researchers [1,6,25,26] have correlated k with volumetric moisture content, θ, based on the fact that for the dry soils, k ranges between 2 and 8, while for pure water its value is 81. The electrical conductivity, σ, a measure of charge mobility within a material due to the application of electric field, is another important parameter that can be employed for the soil mass characterization. In this context, earlier researchers [5,27–30] have correlated σ of the soil mass with its θ, conductivity of pore solution, clay content of the soil and its mineralogy. Incidentally, Gumaste et al. [31] have employed 'anisotropy coefficient', which is the ratio of electrical conductivities of the soil mass in the transverse and longitudinal directions, for quantification of the grain orientation and fabric anisotropy.

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Nomenclature

θ	volumetric moisture content	Hz	hertz
γ_t	soil bulk unit weight	kHz	kilohertz
γ_d	dry unit weight of soil	MHz	megahertz
σ	electrical conductivity	M	molar
σ_{DC}	electrical conductivity corresponding to zero frequency	mm	millimeter
σ_{WQA}	electrical conductivity of water quality analyzer	ml	millilitre
°C	degree celsius	V	voltage
%	percentage	S/m	siemens per meter
d	spacing between the electrodes	A	cross sectional area
d_e	diameter of the electrode	AC	alternating current
t_e	effective diameter of the electric field generated across the electrodes	C	capacitance
		DC	direct current
X	centre to centre distance between the adjacent electrodes	DW	distilled water
		E	electric field
g	gram	GB	glass beads
c/c	centre to centre	IC	impedance cell
k	dielectric constant	RWC	residual water content
ω	angular frequency	S	sand
ε	effective permittivity	V	volt
f	frequency	WC	white clay

Earlier researchers have also employed direct current, DC [6,28,32,33], and alternating current, AC [1,7,26,30,31,34,35], for in-situ & laboratory measurement of the properties of the soil mass. In these studies either plate-electrodes [2,30,31] or point-electrodes [1,2,10] have been used and it has been opined that the plate-electrodes are easy to use, particularly for measuring electrical properties of the soil mass in the laboratory setups [2,6]. However, utility of these electrodes for in-situ applications is cumbersome, if not impossible, due to the difficulties associated with their installation in the field. Moreover, these electrodes cannot be employed for samples with cylindrical geometry. Earlier researchers [18,20,26] have employed point electrodes for studying the real time variations of soil specific parameters (viz., soil moisture content and extent of contamination) and mechanisms (viz., spread or migration of contaminants) occurring in it. However, point-electrodes when located in voids and/or cavities and/or anomalies, might yield erroneous results [26]. Apart from these issues, determination of geometrical properties of the electric field, E, in the sample is another big concern, as elaborated in the following. In case of the plate-electrodes, quantification of the flux area (effective diameter of the electric field), which is equal to the geometrical area (geometrical dimensions) of the electrodes is straight forward, while the same is not true for the point-electrodes, where quantifying flux area is difficult. Also, interference of point-electrodes needs to be addressed, which calls for optimization of the center-to-center and tip-to-tip distances of electrodes. Considering the aforementioned issues associated with the plate- and point electrodes for determination of the electrical properties of the soil mass, relative performances of the plate- and point-electrodes by testing various materials was cross checked and details of the study are presented in the following.

COMSOL Multiphysics® was employed to simulate and study response of various materials (viz., distilled water, standard solutions, glass beads and soils of different types) when they are exposed to an electric field. Simultaneously, two test setups (read Impedance cells) were fabricated and by resorting to Impedance Analysis (1 Hz to 40 MHz), electrical response of these materials was measured by employing the plate- and point-electrodes. The experimental results were validated vis-à-vis those obtained from the simulation carried out by using COMSOL Multiphysics®. Details of this exercise are presented in this manuscript and recommendations regarding the proper choice of electrodes for measurement of electrical properties of the material (read soil mass), have been made. It is believed that such a study would facilitate proper design and installation of sensors in a material to determine its electrical properties, which could be related to various engineering properties of the soil mass, as described above.

2. Materials and methods

2.1. The test setups

Two test setups, termed as impedance cells (IC-I and IC-II), depicted in Figs. 1 and 2, were fabricated and used in the present study. As depicted in Fig. 1, the impedance cell IC-I consists of three pairs of point-electrodes, fitted diagonally opposite to each other on a Perspex cylinder (internal diameter, 50 mm, wall thickness 3 mm and height 120 mm) and fitted to a Perspex base plate. These electrodes are 2 mm in diameter, d_e, and 30 mm in length and are made of stainless steel. The tip-to-tip spacing, d, and the centre to centre spacing, X, of these electrodes was varied from 12 to 42 mm and 10 to 20 mm, respectively. On the other hand, the impedance cell IC-II (refer Fig. 2), is a rectangular box, made of Perspex mould (25 mm in height, 20 mm in length and 12 mm in width) fitted with a pair of mirror-finished, passivated stainless steel electrode

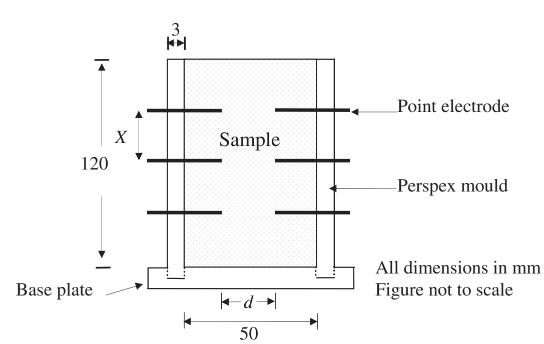

Fig. 1. The impedance cell IC-I.