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Study of Mechanisms Governing Electromagnetic Alteration of Hydraulic Conductivity of Soils

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Abstract

Hydraulic conductivity is a measure of the rate at which water flows through porous media. Because of the dipole properties of water molecules, electric field can affect hydraulic conductivity. In this study, the effect of radio-frequency (RF) waves on hydraulic conductivity is investigated. This is important both for the geophysical measurement of hydraulic conductivity as well as remediation using electromagnetic waves. Bentonite clay and sandy samples are tested in rigid-wall, cylindrical permeameters and stimulated using a CPVC-cased monopole antenna vertically centered in the permeameters. The permeameters are encased within RF cavities constructed of aluminum mesh in order to prevent interference from the outside and to confine the RF wave to the medium. Falling-head and constant-head tests are performed to measure the hydraulic conductivity of the clayey and sandy soil samples, respectively. The results show a correlation between the change in the hydraulic conductivity and various characteristics of the RF stimulation. The change is, however, different for sandy and clayey soils.

Keywords: Hydraulic Conductivity, Electromagnetic Stimulation, Dielectrophoresis.

1. Introduction

Soil contamination typically arises from leaking underground storage tanks, oil and fuel dumping, leaching of waste from landfills, or the direct discharge of industrial waste into the soil (Robinson et al., 1988). Polluted soils can affect human health directly or via inhalation of contaminants that have vaporized or by infiltration into the groundwater aquifers that may be supplying drinking water. Several properties of soils, including hydraulic conductivity, can play important roles in controlling various flow and transport mechanisms. Transport of contaminants and water is controlled by hydraulic conductivity, making hydraulic conductivity and its measurement important to several science and engineering fields. Hydraulic conductivity is a measure of the rate at which water flows through porous media. Various geophysical measurement or remediation methods alter hydraulic conductivity. This phenomenon has traditionally been ignored.

For example, radio frequency (RF) waves are used for radar-based geophysical measurement and remediation. The use of RF waves can enhance various transport mechanisms within soils. Research in the food industry has proven that an RF electric field can enhance diffusion and the mass transfer rate (Liam et al., 1999). RF waves can potentially alter hydraulic conductivity as well. In recent remediation studies, the use of direct or alternating currents (DC and AC, respectively) has been used to stimulate various transport mechanisms in porous saturated media in order to improve soil and groundwater remediation. The application of DC across electrodes inserted in saturated soils results in the controlled production of oxygen by water electrolysis at the electrodes (Akar et al., 1993). During other research on the use of RF waves to enhance soil remediation (Azad et al., 2013), the authors realized the hydraulic conductivity was altered. The hydraulic conductivity of a saturated soil is dependent on the unit weight and viscosity of the permeant fluid (in this case water) as well as on the intrinsic permeability of the porous media, which is in turn dependent on the pore- and grain-size distribution as well as porosity. The hydraulic conductivity is also a function of the level of water-saturation in the medium (Das, 2006).

Understanding the relation between RF stimulation and hydraulic conductivity could have broad use in geoenvironmental and geotechnical applications such as contaminant remediation in soils, grout injection, and landfill-liner design. The main goal of this study is to understand the effect of EM waves and their characteristics (frequency, power, radiation pattern, etc.) on the hydraulic conductivity of soils of various types and characteristics (clay and sand).

2. Background

The fact that water flows implies the existence of a gradient of energy. The measure of energy available for flow is represented by the height of water in a manometer above an arbitrary datum. Higher water levels cause greater availability of energy for flow. The hydraulic head (otherwise known as total head) consists of three components related to elevation, pressure, and velocity.

The permeameters used in this experiment are encased in resonant cavities. A resonator is a device or system that exhibits resonance or resonant behavior, meaning it naturally oscillates at some frequencies called its resonant frequencies with greater amplitude than that of other frequencies.

A potential mechanism that can cause the alteration in the hydraulic conductivity of the soil samples of this work is dielectrophoresis (DEP). DEP is a phenomenon in which a force is exerted on a neutral, dielectric particle when it is subjected to a nonuniform electric field (Pohl, 1978). Unlike traditional cases of dielectrophoresis, in this case the background would theoretically be the porous soil skeleton, and the particles would be water molecules. This equation describing the induced dielectrophoretic force, $\vec{F}_{DEP}$(N), can be described as follows:

$$\vec{F}_{DEP}=2\pi r^3 \varepsilon_m^* Re\left\{\frac{\varepsilon_p^*-\varepsilon_m^*}{\varepsilon_m^*}\right\}\nabla\left|\vec{E}\right|^2 \tag{3}$$

where E is the nonuniform electric field (V/m), and r is the radius (m) of the homogeneous sphere of the particle (water molecules). The symbol *Re* in Equation (3) refers to the real part of a complex variable.

3. Materials and Methods

3.1 Experimental Setup

To experimentally model the effect of RF waves on hydraulic conductivity, a series of bench-top tests was conducted using rigid-wall permeameters. In this work, the permeameters were customized to measure the change in the hydraulic conductivity due to an RF wave launched using a monopole antenna (i.e., transmitter) into the soil medium contained within the permeameter. Another vertical monopole probe (i.e., receiver) is used to measure the electric field within the experimental setups. The laboratory-scale setup was modeled using COMSOL Multiphysics software, and the simulated electric field was validated against the experimentally measured Z component of the electric field.

The rigid-wall, cylindrical permeameters were prepared using acrylic and CPVC material to prevent interference with the RF wave. Figure 1 shows schematics of the setups. The permeameter used for the clayey sample has a diameter of 152 mm and a height of 190 mm, containing soil samples of 76 mm in length (L). The entire body of the permeameter was contained within a 200-mm × 200-mm × 230-mm RF cavity constructed of aluminum mesh. The permeameter was filled with soil in three layers, each 2.54 cm (1 in.) thick, until it was filled the desired 76 mm (3 in.) length of the soil sample (L). The water used for this test was deaerated and deionized. The effect of RF waves on the natural water existing in the environment can be different. However, at this stage of the study, a controlled environment was necessary. It was understood that the cations existing in the clay structure could be washed away by the flow of deionized water with a volume equal to multiple times the sample’s void volume. Nevertheless, repeated flow through the same clay sample

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during the preliminary experiments did not show any sudden change in the hydraulic conductivity. Deaerated water was used to eliminate air entrapment in the soil when the flow direction was changed to a downward direction to study the RF effect while the flow direction was varied.

Sand experiments were similar to clay experiments, except the size of the sample was different. The permeameter for the sand experiment had a diameter of 100 mm and a length of 250 mm, containing soil samples of 150 mm in length (L). In order to measure the flow rate, Q (m^3/s), water flowing out of the plastic drainage tube was collected in a 500-mL graduated cylinder at measured durations, t.

The transmitting, monopole antenna used to launch RF waves was made of an RG8 coaxial cable with 50 mm of its outer conductive shield stripped, cased within a CPVC tube, and submerged into the medium. A continuous-wave (CW) RF signal was generated using an Agilent Model # E4400B signal generator and amplified using an amplifier (RF Lambda Model # 100LM8, manufactured by Amplifier Research). The entire system (i.e., antenna, soil medium, and cavity) was impedance matched with the 50-Ω amplifier using a matching network. The matching network consists of two two-gang variable capacitors built in a BUD box (an aluminum box to contain the EM waves). The impedance measurement was performed using an Agilent N9320A vector network analyzer.

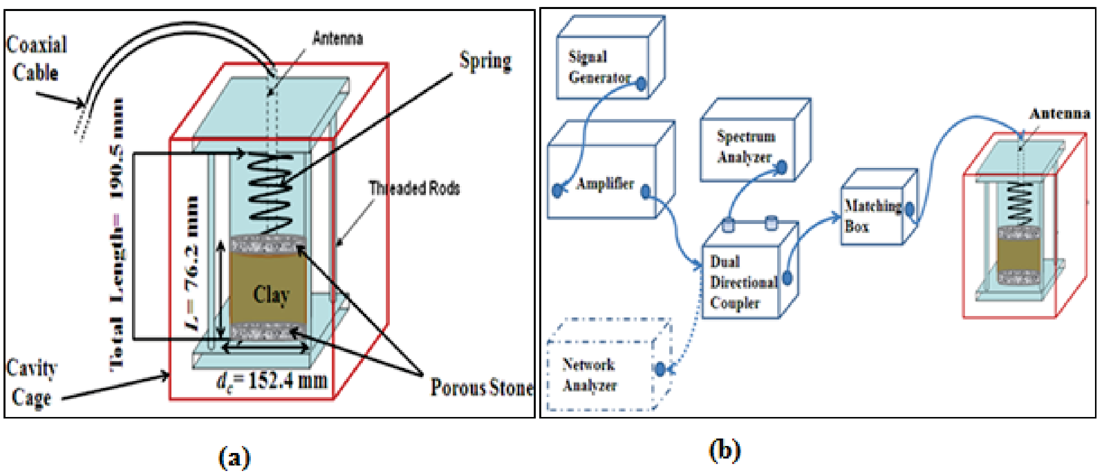


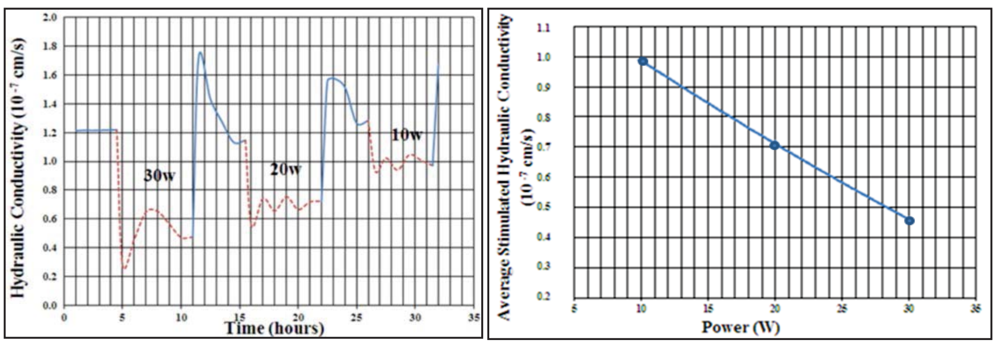
FIG. 1. Schematic of rigid-wall, cylindrical permeameter (d_c: soil sample diameter, L: length of soil sample) designed for EM stimulation of: (a) clayey samples within resonant cavity; (b) schematic of instruments and setup.

4. Summary and Results

Bentonite Clay Sample, Falling-Head-Test (ASTM D5084-10, 2006): The RF stimulation was conducted on the Bentonite sample with a 30-W input power carried out within 3 consecutive days. The tests were implemented at frequencies of 80, 94, and 153 MHz. Pre-stimulation, the hydraulic conductivity was allowed to stabilize to values roughly between 0.75 $\times 10^{-7}$ cm/s and 1.1 $\times 10^{-7}$ cm/s, typical of clay [7]. During the first half hour of RF excitation, the stimulation (dashed line in Figure 2a) caused a sharp decrease in the hydraulic conductivity (k) through the clay. The reduction of k in this period of stimulation was different for each frequency. At 153 MHz, the permeability of the sample decreased from 1×10^{-7} cm/s to about 2.6×10^{-8} cm/s, a reduction to ¼ of the initial unstimulated hydraulic conductivity. The sharp decline in k at the frequencies of 80 and 94 MHz were about 4/5 and 1/2 of the initial unstimulated values, respectively. RF stimulation (dashed lines) was continued about 6 hours in each cycle. Right after the sharp reduction in k, some degree of relaxation occurs during the stimulation. The frequency of 153 MHz resulted in a much larger reduction of k compared to the other two frequencies. This could be related to the resonance and radiation pattern at this frequency and relaxation mechanisms of water molecules in response to RF waves. In other words, cavities of various sizes, and in turn various resonant frequencies, are necessary to truly evaluate the RF-frequency effect —independent of cavity size and corresponding resonance— on hydraulic conductivity. Termination of RF stimulation (solid lines in Figure 2a) caused an increase to a value greater than the average pre-stimulation hydraulic conductivity of the clay sample, referred to as rebound. This rebound relaxes after 10-12 hours.

To evaluate the effect of the RF power and electric-field intensity on the reduction of the clay sample's *k*, the stimulated experiment was replicated at 153 MHz but at three power levels (10, 20, and 30 W). The experiment was continued for 33 hours. In each cycle of RF stimulation from on (dashed lines) to off (solid lines), the duration of the stimulation was constant, and the RF power level was gradually reduced in subsequent cycles. Figure 2b reveals that higher electric-field intensities result in larger reductions in the permeability. Figure 2b also shows the average stable value of *k* versus the RF power. It appears that the reduction in the average hydraulic conductivity of the clay samples will be smaller at lower RF powers. The power level of 30 W achieves the most reduction in the clay permeability to 2/5 of the initial value.

Sand Sample's Constant-Head Test (ASTM D2434-68, 2006): The RF stimulation was conducted on the sand sample at 20-W input power carried out within 60 hours. The test was implemented at a frequency of 153 MHz. Pre-stimulation, the hydraulic conductivity was allowed to stabilize to a value roughly at 2.19×10^{-4} cm/s (Figure 3), typical for sand (Fetter, 2001). During the first hour of RF excitation, the RF stimulation (dashed lines in Figure 3) caused an increase in the hydraulic conductivity through the sand. In the first cycle of the stimulation, the permeability increased from 2.19×10^{-4} cm/s to about 2.5×10^{-4} cm/s, an increase of 14%. RF stimulation was continued about 20 hours in each cycle. Within 5 hours after the sharp increase in *k*, some degree of relaxation occurred during the stimulation. Termination of RF stimulation (solid lines of Figure 3) caused a sudden decrease in the hydraulic conductivity until it stabilized at its typical value of *k*, after about 5 hours. It took about 15 hours for the unstimulated hydraulic conductivity to stabilize at typical *k* values. Then a second cycle of RF stimulation started with similar results.



(a) **(b)**

FIG. 2. (a) Change in hydraulic conductivity at a constant frequency of 153 MHz and power levels of 30, 20, and 10 W (solid line: unstimulated; dashed line: RF-stimulated) and (b) average change in hydraulic conductivity versus RF power level.

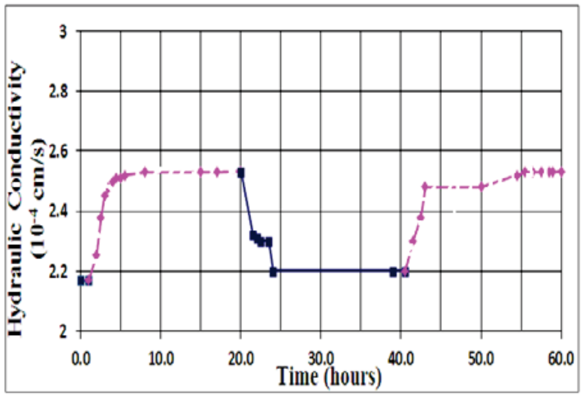


FIG. 3. Variation of hydraulic conductivity of a sandy soil sample under RF stimulation, power output of 20 W (solid line: unstimulated; dashed line: RF-stimulated) at a frequency of 153 MHz.

5. Experimentally Validated Simulation

Acquiring the full 3D vector electric field is necessary to correlate the RF waves and alteration of hydraulic conductivity. Hence, the permeameter containing the soil, water, resonant cavity, and coaxial antenna was modeled using COMSOL Multiphysics. The RF effect on flow was considered. However, even though the flow of water might affect the EM waves, any possible effect from the laminar flow on the EM waves was neglected. Hence, this model was used to enable the visualization of the EM field without simulating the seepage flow. Typical electrical properties of water and Bentonite clays were assigned to the model (Von Hippel, 1969).

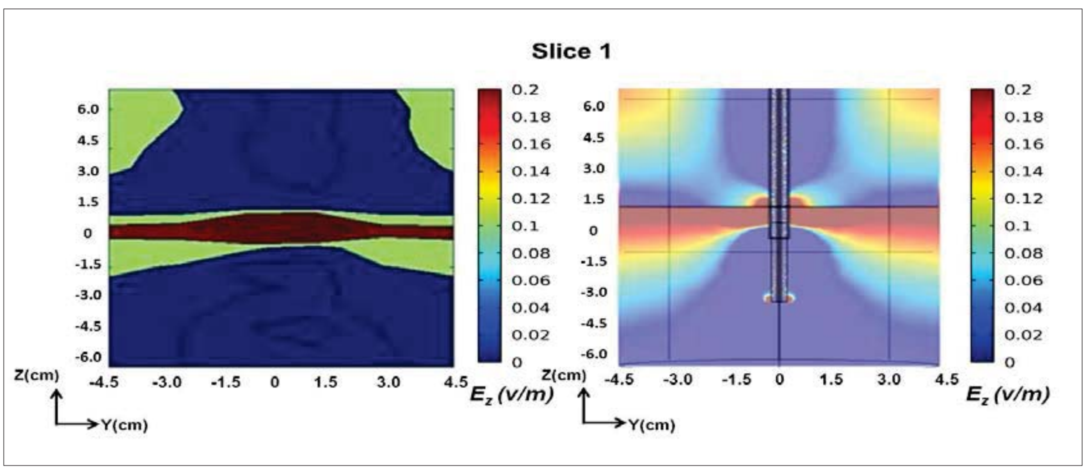


FIG. 4. Contour maps of experimentally measured *amplitude* (left) and simulated Z component using COMSOL Multiphysics (right) of electric field on: (a) Slice 1 through the center.

The electric field was then mapped in the test region using a 3D computer-controlled translation table. The experimental measurements were used to validate the Z component of the simulated electric field. A typical slice is shown in Figure 4. As seen, the equivalent slice provide the same pattern of the electric field. The probe is not a calibrated probe. Hence, experimental measurements are representatives of the electric-field pattern, and absolute values do not match.

6. Mechanisms Behind EM Effect on Hydraulic Conductivity

A potential mechanism that can cause the alteration in the permeability of the soil samples is dielectrophoresis (DEP). In order to measure the dielectrophoretic force applied to the water, flowing through the saturated soil (with a bulk dielectric constant), water should not be viewed as the background. In other words, the background would be the dry soil skeleton, and the particles would be the water molecules. This is not the traditional view of dielectrophoresis. However, for our evaluation of dielectrophoresis as the potential mechanism behind the RF waves' effect on hydraulic conductivity, this viewpoint can be justified. Since the dielectric constant of the particles (water molecules in this case, $\varepsilon_p^* \approx 81$) is higher than that of the medium (dry Bentonite clay in this case, $\varepsilon_m^* = 2.38$), dielectrophoresis would exert a force to the particles (water molecules) moving them toward the area of lower electric-field intensities. The dielectrophoretic force was calculated using simulated electric fields, using a code developed in MATLAB interface. The three components of the simulated electric field developed using COMSOL were imported as a matrix into MATLAB. The imported matrices contained the three electric-field components at all nodes on a 100-mm × 100-mm horizontal grid and 120-mm × 170-mm vertical grid on the cross-sectional (horizontal) and depth (vertical) slices, respectively. A MATLAB script (*m.file*) was then developed using a central finite-difference method to calculate the gradient of the squared electric field, $\vec{\nabla}|E|^2$ based on the following discretized equation where *r* is the particle diameter, and ε^*_m and ε^*_p are the dielectric permittivity of the particles and background.

$$\vec{F}_{DEF} = 2\pi r^3 \varepsilon_m^* \operatorname{Re}\left\{\frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_m^*}\right\} \vec{\nabla}|E|^2$$
$$= 2\pi r^3 \varepsilon_m^* \operatorname{Re}\left\{\frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_m^*}\right\}\left(\frac{|E|^2_{i,j+1,k} - |E|^2_{i,j-1,k}}{2dx}\hat{i} + \frac{|E|^2_{i+1,j,k} - |E|^2_{i-1,j,k}}{2dy}\hat{j} + \frac{|E|^2_{i,j,k+1} - |E|^2_{i,j,k-1}}{2dz}\hat{k}\right) \quad (4)$$

Figure 5 shows the X and Z components of the dielectrophoretic force on the depth and cross-sectional slices for the clayey and sandy soil samples, respectively. According to Figure 5b, the Z-component of the force is negative in the soil domain and positive closer to the water domain. In other words, the direction of the dielectrophoretic force is in the negative Z-direction (i.e., downward) within the majority of the soil domain and reverses as it approaches the top of the soil. This works as a barrier against the flow regardless of the seepage flow direction. This is in agreement with the observation that the change of flow direction does not affect the nature of the EM effect on the flow. However, it can be observed that the value of the F_{DEF} force in the Bentonite clay sample is four times larger than in the sandy soil sample. The result is in agreement with the results from the experimental investigation of the Bentonite clay sample, since the seepage flow direction of water was upward —opposite the dielectrophoretic force— while a reduction of the permeability was observed during the application of the EM waves. Moreover, the same force vector direction was observed for the sandy soil while an increase in hydraulic conductivity was observed during the experimental investigation, which results in a disagreement between the direction of the dielectrophoretic force and alteration of flow rate. The energy absorbed by the water could reduce the viscosity and hence increase the hydraulic conductivity of the sand. However, the cation complex in the clay could be the factor causing the reduction of the hydraulic conductivity of the clay.

On the other hand, the X-component of the force creates a force that drags the water away from or toward the center of the permeameter (Figure 5a). The magnitude of the horizontal component is almost 1/40 the vertical component of dielectrophoretic forces, for both soil samples.

The temperature of the medium was also recorded. The temperature was recorded at 1-minute intervals for a test at one of the applied frequencies (153 MHz) at 30 W of power. The total temperature variation at that frequency over about 11 hours of RF stimulation was only 1.6ºC. The temperature variation between the center and boundary of the cylindrical soil sample was only 0.1ºC. Therefore, even though the temperature change and gradient can cause a minor convective flow, the small temperature increase within the medium may not be strong enough to create such strong convective flow, causing the change in *k* —especially in clay. In addition, a convective flow due to the generated heat would not cause the relaxation and rebound behavior observed in both sandy and clayey samples.

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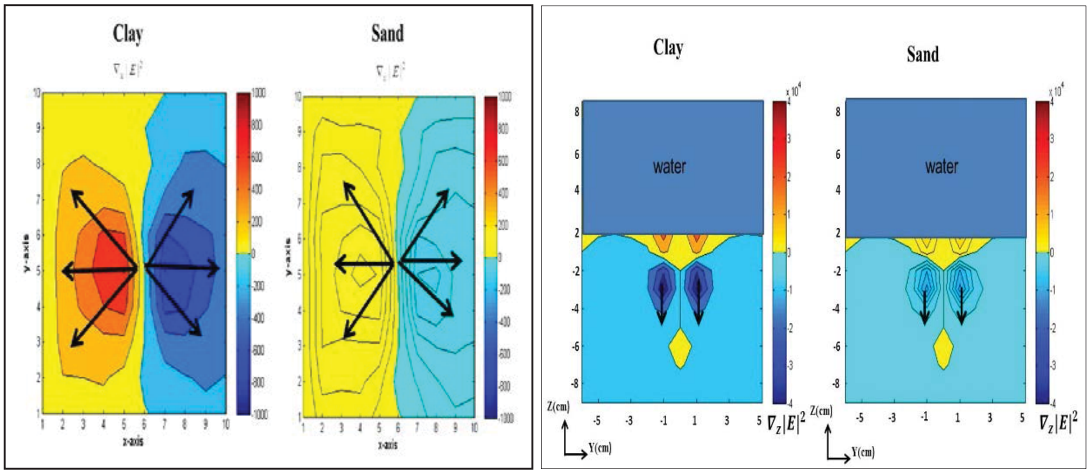

(a) **(b)**

FIG. 5. Dielectrophoretic force: (a) X component ($\nabla_x |E|^2$) on a cross-sectional slice, 5 cm from bottom of permeameter and (b) Z component ($\nabla_z |E|^2$) on a depth slice, 0 cm from antenna.

7. CONCLUSION

This work demonstrated two opposite effects by RF waves on the hydraulic conductivity of clayey and sandy soils. Dielectrophoresis can be the cause of rapid reduction in the hydraulic conductivity of clay. However, even though dielectrophoresis exists in sand, it is much weaker and dominated by other factors such as the RF energy absorbed by water, resulting in an increase in its hydraulic conductivity.

The results show that dielectrophoresis is not the mechanism governing the increasing effect on the hydraulic conductivity of the sand sample. A potential cause could be the fact that the EM energy absorbed by water reduces its viscosity and hence increases the hydraulic conductivity. In the case of clay, the results cannot conclusively prove whether dielectrophoresis is the governing mechanism decreasing the hydraulic conductivity. The effect of EM waves on the double-diffuse layer and cation exchange complex of clay could be the cause behind the decrease in the hydraulic conductivity of clay. More experiments and analysis are needed to further investigate these hypothesis.

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