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Consequences of Electromagnetic Stimulation on 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, any 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 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 the characteristics of the RF stimulation. The change is, however, different for sandy and clayey soils.

1. INTRODUCTION

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 [1]. During other research on the use of RF waves to enhance soil remediation [2], 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 [3]. Understanding the relation between RF stimulation and hydraulic conductivity could have a broad use in geoenvironmental and geotechnical applications such as contaminant remediation in soils, grout injection, and landfill-liner design.

2. METHODOLOGY

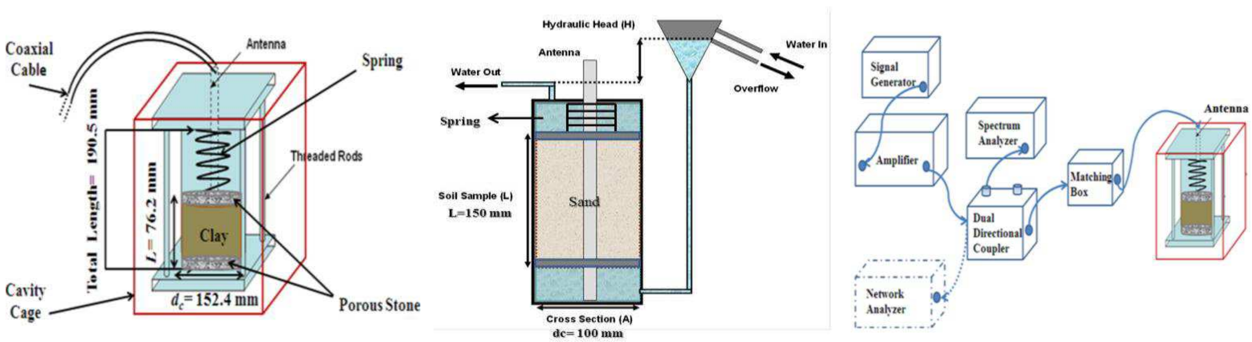
To experimentally model the effect of RF waves on hydraulic conductivity, a series of bench-top tests was conducted using rigid-wall permeameters. In this work, the permeameters were customized to measure the change in the hydraulic conductivity due to an RF wave launched into the medium contained within the permeameter. A vertical monopole probe 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.

3. EXPERIMENTAL SETUP

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 is 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 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 is necessary. It is understood that the cations existing in the clay structure can 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 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 downward to study the RF effect while flow direction was varied.

Sand experiments are similar to clay experiments, except the size of the sample is different. The permeameter for the sand experiment had a diameter of 100 mm and 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 monopole antenna, used to launch RF waves, was made of an RG8 coaxial cable with 50 mm of its conducting shield stripped, cased within a CPVC tube, 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.



(a) (b) (c)

Figure 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, (b) sandy samples, and (c) schematic of instruments and setup.

4. SUMMARY AND RESULTS

4.1. Bentonite Clay Sample, Falling-Head-Test [4]

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 0.75×10^{-7} cm/s and 1.1×10^{-7} cm/s, typical of clay [5]. During the first half hour of RF excitation, the stimulation (dashed line in Figure 2(a)) caused a sharp decrease in the hydraulic conductivity 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 1/4 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 results 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 2(a)) 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 2(b) reveals that higher electric-field intensities result in larger reductions in the permeability. Figure 2(b) 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 sample will be smaller at lower RF power. The power level of 30 W achieves the most reduction in the clay permeability, to 2/5 of the initial value.

4.2. Sand Sample Constant-Head Test [6]

The RF stimulation was conducted on the sand sample with a 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 [5]. 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 occurs 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.

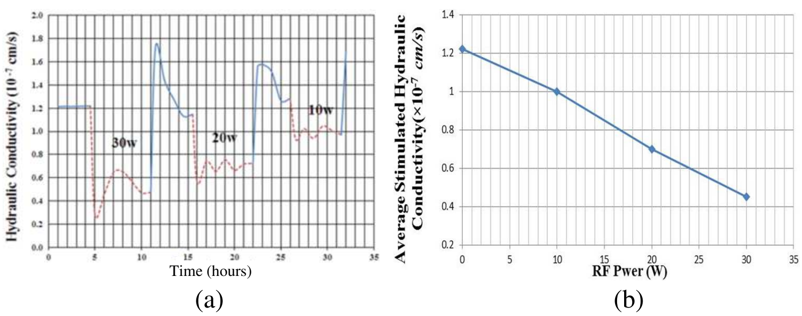


Figure 2: (a) Change in hydraulic conductivity at a constant frequency of 153 MHz and power levels of 30, 20, and 10 W (solid line: unstimulated; dashed line: RF-stimulated) and (b) average change in hydraulic conductivity versus RF power level.

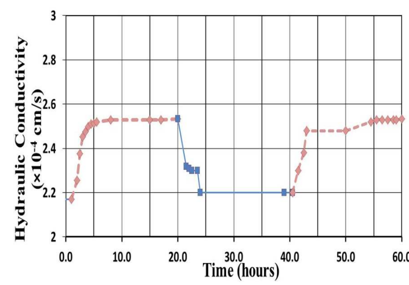


Figure 3: Variation of hydraulic conductivity of a sand sample under RF stimulation, power output of 20 W (solid line: unstimulated; dashed line: RF-stimulated) at a frequency of 153 MHz.

5. EXPERIMENTALLY VALIDATED SIMULATION

Acquiring the full 3D vector electric field is necessary. 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 water affects the EM waves, the effect from the laminar flow on the EM waves was neglected. Hence, this model was used only 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 [7].

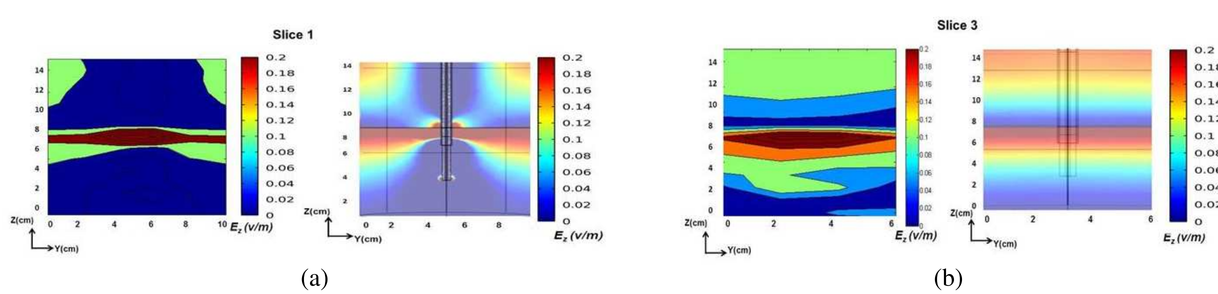


Figure 4: Contour maps of experimentally measured *amplitude* (left) and simulated *Z component* using COMSOL Multiphysics (right) of electric field on: (a) centric Slice 1 through the center and (b) Slice 3, 4 cm from the center.

Then the electric field was 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. Typical slices are shown in Figure 4. As seen, the equivalent slices 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

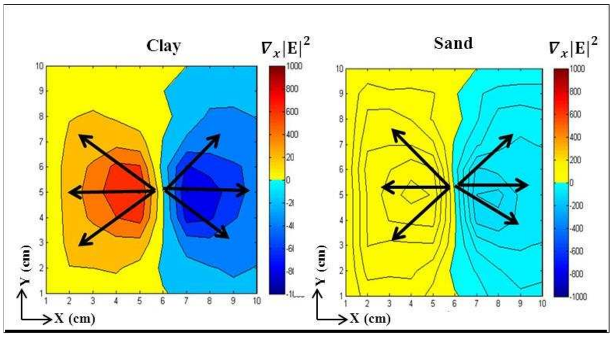
A potential mechanism that can cause the alteration in the permeability of the soil samples is dielectrophoresis (DEP). In order to measure the force applied to the water, flowing through the soil, saturated soil (with a bulk dielectric constant) should not be viewed as the background. In other words, 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-stimulation effect, 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 $\times$ 100-mm horizontal grid and 120-mm $\times$ 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, $\nabla|E|^2$, 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.

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

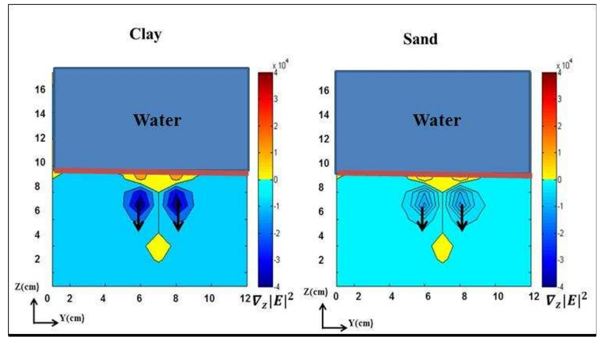
Figure 5 shows the X and Z components of the dielectrophoretic force on the depth and cross-sectional slices for the clay and sand samples, respectively. According to Figure 5(b), the Z-component of the simulated force is negative in the soil domain and positive closer to the water domain. In other words, the direction of the simulated dielectrophoretic force is in the negative Z-direction (i.e., downward) within the majority of the soil domain and reverses approaching the top of the soil. The resultant of these two is always downward regardless of the flow direction (i.e., resists upward flow and helps downward flow). However, the change in the direction of F_{DEP} within the sample could act as a barrier for the seepage flow regardless of the flow direction. As mentioned, regardless of the seepage flow, a reduction in the k of the clay sample is always experimentally observed. This cannot conclusively prove or refute the hypothesis about the role of dielectrophoresis on the experimentally observed reduction of hydraulic conductivity of clay by EM waves, which is independent of the seepage flow direction.

On the other hand, it can be observed that the value of F_{DEF} force in the clay sample is four times larger than in the sand sample. Moreover, the same simulated force vector direction was observed for the sand 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. 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 5(a)). The magnitude of the horizontal component is almost 1/40 the vertical component of dielectrophoretic forces, for both soil samples. 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.

The temperature of the medium was 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 1.6°C. The temperature variation between the center and boundary of the cylindrical soil sample was only 0.1°C. 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 sand and clay samples.



(a)



(b)

Figure 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 energy absorbed by water, resulting in an increase in its hydraulic conductivity.

ACKNOWLEDGMENT

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